GENERAL SENIOR SYLLABUS 2025

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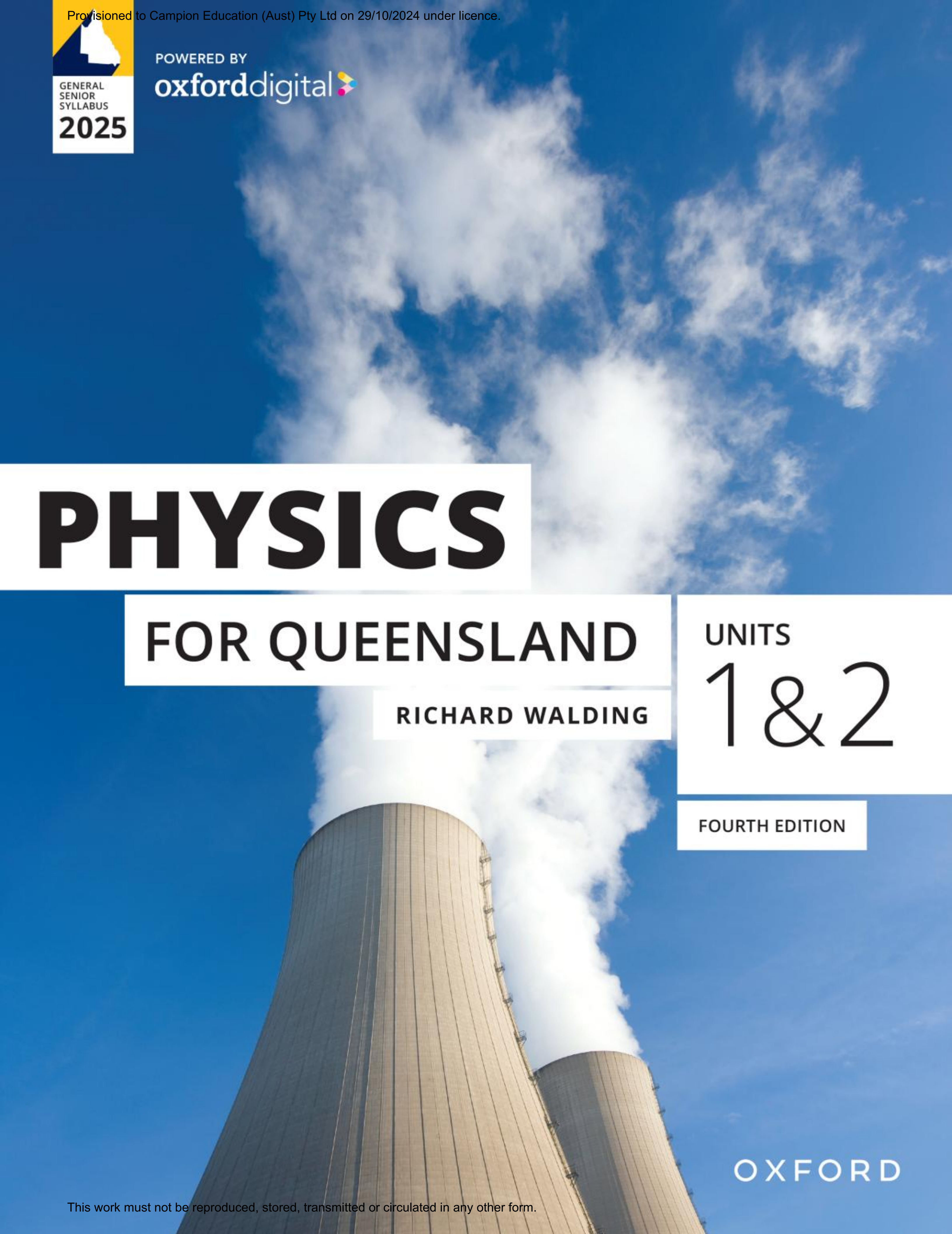

PHYSICS FOR QUEENSLAND

UNITS 1&2

RICHARD WALDING

FOURTH EDITION

OXFORD

GENERAL SENIOR SYLLABUS 2025

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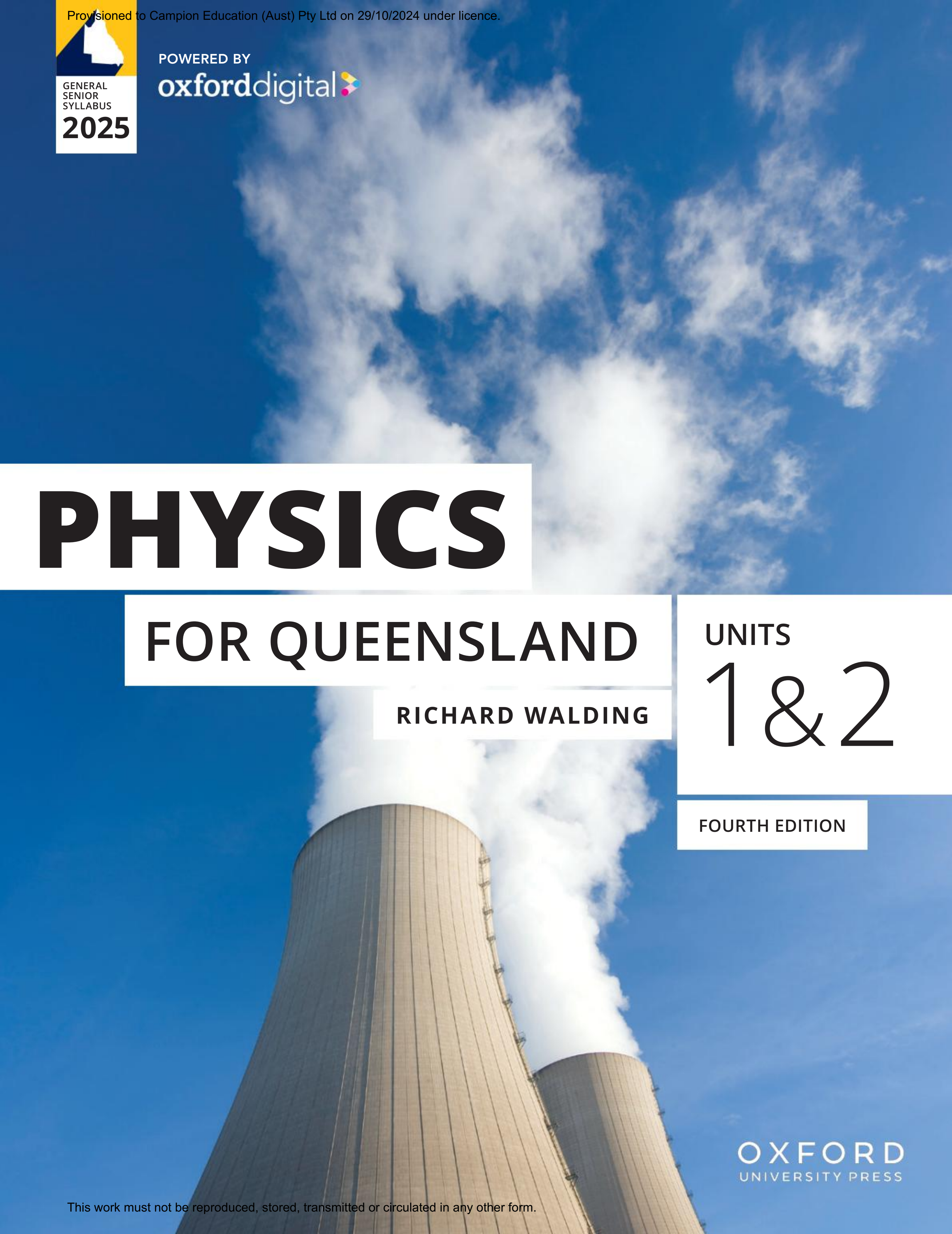

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Warning to First Nations Australians
Aboriginal and Torres Strait Islander peoples are advised that this publication may include images or names of people now deceased.

Contents

Lessons available on Oxford Digital.

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Introducing *Physics for Queensland Units 1 & 2* (Fourth edition)

Congratulations on choosing *Physics for Queensland Units 1 & 2* as part of your studies this year!

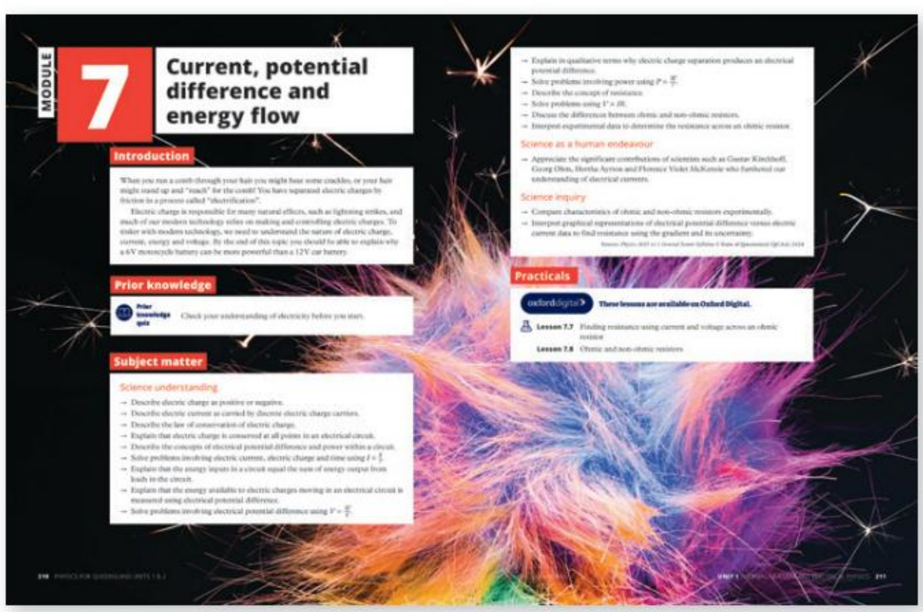
Physics for Queensland Units 1 & 2 has been purpose-written to meet the requirements of the QCAA Physics 2025 General senior syllabus. It includes a range of flexible print and digital products to suit your school and incorporates a wide variety of features designed to make learning fun, purposeful and accessible for all students!

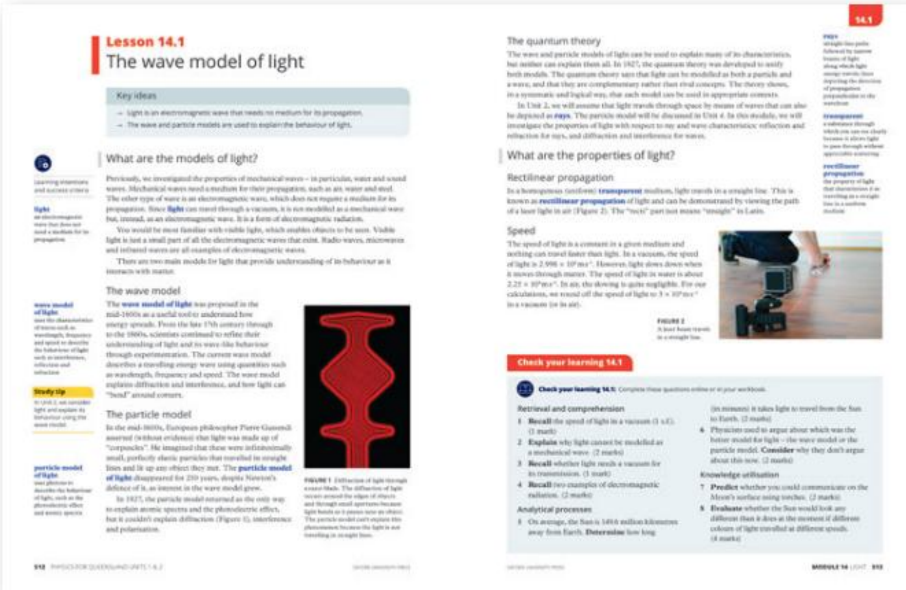
Key features of the Student Books

The Physics toolkit module provides an overview of the syllabus, student-friendly guidance for every science inquiry skill and tips for success on assessment tasks.

Each module begins with a module opener that includes:

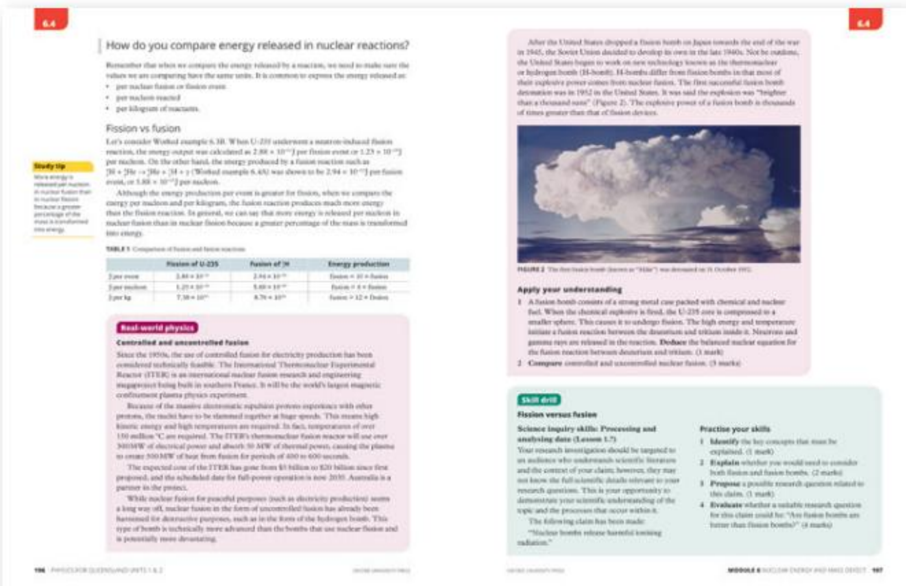
- QCAA subject matter
- reference to a supporting prior knowledge quiz that assesses and informs student understanding of pre-requisite concepts
- a list of practical lessons that support science inquiry




Lesson 14.1
The wave model of light
What are the models of light?
The wave model
The particle model
The quantum theory
What are the properties of light?
Rectilinear propagation
Speed
Check your learning 14.1

Each lesson includes:

- **learning intentions and success criteria**
- clearly structured content written in clear, concise language
- definitions for all key terms on the page
- engaging, relevant and informative images and illustrations
- a range of tips and features designed to bring course content to life including **study tips, worked examples, skill drills** and examples of **real-world science applications**
- references to supporting **digital resources**
- **Check your learning** activities organised according to **Marzano and Kendall's taxonomy** and incorporating cognitive verbs.xonomy and incorporating **cognitive verbs**.


How do you compare energy released in nuclear reactions?
Fission vs fusion

Each module contains a range of practical activities designed to meet the requirements of science understanding and science inquiry subject matter and develop science inquiry skills.

Find out more

For a complete overview of all the features and benefits of this Student Book – as well as helpful videos showing you how to get the most out of the series:

> activate your digital access (using the instructions on the inside front cover of this book) and click on "Introducing *Physics for Queensland Units 1 & 2*" in the Course menu

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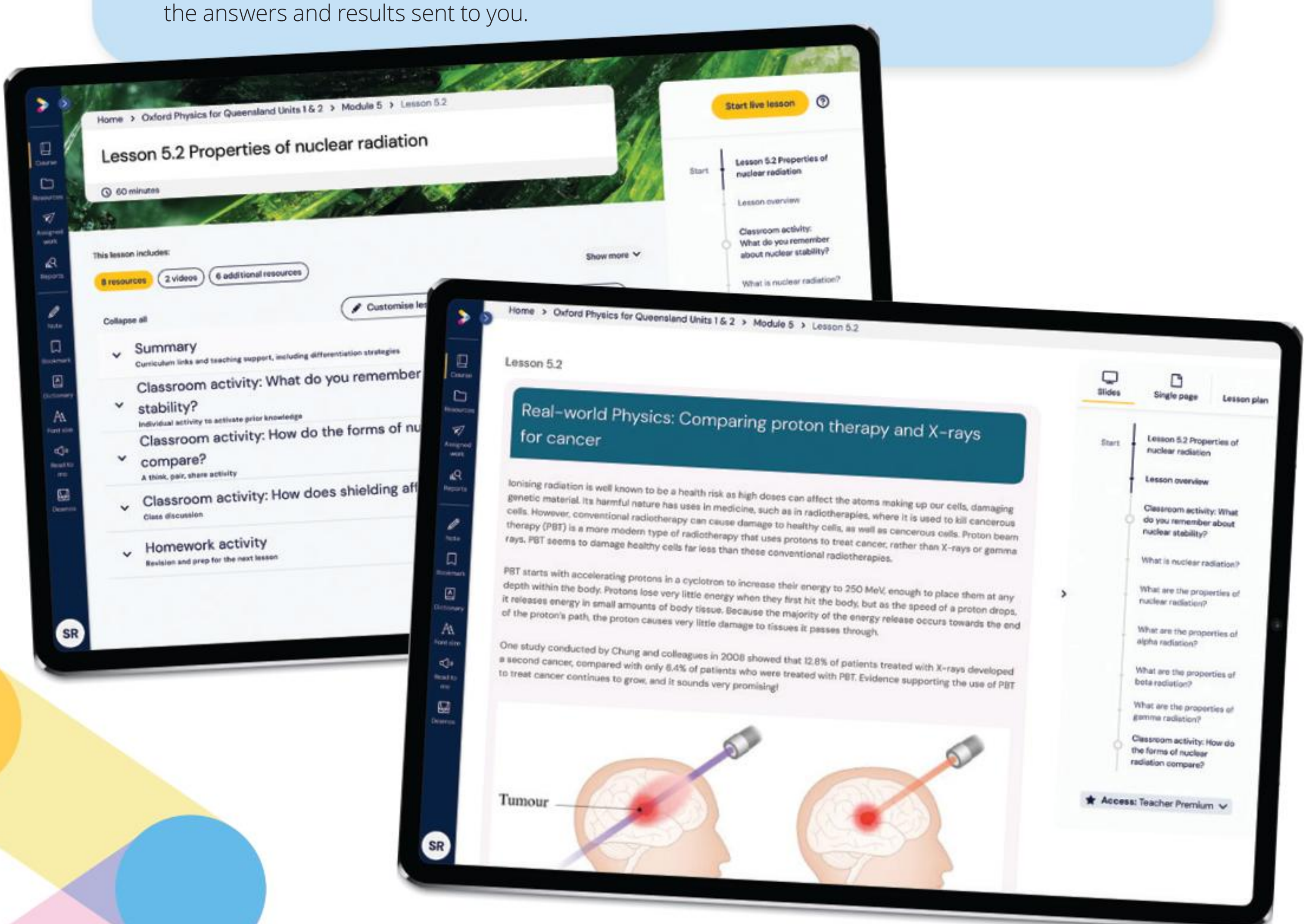

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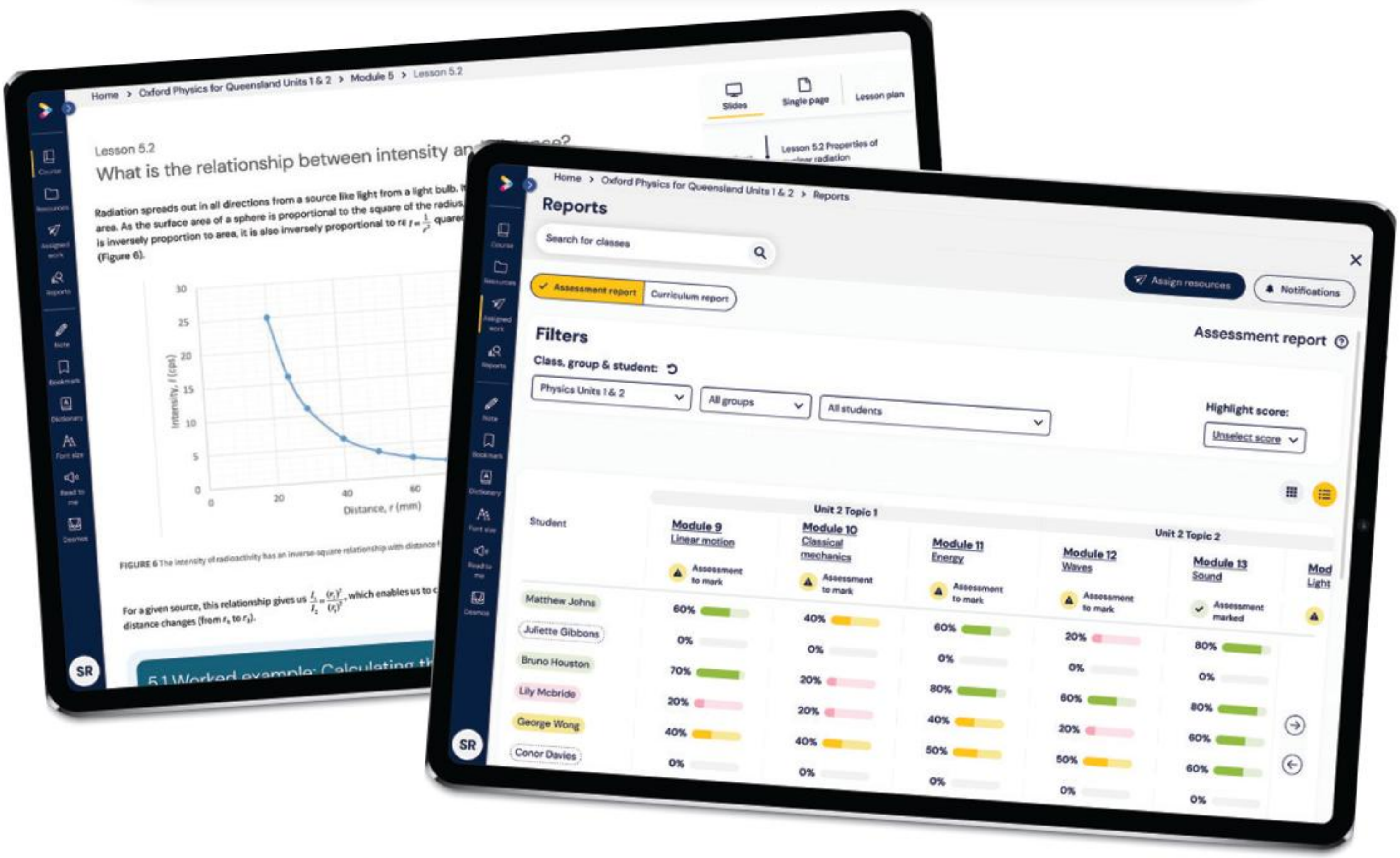

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Meet the authors & reviewers

Richard Walding

Author

Dr Richard Walding began his career as a scientist and has extensive experience teaching both Physics and Chemistry, including two decades as Head of Science. Richard is also a research fellow at Griffith University and for the past decade has been researching the history and applications of electromagnetic induction particularly as related to harbour defence. Richard was elected Fellow of both the Australian Institute of Physics and the Royal Australian Chemical Institute for his lifetime contribution to these disciplines. He was also awarded a Peter Doherty Award for work in STEM education and in 2019 received the Australian Institute of Physics (QLD Branch) Excellence in Physics Teaching award.

Bernice Zaro

First Nations consultant

Bernice is a proud Aboriginal and Torres Strait Islander Woman with a strong passion for educational greatness through culturally-inclusive learning. With family cultural heritage connection to the Gubbi Gubbi and Bundjalung of South East Queensland area and Kemer Kemer Meriam Nation and Maluligal Nation of the Torres Strait, she is inspired to share and learn continuously. Bernice along with her husband Aicey Zaro, a recognised traditional Artist, have been educating schools and communities through Cultural Awareness art workshops for over 15 years during their time managing the Zaro Cultural Gallery in the Burdekin region. Bernice has a passion for learning through her ongoing studies in Community Development, Child Wellbeing, Cultural Diversity and also sharing personal experiences through family, community and business, which inspire her to take on new opportunities.

Matthew Flinders

Reviewer

Matthew completed a Bachelor of Science and Bachelor of Education at the University of Queensland. For the last 18 years, he has worked in both state and independent schools, enjoying a teaching load of mainly Science and Physics. He is the Physics Coordinator at Hillbrook Anglican School, where he is also involved in many other aspects of the school, such as data analysis.

Reeja Mathew

Reviewer

Since completing a Bachelor's degree in Education and a Master's degree in Physics at Mahatma Gandhi University (Kerala, India), Reeja Mathew has been teaching QCE Physics and Engineering in Queensland state schools over the past 13 years. She also has a long-standing involvement with QCAA, contributing as a Physics panel member in the old QCE system and now, holding various assessor roles in the new QCE system.

We would also like to acknowledge and thank Adam Warren, Andrew Chung, Anja van Hooydonk, Carla Kalweit, Michael Tomlin and Timothy Butler for their contributions.

MODULE 1 Physics toolkit

Introduction

Physics, like the other sciences, is all about explaining the natural world. Measurement is at its very heart. Ever since humans have been thinking about their place in the universe, they have been making measurements. There are many different things that humans measure, and therefore there are different types of measurement and different ways of interpreting the measurements taken. As you study physics, you will learn about how different questions have been solved. Eventually, you will ask your own questions and make your own measurements.

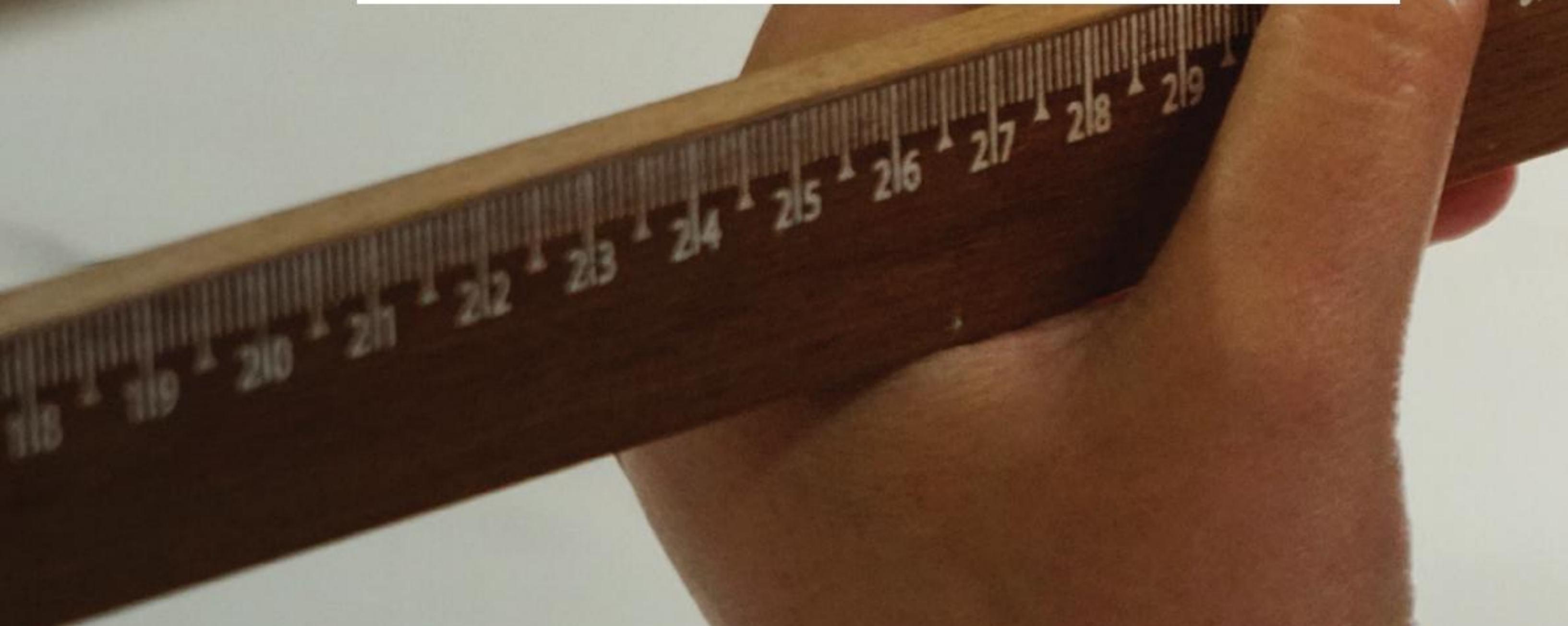
This module will become a useful reference throughout Units 1 and 2 of Physics. Physics applies a rigorous scientific method to collect information and test theories, so in some ways this module tells you many of the most important things in all of physics. It *should* come first!

This module is set out in a way that makes each piece of information easy to access. It is not meant to be read from beginning to end. Rather, it's like a toolbox – you dip your hand into it, get the tool you need and then use it.

Prior knowledge

Prior knowledge quiz

Check your understanding of the science inquiry skills before you start.



oxforddigital Full lessons for this module are available on Oxford Digital.

Online-only Lessons

Lesson 1.2 Considering First Nations perspectives in Physics
Lesson 1.3 Understanding the scientific method
Lesson 1.4 Planning investigations
Lesson 1.5 Considering safety and ethics
Lesson 1.6 Collecting data
Lesson 1.8 Evaluating evidence
Lesson 1.9 Communicating scientifically
Lesson 1.10 Preparing for your data test
Lesson 1.11 Conducting your student experiment
Lesson 1.12 Conducting your research investigation
Lesson 1.13 Preparing for your exams

Lesson 1.1
Studying QCE Physics

Key ideas

→ In QCE Physics, you will gain a variety of science understanding and inquiry skills that will help you succeed in assessments, as a scientific professional, and as a science citizen.

Rationale

Learning intentions and success criteria

Physics aims to develop students':

- appreciation of the wonder of physics and the significant contribution physics has made to contemporary society
- understanding that diverse natural phenomena may be explained, analysed and predicted using concepts, models and theories that provide a reliable basis for action
- understanding of the ways in which matter and energy interact in physical systems across a range of scales
- understanding of the ways in which models and theories are refined, and new models and theories are developed in physics; and how physics knowledge is used in a wide range of contexts and informs personal, local and global issues
- investigative skills, including the design and conduct of investigations to explore phenomena and solve problems, the collection and analysis of qualitative and quantitative data, and the interpretation of evidence
- ability to use accurate and precise measurement, valid and reliable evidence, and scepticism and intellectual rigour to evaluate claims
- ability to communicate physics understanding, findings, arguments and conclusions using appropriate representations, modes and genres.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

What is physics?

physics
the systematic study of energy and matter and how they interact with each other to explain observed phenomena

Physics is fundamentally concerned with energy and matter, and how they interact with each other. It deals with energy in the form of heat, radiation, electricity, motion, sound, light, magnetism and gravity, and explains how energy is transferred and transformed. Physics deals with matter on scales ranging from tiny subatomic particles to stars, galaxies, the edge of the universe and beyond.

Physics is not just about observing the universe. It is an experimental science – it measures and probes the world to formulate and test hypotheses. The results of these experiments are used to formulate models, laws and theories (usually expressed mathematically), and this allows us to predict other phenomena. However, models and laws are not unchanging – the ideas are quite dynamic. Some models used in physics decades ago have been modified or discarded as new information and understandings have become known. Such an example is the Higgs field to account for the mass of particles. This new idea was proposed in 1960s and confirmed 50 years later. Other ideas have been around for a century or more and have not changed.

Physics doesn't just deal with theoretical ideas. It has a practical role in nearly every sphere of human activity, such as the development of sustainable and efficient forms of energy production, biomechanics and the understanding of athletic performance, reducing noise pollution by acoustic design, and monitoring earthquakes and tsunamis. Physics is also called upon to answer some of the most fundamental questions about human existence.

Many physicists are researchers working to find answers to some of these fundamental questions. Their answers often lead to unexpected technological applications. For example, all the technology we rely on today, including computers, mobile phones and the internet, is based on a theoretical understanding of electric fields developed in the 1830s.

Whether physicists are researchers or work in industry developing new products, they all problem-solve. They take a situation and apply their knowledge and understanding of physics principles, models and laws to improve on what has been done before. Physicists are also the ones who say to manufacturers who ask for their product to be made faster, cheaper and safer, “You can only choose two of those”. A physicist will often be the one to remind others that you can’t break the laws of thermodynamics. They can give sound advice.

Their ability to problem-solve and tackle challenging questions allows them to work in diverse industries outside of the laboratory, such as in museums, the military, teaching in high schools, lecturing at universities, in hospitals, power generation and distribution companies, the IT industry, astronomical and meteorological observatories, in law firms, the finance sector, engineering firms and in businesses.

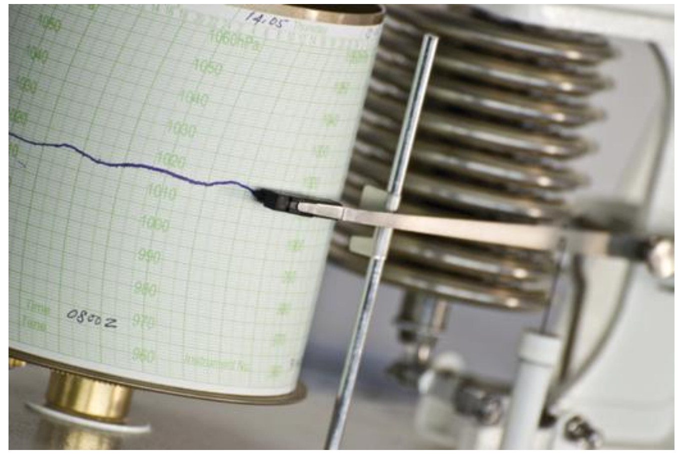


FIGURE 1 Physics has a role in monitoring earthquakes and tsunamis.

FIGURE 2 A physicist could be in charge of curating a museum exhibit to educate the general public about physics.

How is the QCE Physics course structured?

Studying QCE Physics provides you with the opportunity to engage in a range of inquiry tasks and develop science inquiry skills. You will develop an understanding of the ways in which matter and energy interact in physical systems to produce diverse natural phenomena, and be able to make links between theory, knowledge and practice.

Syllabus objectives

As for the other senior sciences, there are six syllabus objectives in QCE Physics.

1 **Describe ideas and findings**

Students use scientific representations and language in appropriate genres to give a detailed account of scientific phenomena, concepts, theories, models and systems.

2 **Apply understanding**

Students use scientific concepts, theories, models and systems within their limitations. They use algebraic, visual and graphical representations of scientific relationships and data to determine unknown scientific quantities or features. They explain phenomena, concepts, theories, models, systems and modifications to methodologies.

3 Analyse data

Students consider scientific information from primary and secondary sources to identify trends, patterns, relationships, limitations and uncertainty. In qualitative data, they identify the essential elements, features or components. In quantitative data, they use mathematical processes and algorithms. They identify data to support ideas, conclusions or decisions.

4 Interpret evidence

Students use their understanding of scientific concepts, theories, models and systems and their limitations to draw conclusions and develop scientific arguments. They compare, deduce, extrapolate, infer, justify and make predictions based on their analysis of data.

5 Evaluate conclusions, claims and processes

Students critically reflect on the available evidence and make judgements about its application to research questions. They extrapolate findings to support or refute claims. They use the quality of the evidence to evaluate the validity and reliability of inquiry processes and suggest improvements and extensions for further investigation.

6 Investigate phenomena

Students develop rationales and research questions for experiments and investigations. They modify methodologies to collect primary data and select secondary sources. They manage risks, environmental and ethical issues, and acknowledge sources of information.

Study tip

Your assessments in QCE Physics are mapped to these syllabus objectives. The data test (Lesson 1.10) assesses objectives 2 to 4. The student experiment (Lesson 1.11) and research investigation (Lesson 1.12) assess objectives 1 to 6. The external exam (Lesson 1.13) assesses objectives 1 to 4.

Subject matter

The structure of the QCE Physics course is laid out in the Physics General Senior Syllabus. The course consists of four units. Units 1 and 2 are completed in the first year of the QCE Physics course and Units 3 and 4 in the second year. Each unit is divided into topics and each topic can include science understanding, science as a human endeavour and science inquiry subject matter. You should be familiar with these categories of understanding from your studies in Years 7 to 10.

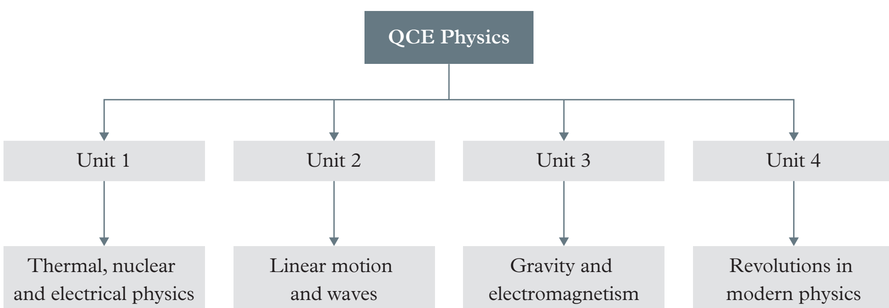


FIGURE 3 The structure of the QCE Physics course

An overview of the QCE Physics units is shown in Figure 3, and Units 1 and 2 are summarised in Table 1. Each unit has its own specific objectives, which are outlined in the Unit 1 and Unit 2 openers.

TABLE 1 Topics in Units 1 and 2 Physics

Unit 1 Thermal, nuclear and electrical physics	
Topic	**Description**
1. Heating processes	In this topic, you will learn about: • the kinetic particle model and specific heat capacity • phase changes and energy conservation.
2. Ionising radiation and nuclear reactions	In this topic, you will learn about: • the nuclear model and stability • energy and mass defect.
3. Electrical circuits	In this topic, you will learn about: • current, potential difference and energy flow • circuit analysis and design.

Unit 2 Linear motion and waves	
Topic	**Description**
1. Linear motion and force	In this topic, you will learn about: • linear motion • classical mechanics • energy.
2. Waves	In this topic, you will learn about: • wave properties • sound • light.

Source: Adapted from *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Assessment in QCE Physics

In Units 1 and 2, you can be assessed in several ways across the different topics. The syllabus requires that you:

- complete at least two, but no more than four assessments
- complete at least one assessment for each unit
- are assessed on each unit objective at least once.

Many schools assess students studying Units 1 and 2 as they would for students studying Units 3 and 4. This means that you will likely complete three assessment pieces and an end-of-year examination or examinations. One possible structure of your assessment is outlined in Table 2. Keep in mind that your school might choose to conduct the data test, student experiment and research investigation in any of Units 1 or 2.

TABLE 2 Units 1 and 2 assessments

Unit and assessment type	Assessment description	Assessment objectives
Unit 1 Thermal, nuclear and electrical physics: Data test	Students respond to items using qualitative data and/or quantitative data derived from practicals, activities or case studies from Unit 1.	2. Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits. 3. Analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits. 4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.
Unit 1 Thermal, nuclear and electrical physics: Student experiment	Students modify (i.e. refine, extend or redirect) an experiment relevant to Unit 1 subject matter to address their own related hypothesis or question. This assessment provides opportunities to assess science inquiry skills.	1. Describe ideas and findings about heating processes, ionising radiation and nuclear reactions, and electrical circuits. 2. Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits. 3. Analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits. 4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits. 5. Evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits. 6. Investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Unit and assessment type	Assessment description	Assessment objectives
Unit 2 Linear motion and waves: Research investigation	Students gather evidence related to a research question to evaluate a claim relevant to Unit 2 subject matter. This assessment provides opportunities to assess science inquiry skills and science as a human endeavour (SHE) subject matter.	1. Describe ideas and findings about linear motion and force, and waves. 2. Apply understanding of linear motion and force, and waves. 3. Analyse data about linear motion and force, and waves. 4. Interpret evidence about linear motion and force, and waves. 5. Evaluate processes, claims and conclusions about linear motion and force, and waves. 6. Investigate phenomena associated with linear motion and force, and waves.
Units 1 and 2 examination(s)		

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You can use Lesson 1.10 Preparing for your data test, Lesson 1.11 Conducting your student experiment, Lesson 1.12 Conducting your research investigation and Lesson 1.13 Preparing for your exams to guide you through these assessments. Note that science as a human endeavour content will not be directly assessed in your examinations.

What are the science inquiry skills?

In addition to developing your science understanding in physics (which we will cover in Modules 2 to 14), the QCE course requires you to develop and apply a range of science inquiry skills. These skills are specified in the QCE Physics General Senior Syllabus and are listed on the opening pages of this module. This module will help you develop these skills.

The science inquiry skills are applicable to all areas of study in Units 1 to 4 of the QCE Physics course. They are especially important for preparing and planning for your data test, student experiment and research investigation assessment tasks.

Check your learning 1.1

Check your learning 1.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the term “physics” in 10 words or less. (1 mark)

Analytical processes

2 **Distinguish** between “problem-solving” and “developing technology” as applied to the use of physics. (2 marks)

3 **Judge** whether this is true: “Physics is said to be an experimental science, so all physics theories have to come from experiments.” (2 marks)

Knowledge utilisation

4 **Investigate** what role physicists may play in the finance and business sectors. (2 marks)

5 **Evaluate** the statement “physics is a practical science”. Does it mean that all research has to have a practical outcome such as saving energy or making more powerful satellites? (2 marks)

6 **Propose** a response to this question from a friend: “How can they say the Big Bang really occurred when no one was there?” (1 mark)

7 **Propose** how physics might be used in chemistry and biology, and how physics relies on mathematics. (3 marks)

Lesson 1.2
Considering First Nations perspectives in Physics

Key ideas

→ First Nations peoples have longstanding scientific knowledge.

→ First Nations peoples have developed knowledge about the world by observing using all the senses, predicting and hypothesising, testing (trial and error), and making generalisations within specific contexts such as the use of food, natural materials, navigation and sustainability of the environment.

→ Correctly acknowledging cultural and/or language groups, rejecting deficit discourse, avoiding Eurocentrism and critically evaluating sources of information can help you to respectfully engage with First Nations perspectives in QCE Physics.

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- identify and implement strategies to manage risks, ethics and environmental impact, e.g.
  - cultural guidelines, protocols for working with the knowledges of First Nations peoples.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Learning intentions and success criteria

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Lesson 1.3
Understanding the scientific method

Key ideas

→ The scientific method is an iterative and cyclic process.

→ Research questions define the scope of an investigation. They can be used to develop hypotheses that predict the outcome of the investigation.

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- identify, research and construct questions for investigation
- propose hypotheses and/or predict possible outcomes.

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Learning intentions and success criteria

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Lesson 1.4
Planning investigations

Key ideas

→ A method outlines the steps followed in an experiment and lists all of the materials and equipment used.

→ Valid and reliable measurements can be obtained by carefully designing your investigation to collect sufficient data and minimise errors.

→ All measurements include errors or uncertainties, either systematic or random. It is important to consider these and implement strategies to minimise their effects when planning your experiments.

Learning intentions and success criteria

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- design investigations, including the procedure/s to be followed, the materials required, and the type and amount of primary and/or secondary data required to obtain valid and reliable evidence, e.g.
  - consider replicates, number of data points, and quality of sources
  - identify the types of errors, extraneous variables or confounding factors that are likely to influence results and implement strategies to minimise systematic and random error
- use appropriate equipment, techniques, procedures and sources to systematically and safely collect primary and secondary data, e.g.
  - laboratory and field techniques: measurement, and equipment calibration
  - ICTs, scientific texts, databases, online sources
- suggest improvements and extensions to minimise uncertainty, address limitations and improve the overall quality of evidence.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

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Lesson 1.5
Considering safety and ethics

Key ideas

→ Laboratory safety is important to prevent harm to yourself and those sharing the lab space with you.

→ Safety and ethics extend beyond the lab; you should be considering the broader potential impacts of your experiment.

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- identify and implement strategies to manage risks, ethics and environmental impact, e.g.
  - workplace health and safety guidelines
  - standard operating procedures.

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Learning intentions and success criteria

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Lesson 1.6
Collecting data

Key ideas

→ Single experimental measurements are reported using best estimates, indicators of measurement uncertainty and units.

→ Scientific notation is used to easily express extremely large or small values.

→ Significant figures are digits in a number that are known with certainty and the first digit that is uncertain.

→ All measurements, information and observations should be recorded in your logbook.

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- use scientific language and representations to systematically record information, observations, data and measurement error, e.g.
  - symbols, units and prefixes
  - tables, graphs and diagrams
  - logbooks
- translate information between graphical, numerical and/or algebraic forms.

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Learning intentions and success criteria

Worked examples

This lesson is supported by the following Worked examples:

- **Worked example 1.6A** Writing numbers using scientific notation
- **Worked example 1.6B** Converting between units for physical quantities

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Lesson 1.7
Processing and analysing data

Key ideas

→ Data is processed and analysed to identify trends, patterns, relationships, limitations and uncertainty.

→ Absolute and percentage uncertainty give an idea of the precision of measurements.

→ Absolute and percentage error give an idea of the accuracy of measurements.

→ Data can be summarised in a variety of ways, such as in a table, a scatterplot, or a scientific diagram.

→ Linearising data helps you to identify the exact relationship between variables.

Science inquiry skills

Learning intentions and success criteria

This lesson provides support for the following science inquiry skills:

- use scientific language and representations to systematically record information, observations, data and measurement error, e.g.
  - indicators of measurement uncertainty and state measurement uncertainties as a range (±) to an appropriate precision, e.g. when adding or subtracting, the final answer should be given to the least number of decimal places, when multiplying or dividing, the final answer should be given to the least number of significant figures
- use mathematical techniques to summarise data in a way that allows for identification of relevant trends, patterns, relationships, limitations and uncertainty, e.g.
  - mean
  - gradient analysis
  - discriminate between absolute and percentage error
- select and construct appropriate representations to present data and communicate findings, e.g.
  - summary tables
  - scatterplots (with maximum and minimum trendlines and R^2)
  - scientific drawings
- analyse data to identify trends, patterns and relationships
- extrapolate findings to determine unknown values, predict outcomes and evaluate claims.

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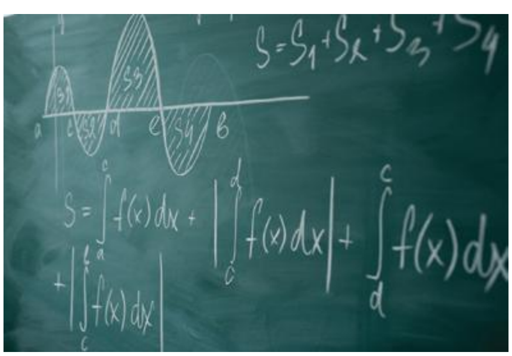


FIGURE 1 Analysing data, for example by using mathematical techniques, helps us to draw conclusions from an investigation.

What information does data analysis give us?

Once we have obtained our raw data, we are ready to process it. This typically involves completing calculations and constructing scatterplots. By transforming the data into more meaningful forms, we can analyse it to quantify uncertainty, identify limitations, construct evidence-based arguments and draw conclusions.

What are precision and accuracy?

A part of any physics experiment is to record and analyse your measurements for quality. This is called an error analysis and is done by assessing both the precision and accuracy of the experimental observations. Precision and accuracy mean very different things, so it is important that these terms are used correctly. For a set of measurements:

- **precision** is the range of values found around the observed (measured) value, or how close two or more measurements of the same object or phenomenon are to each other. Precision may be represented as an absolute uncertainty or as a percentage uncertainty. The higher the uncertainty, the lower the precision.
- **accuracy** is the difference between the best estimate or observed (measured) value and the accepted (true) value of the observed quantity. Accuracy may be represented as an absolute error or as a percentage error.

precision
the range of values found around the observed (measured) value; how close two or more measurements of the same object or phenomenon are to each other (i.e. the "uncertainty" of the measurement); the higher the uncertainty the lower the precision

accuracy
the difference between the observed (measured) value and a currently accepted value of a quantity

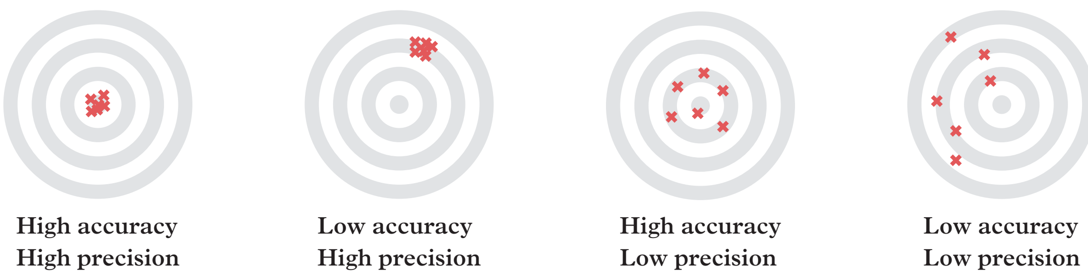


FIGURE 2 Accuracy (closeness to the centre) and precision (closeness to each other) are different concepts.

A low systematic error is likely to make the results of an experiment accurate and therefore valid. A large systematic error would mean the experiment is not accurate and hence the results would not be valid. Results with a low random error, and hence low uncertainty, are said to be precise and thus reliable. Low precision (high uncertainty) means the result is imprecise and thus unreliable.

TABLE 1 Links between accuracy, precision and errors

Size of experimental error	Systematic error	Random error
Small	accurate, therefore valid	precise, therefore reliable
Large	not accurate, therefore lacks validity	imprecise (low precision), therefore unreliable

Systematic error affects accuracy and therefore validity. Random error affects precision and therefore reliability. Both these concepts should be carefully considered when you analyse your data. Understanding them helps you to analyse the uncertainty in your results. Let's look at some ways you can process your data to determine uncertainty.

How do you report repeated measurements?

Single measurements are reported using half-scale divisions. When you make repeated single measurements, you need to complete additional calculations (i.e. process the data) to obtain your best estimate. In this case, the best estimate is the **mean** (average) of your replicate measurements.

mean
the average of multiple values

The mean, $\overline{x}$, is calculated by dividing the sum of the measurements by the number of measurements taken:

$$\overline{x} = \frac{\Sigma x}{n}$$

where x is a measurement and n is the number of replicates.

Averaging your results gives you a single value (best estimate), but you need to also state the spread of results around this value. This is called the uncertainty of the results and can be expressed as absolute or percentage uncertainty.

How do you calculate absolute uncertainty?

absolute uncertainty
the dispersion (spread) of values around the mean, $\delta\bar{x}$, reported by half the range of the measurements; an indicator of the precision of measurements

Study tip

Absolute uncertainty can be represented by $\delta\bar{x}$, or just δx to keep it simple. Some sources use the capital delta and write $\Delta\bar{x}$.

Absolute uncertainty ($\delta\bar{x}$) is the dispersion (spread) of values around the mean, reported by half the range of the measurements. It gives you information about the precision of your results. It is calculated by subtracting the highest from the lowest value and dividing by two:

$$\delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$$

where x_{max} is the largest value and x_{min} is the smallest value.

As when reporting single measurements, you would report your result as the best estimate ± uncertainty. Say you measured the diameter of a piece of wire four times using a vernier calliper. We often do this because wire is not always perfectly round, so measurements are taken at different angles around a point on the wire. Let the readings be 0.602 mm, 0.62 mm, 0.62 mm and 0.654 mm. The best estimate is the average (mean) of 0.6475 mm and the range is 0.60 – 0.65 = 0.05 mm. Half the range of 0.05 mm is 0.025 mm, so $\delta\bar{x}$ = 0.025 mm. The results are 0.6475 ± 0.025 mm. However, using the following rules, this would be reported as 0.65 ± 0.03 mm.

How to quote uncertainties

The function of uncertainties is to quantify the interval in which the true value of the measurement lies. There is no point in quoting the uncertainty to more than one or two significant figures, and usually one significant figure is enough. Often your calculation for uncertainty will give you many digits, as shown above. The rule is to round the uncertainty to one significant figure (or two if the first figure is a "1"). For example, say you calculated the mean of a set of distances to be 123.456 m and the uncertainty to be 0.789 m. You would round the uncertainty to 1 s.f. or 0.8 m, and then round the best estimate (mean) value to the same number of decimal places (1 d.p.). You would then state the measurement as 123.5 ± 0.8 m.

Where your best estimate (mean) has an uncertainty that starts with a "1", such as in 0.167 m, you would round this to two significant figures (0.17) and round your best estimate to the same number of decimal places (2 d.p.). For example, if a best estimate (mean) was 9.234 m s^{-1} and the uncertainty was 0.167 m s^{-1}, you would show your uncertainty to 2 s.f. as 0.17 m s^{-1} and then round the best estimate to 2 d.p. or 9.23 m s^{-1}. You would report your measurement as 9.23 ± 0.17 m s^{-1}.

The same rule applies to percentage uncertainty: round the uncertainty to one significant figure (or two if the first figure is a "1").

Worked example 1.7A

Calculating the mean value and the absolute uncertainty

The diameter of a wire was measured four times using a digital vernier calliper that has a resolution of 0.01 mm. The readings were 0.72 mm, 0.75 mm, 0.70 mm, 0.73 mm. **Calculate** the mean and the absolute uncertainty, and report your final answer correctly. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the mean and absolute uncertainty. The question is worth 2 marks, so we must correctly apply the formulas to complete the calculations and express the answer correctly.
Step 2: Select the appropriate equations and gather any data required.	$\bar{x} = \frac{\Sigma x}{n}$ $\delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$ $x_{max} = 0.70\,\text{mm}$; $x_{min} = 0.75\,\text{mm}$; $n = 4$
Step 3: Substitute the known values into the formulas and solve for the final answers.	$\bar{x} = \frac{0.72 + 0.75 + 0.70 + 0.73}{4}$ $= 0.725$ $\delta\bar{x} = \pm\frac{(0.75 - 0.70)}{2}$ $= \pm 0.025$
Step 4: Report your final answer as the best estimate (mean), absolute uncertainty, and the correct units. Make sure you use the correct number of significant figures in the mean and the same number of decimal places in the uncertainty.	The absolute uncertainty is rounded to 1 s.f. (as it doesn't start with a '1'), so it is 0.03 mm (remembering that "5 rounds up"). The mean is then rounded to 2 d.p., the same number of decimal places as the uncertainty, so it becomes 0.73 mm. The final answer is 0.73 ± 0.03 mm. (1 mark for correct mean; 1 mark for correct absolute uncertainty)

Your turn

The distance travelled by a projectile was measured with a metre ruler marked in 1 mm increments. The distances were 52.0 mm, 58.5 mm, 49.5 mm, 52.0 mm, 56.5 mm. **Calculate** the mean distance and the absolute uncertainty, and report your final answer correctly. (2 marks)

Which uncertainty value do you report?

You have learnt that uncertainty for single measurements is reported as the half-scale division or resolution of the measurement instrument. When dealing with measurements that rely on reaction time, there is also the reaction time uncertainty to consider when reporting data. What if these values are larger than the absolute uncertainty? Which value should you use?

The rule is that the uncertainty value you report should be the largest one. This is because we don't want to underestimate the uncertainty of the result. This would make the result appear more precise and reliable than is justified or warranted.

Uncertainty for periodic motion

In "Your turn" for Worked example 1.7B, the period (time) for one oscillation was measured. Often, with periodic motion such as this, we measure the time for 10 oscillations and divide by 10. The reaction time uncertainty of 0.2 s is spread over 10 periods of time, so instead of it being 1.28 ± 0.2 s for one oscillation, it would be 12.8 ± 0.2 s for 10 oscillations, or 1.28 ± 0.02 s for the one oscillation. This reduces the percentage uncertainty from 16% to 1.6%. You will use this technique if you do pendulum experiments, or in the "Gravity and motion" topic in Unit 3, in which you will perform circular motion experiments.

Study tip

Like uncertainty for single measurements, the absolute uncertainty is reported to the same number of decimal places as the best estimate (mean).

Study tip

You should compare the uncertainty based on the size of half-scale division of the instrument with the uncertainty based on the calculation using half the maximum minus the minimum. When you report your final answer, always take the larger uncertainty of the two.

Worked example 1.7B

Calculating the mean and uncertainty for stopwatch measurements

A ball is dropped from a set height and the time taken to fall was measured using a digital stopwatch. The readings were 1.12 s, 1.05 s, 1.15 s, 0.95 s, 1.00 s, and 1.20 s. The uncertainty for a hand-held stopwatch is 0.2 s. **Calculate** the mean and uncertainty and report your final answer correctly. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the mean and uncertainty. The question is worth 2 marks, so we must correctly apply the formulas to complete the calculations and express the answer correctly.
Step 2: Select the appropriate equations and gather any data required.	$\bar{x} = \frac{\sum x}{n}$ $\delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$ $x_{max} = 1.20\,\text{mm}$; $x_{min} = 0.95\,\text{mm}$; $n = 6$
Step 3: Substitute the known values into the formulas and solve for the final answers.	$\bar{x} = \frac{1.12 + 1.05 + 1.15 + 0.95 + 1.00 + 1.20}{6}$ $= 1.0783$ $\delta\bar{x} = \pm\frac{(1.20 - 0.95)}{2}$ $= \pm 0.125$
Step 4: Recognise that reaction time error is relevant and consider it when reporting your measurements. Select the largest value and adjust uncertainty as required.	Reaction time error = ±0.2 s Digital stopwatch resolution = ±0.01 s Absolute uncertainty = ±0.125 The reaction time error is the largest.
Step 5: Report your final answer as the best estimate (mean), uncertainty, and the correct units. Make sure you use the correct number of significant figures in the mean.	Uncertainty is expressed to 2 s.f. as it starts with a "1", so it is 0.13 s. However, the reaction time uncertainty is 0.2 s, so we will just report this. The mean has to have the same number of d.p. as the uncertainty, so the final answer is 1.1 ± 0.2 s. (1 mark for correct mean; 1 mark for correct absolute uncertainty)

Your turn

A pendulum consisting of a brass bob on a 2.00 m string is pulled to one side and allowed to swing for one complete oscillation (back and forth). The duration of one oscillation was timed using a digital stopwatch. This was repeated and the readings were 1.28 s, 1.26 s, 1.29 s and 1.30 s. Use an uncertainty of 0.2 s for the stopwatch. **Calculate** the mean and uncertainty, and report your final answer correctly. (2 marks)

How do you calculate standard deviation?

standard deviation
a measure of the amount of variation of a set of data values

When we deal with a small set of values (as is typical in senior Physics), absolute uncertainty may not be so useful. A large spread could arise because a single reading is very different from the others. An alternative is to report the **standard deviation** (SD, or sigma, σ). This is calculated using the following formula or the "stdev.s" function in Excel:

$$\sigma = \sqrt{\frac{\sum(x - \bar{x})^2}{n - 1}}$$

For example, the SD of the four results for the diameter of a piece of wire (0.62 mm, 0.63 mm, 0.63 mm, 0.64 mm) using "stdev.s" is 0.008 mm. Therefore, the results could also be reported as 0.63 ± 0.008 mm. A low SD means the data points tend to be close to the mean of the dataset and your data is precise; a high SD indicates that the data points are spread out over a wider range of values.

SD is highly unlikely to appear in your data test, but you could use it in your student experiment to identify errors and **outliers**, and to evaluate the reliability of your results. Expressing uncertainty using absolute uncertainty is more common in physics.

outlier
a value data point that is much smaller or larger than most of the other values in a set of data; often quantified as being greater than three standard deviations from the mean

How do you calculate percentage uncertainty?

Once you have collected the data, you may need to transform it in some way or apply a formula to it to calculate other quantities. For example, if you gather mass, time or voltage data, you can calculate speed, acceleration, density or resistance, and compare these calculated values with accepted (true) values.

If you add, subtract, multiply or divide the data, you can propagate uncertainty through your calculations. First, you may need to get the data into the right form. Often, this can involve different units and scales, so absolute uncertainty may no longer be useful. You will need to make adjustments to take into account the calculations you have performed, and the value you use may instead be percentage uncertainty.

Percentage uncertainty ($\delta\%$) is calculated by dividing the absolute uncertainty by the observed measurement and multiplying the result by 100 to give a percentage:

$$\delta\% = \frac{\text{absolute uncertainty } (\delta\bar{x})}{\text{observed measurement } (x_\text{o})} \times 100$$
$$= \frac{\delta\bar{x}}{x_\text{o}} \times 100$$

percentage uncertainty
an indicator of uncertainty in which the range of values for a measurement result (the absolute uncertainty) is expressed as a percentage of the observed measurement

Reporting percentage uncertainty

When percentage uncertainty is reported, the format is:

1 observed measurement (best estimate)
2 unit symbol
3 ± the percentage uncertainty.

Study tip

In the QCAA Formula and data book, this equation is shown as:

Percentage uncertainty (%)

$$= \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100$$

Worked example 1.7C

Calculating percentage uncertainty

Calculate the percentage uncertainty for each measurement and report your final answer correctly.

a A digital multimeter reading of 0.818 V and an absolute uncertainty of ±0.001 V (2 marks)

b A voltmeter reading of 0.75 ± 0.05 V (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	“Calculate” means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the percentage uncertainty. The questions are worth 2 marks each, so we must correctly apply the formula to complete the calculation and express the answer correctly.
Step 2: Select the appropriate equation and gather any data required.	$\delta\% = \frac{\delta\bar{x}}{x_\text{o}} \times 100$ **a** $x_\text{o} = 0.818$, $\delta\bar{x} = 0.001$ **b** $x_\text{o} = 0.75$, $\delta\bar{x} = 0.05$

Think	Do
Step 3: Substitute the known values into the formula and solve for the final answer.	**a** $\delta\% = \frac{0.001}{0.818} \times 100$ $= \pm 0.122\%$ **b** $\delta\% = \frac{0.05}{0.75} \times 100$ $= \pm 6.67\%$
Step 4: Report your final answer as the best estimate (mean), uncertainty, and the correct units.	**a** $\delta\% = 0.122$, so, using the rule, round to 2 s.f. to become 0.13, then express 0.812 to the same number of d.p. as $\delta\bar{x}$ (2 d.p). Report final answer as 0.82 V ± 0.13%. (1 mark for correct uncertainty; 1 mark for correct reporting) **b** $\delta\% = 6.67$, so, using the rule, round to 1 s.f. to become 7%, then express 0.75 to the same number of d.p. as $\delta\bar{x}$ (2 d.p.). Report final answer as 0.75 V ± 7%. (1 mark for correct uncertainty; 1 mark for correct reporting)

Your turn

Calculate the percentage uncertainty for each measurement and report your final answer correctly.

a A digital multimeter reads the resistance of nichrome wire as 24.5 Ω with an absolute uncertainty of 0.1 Ω. (2 marks)

b A spring balance gives a reading of 15.5 ± 1 N. (2 marks)

Study tip

When calculating percentage uncertainty for repeated measurements, "measured value", "observed measurement", "observed value", "experimental value" and "best estimate" are the same thing.

Percentage uncertainty in temperature calculations

All percentage uncertainty calculations for temperature readings should be completed in kelvin (K). This means you need to convert all Celsius temperatures (T_C) to kelvin (T_K) before performing the calculation. The formula to convert Celsius to kelvin is $T_K = T_C + 273$.

To understand why, let's consider the following: what would the percentage uncertainty be for the temperature of an ice cube measured at 0.0°C? If the absolute uncertainty was ±0.5°C, the percentage uncertainty would be $\frac{0.5}{0.0} \times 100$ = infinity. This is clearly wrong and does not make sense.

TABLE 2 Estimating uncertainty with temperature

Measurement	Celsius	Kelvin
Best estimate and absolute uncertainty	5.0 ± 0.5°C	278 ± 0.5 K
Percentage uncertainty	$\frac{0.5}{5.0} \times 100 = 10\%$. This is incorrect.	$\frac{0.5}{278} \times 100 = 0.2\%$. This is correct.

How is uncertainty propagated in calculations?

Uncertainty can be propagated through calculations. Because you will be multiplying, dividing, adding and subtracting data, the uncertainty needs to have mathematical operations performed on it as well. Therefore, when you complete calculations with multiple measurements, you need to consider the uncertainties of each measurement. The following rules apply:

- When you add or subtract measurements, add **absolute** uncertainties (see Worked example 1.7D).
- When you multiply or divide measurements, add **percentage** uncertainties (see Worked examples 1.7E and 1.7F).

Worked example 1.7D

Calculating uncertainties involving subtraction

When a piece of heated brass was placed in 50.0 g of water at 25.0°C, the temperature of the water rose to 33.5°C. The temperature was measured with an analogue thermometer with 1°C divisions. **Calculate** the change in temperature and the percentage uncertainty of the result, and report it correctly. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the change in temperature and percentage uncertainty. The question is worth 3 marks, so we must gather the correct information and correctly apply the formula to complete the calculations.
Step 2: Select the appropriate equation(s) and gather any data required. An analogue (print) scale is used, so the uncertainty is the half-scale division.	$\delta\% = \frac{\delta\bar{x}}{x_0} \times 100$ uncertainty $= \frac{\text{resolution}}{2} = \frac{1}{2} = \pm 0.5°C$ $x_0 = \Delta T = T_f - T_i$ $T_f = 35.5°C$, $T_i = 25.0°C$
Step 3: Substitute the known values into the formula(s) and solve for the final answer(s). Subtraction is used to obtain this value, so the absolute uncertainties must be added. The absolute and percentage uncertainties are rounded to 2 s.f. as they start with a "1".	$\Delta T = 35.5 - 25.0$ $= 8.5°C$ (1 mark) $\delta\bar{x} = 0.5 + 0.5$ $= \pm 1.0°C$ $\delta\% = \frac{1.0}{8.5} \times 100$ $= \pm 11.76\%$ rounded to 12% (1 mark)
Step 4: Report your final answer as the best estimate (mean), uncertainty, and the correct units. Note: the absolute uncertainty is to 2 s.f. (1.0°C) as it starts with a "1", which means it has 1 d.p. The best estimate must also then be expressed to 1 d.p. to match, so it is 9°C. The percentage uncertainty has the same number of s.f. (2) as the absolute uncertainty, so it is 12%.	9 ± 1.0°C, which is expressed as a percentage as 9°C ± 12% (1 mark)

Your turn

A piece of copper measures 23.5 ± 0.5 mm long and 15.0 ± 0.5 mm wide. **Calculate** the perimeter (3 s.f.) and percentage uncertainty, and express your answer in "best estimate, percentage uncertainty, unit symbol" format. (3 marks)

Worked example 1.7E

Calculating uncertainties involving multiplication

A golf ball has a mass (as measured on a digital scale) of 46.93 ± 0.01 g. The golf ball is raised to a vertical height of 755.0 mm (as measured on a metre ruler that is calibrated in 1 mm divisions). **Calculate** the gravitational potential energy (E_p) of the ball ($E_p = mgh$ and $g = 9.807\ \text{m s}^{-2}$). Report your answer in the correct format, showing the percentage uncertainty. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the gravitational potential energy and percentage uncertainty. The question is worth 3 marks, so we must correctly apply the formulas to complete the calculations.
Step 2: Select the appropriate equation(s) and gather any data required. A mix of digital and analogue scales were used, so you will use the resolution and half-scale division.	$\delta\% = \frac{\delta x}{x_O} \times 100$ uncertainty (digital scale) = resolution = $\pm 0.01\,g$ uncertainty (metre ruler) = $\frac{\text{resolution}}{2} = \frac{1}{2} = \pm 0.5\,mm$ $x_O = E_P = mgh$, $g = 9.807\,m\,s^{-2}$ $m = 46.93\,g$, $g = 9.807\,m\,s^{-2}$, $h = 755.0\,mm$
Step 3: Convert mass and height to SI units. In this case divide the mass in grams (g) by 1,000 to get kilograms (kg); and divide the height in millimetres (mm) by 1,000 to get metres (m). Substitute the known values into the formula(s) and solve for the final answer(s). Multiplication is used, so the percentage uncertainties must be added.	$E_P = \frac{46.93}{1,000} \times 9.807 \times \frac{755.0}{1,000}$ $= 0.3475\,J$ (4 s.f.) (1 mark) $\delta\%$ (digital scale) $= \frac{0.01}{46.93} \times 100$ $= \pm 0.085\%$ $\delta\%$ (metre ruler) $= \frac{0.5}{755.0} \times 100$ $= \pm 0.066\%$ $\delta\% = 0.085 + 0.066$ $= \pm 0.15\%$ (1 mark)
Step 4: Report your final answer as the best estimate (mean), uncertainty, and the correct units. Note: this is a difficult one, as the uncertainty is so small. The absolute uncertainty would be $0.15\% \times 0.3475 = 0.00052$. This does not start with a "1" so use 2 s.f., so the % uncertainty would have 2 s.f. as well (= 0.15%). The best estimate should then have the same number of d.p. as the absolute uncertainty (5), but this is not reasonable as there are only 4 s.f. in each of the original measurements. The best we can do is leave the best estimate at 0.3475 and the % uncertainty as 0.15%.	$0.3475\,J \pm 0.15\%$ (1 mark)

Your turn

A piece of copper (measured using a metre ruler marked in 1 mm increments) is 34.5 mm long and 25.0 mm wide. **Calculate** its area and report the answer with the absolute uncertainty. Use the correct number of significant figures and units. (3 marks)

Study tip

You can convert between absolute and percentage uncertainty by rearranging the δ% formula.

Worked example 1.7F

Calculating uncertainties involving division

The winning time for the 100 m sprint in a recent Olympic Games was 9.81 s. For uncertainties in this measurement, assume the time was 9.81 ± 0.01 s and the distance was 100.0 ± 0.1 m. **Calculate** the average speed and absolute uncertainty, and report your answer in the correct format. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the speed and absolute uncertainty. The question is worth 3 marks, so we must correctly apply the formulas to complete the calculations.
Step 2: Select the appropriate equation(s) and gather any data required. The uncertainties for each measurement are provided.	$\delta\% = \frac{\delta\bar{x}}{x_O} \times 100$ uncertainty (time) = ±0.01 s uncertainty (distance) = ±0.1 m $x_O = v = \frac{d}{t}$ $d = 100.0\,\text{m}$, $t = 9.81\,\text{s}$
Step 3: Substitute the known values into the formula(s) and solve for the final answer(s). Division is used, so the percentage uncertainties must be added.	$v = \frac{100.0}{9.81}$ $= 10.2\,\text{m s}^{-1}$ (1 mark) $\delta\%\,(\text{time}) = \frac{0.01}{9.81} \times 100$ $= \pm 0.1\%$ $\delta\%\,(\text{distance}) = \frac{0.1}{100.0} \times 100$ $= \pm 0.1\%$ $\delta\% = 0.1 + 0.1$ $= \pm 0.2\%$
Step 4: The question asks for absolute uncertainty, so we will need to convert it from percentage uncertainty.	$\delta\bar{x} = \frac{\delta\%}{100} \times x_O$ $= \frac{0.2}{100} \times 10.2$ $= 0.02\,\text{m s}^{-1}$ (1 mark)
Step 5: Report your final answer as the best estimate (mean), uncertainty, and the correct units. Make sure you use the correct number of significant figures in the mean. The absolute uncertainty in velocity is 0.0204, which is expressed with 1 s.f. as 0.02, as the first number is not a "1". This means the velocity should have 2 d.p. but can't as there are just 3 s.f. in the original measurements, so we leave it as $10.2\,\text{m s}^{-1}$.	$10.2 \pm 0.02\,\text{m s}^{-1}$ (1 mark)

Your turn

A cube of iron, of 62.99 ± 0.01 g mass, measures 2.000 ± 0.001 cm along each side. **Calculate** its density ($\rho = \frac{m}{V}$) in g cm^{-3} and absolute uncertainty, and report your result in the correct format. (2 marks)

How do you calculate errors?

We have seen that uncertainty is used to express the precision of a set of measurements. However, students often find their results are different from the accepted result, even though they performed the experiment as carefully as possible and read the instruments as best they could. This measurement discrepancy is known by the term "error" and is a measurement of the accuracy of a result. Error can be represented as absolute error or percentage error.

Absolute error (E_a) is the difference between the observed (measured) value (x_O) and the accepted (true) value (x_A). It is a measure of the accuracy of a result.

$$\text{absolute error} = \text{measured value} - \text{accepted value}$$

$$E_a = |x_O - x_A|$$

Study tip

The term "accepted result" is also called "true value". All this means is that it is accepted by the scientific community.

absolute error the difference between the observed (measured) value and the accepted (true) value

The straight lines (modulus signs, |) in the equation indicate the "absolute value", which means the sign (+/–) of the answer is ignored.

percentage error
the absolute error expressed as a percentage of the accepted (true) value

Percentage error ($E\%$) is the absolute error expressed as a percentage of the accepted (or true) value.

$$\text{percentage error} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100$$

$$E\% = \left|\frac{x_O - x_A}{x_A}\right| \times 100$$

$$= \left|\frac{E_a}{x_A} \times 100\right|$$

When you express errors, you should use the least number of s.f. used in the observed or accepted value, unless otherwise specified.

Worked example 1.7G

Calculating absolute and percentage error

A student measured the acceleration due to gravity as $9.73\,\text{m}\,\text{s}^{-2}$. The accepted value at their location is $9.813\,\text{m}\,\text{s}^{-2}$. **Calculate** the absolute and percentage errors. Express your answer to 1 s.f. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We are being asked to calculate the absolute and percentage errors. This question is worth 2 marks, so we must correctly apply the formulas to complete the calculations.
Step 2: Select the appropriate equation(s) and gather any data required.	$E_a = \lvert x_O - x_A \rvert$ $E\% = \frac{E_a}{x_A} \times 100$ $x_O = 9.73\,\text{m}\,\text{s}^{-2}$, $x_A = 9.813\,\text{m}\,\text{s}^{-2}$
Step 3: Substitute the known values into the formula(s) and solve for the final answer(s).	$E_a = \lvert 9.73 - 9.813 \rvert$ $= \lvert -0.083 \rvert$ $= 0.083$ $E\% = \frac{0.083}{9.813} \times 100$ $= 0.846\%$
Step 4: Finalise your answer(s) and make sure you use the correct number of s.f. and units.	$E_a = 0.08\,\text{m}\,\text{s}^{-2}$ (1 s.f.) (1 mark) $E\% = 0.9\%$ (1 s.f.) (1 mark)

Your turn

The resistance of a 1.00 m length of nichrome wire was found to be 8.44 Ω, whereas the accepted value is 9.12 Ω. **Calculate** the percentage error (1 s.f.). (2 marks)

Study tip

Absolute and percentage uncertainty are measures of precision. Absolute and percentage error are measures of accuracy.

Challenge

A carbon resistor of nominal resistance 330 Ω is manufactured to a tolerance of 5%. This is the maximum percentage error. **Determine** the range of resistances that a resistor marked 330 Ω may have. (2 marks)

How can you present your results?

Once you have finalised your measurements and uncertainties, you can use summary tables and graphs to present the data. Both are useful to help you clearly observe relationships between variables.

Summary tables

Whereas a data table states what has been measured and presents the raw data, a summary table can bring together processed data. Sometimes, summary tables for simpler investigations will present measurements, but they generally also show values such as mean, values derived from calculations and even absolute or percentage uncertainty. For example, the data table in Figure 7 of Lesson 1.6 could be further summarised by removing the observations and only including the mean and uncertainty values for each trial. Summary tables present the most important information for later analysis.

Scatterplots

Graphs are useful to show how one quantity depends on another. On a graph, the horizontal x-axis is where the IV (or the cause) is plotted. The DV (or the effect of that cause) is plotted on the vertical y-axis. All graphs should include:

- a graph title that succinctly describes what the graph is showing (typically includes the IV and DV)
- clearly labelled axes, including units of measurement
- equally spaced units of measurement along the axes (scaling)
- axes that start at zero (where possible)
- data plotted within the confines of each axis
- distinguishing symbols, colours or keys when more than one dataset is plotted on a single graph
- absolute uncertainty (where relevant) as error bars; do not use percentage uncertainty value for absolute uncertainty
- a trendline that fits between all error bars (see below).

By analysing the shape of your graphs, you can construct arguments about the relationship between variables.

Study tip

The term "error bars" implies that they are to do with the accuracy of a data point. They are not – they are about the uncertainty of results around that data point. Some teachers prefer to call them "uncertainty bars" although Excel calls them "error bars".

How do you graph linear relationships?

A linear relationship produces a straight line when graphed. The variables being measured can be **directly proportional** (i.e. the straight line goes through the origin (0, 0)) or not directly proportional (i.e. the straight line does not go through (0, 0)).

Consider an experiment to determine how much a certain rubber band stretches when masses are hung vertically from it. The single measurements are shown in Table 3.

directly proportional relationship that is linear and the line goes through the origin (0, 0)

TABLE 3 Data obtained from a rubber band experiment

Independent variable: mass, m (g)	0	20	40	60	80
Dependent variable: stretch, d (mm)	0	10	21	28	42

When the points are plotted, it is obvious that the relationship is linear and directly proportional. Note that each point is plotted as a dot (or cross) that is big enough to still be seen once a line of best fit or **trendline** is drawn. The trendline has as many points on the

trendline a line of best fit which shows the general direction that a group of points seem to follow line as possible. There are usually some points that do not sit exactly on the line, so the line should be drawn with the same number of points below it as above it.

anomaly
a false data point often the result of a faulty observation or wrong equipment

Scientists and engineers use a complex mathematical procedure to determine where the trendline should be. Any point that is a long way out of place is called an outlier or an **anomaly**, and could be false. Outliers "lie outside" (are much smaller or larger than) most of the other values in a set of data. It is a legitimate data point originated from a real observation. There are mathematical ways of deciding whether the value is within the acceptable range for that set of data points. In general, outliers are discarded if they are more than three standard deviations away from the mean. An anomaly is something that deviates from what is standard, normal, or expected. It is not a legitimate value and is produced by an artificial process (such as mistakes in the method, wrong equipment or a badly recorded result).

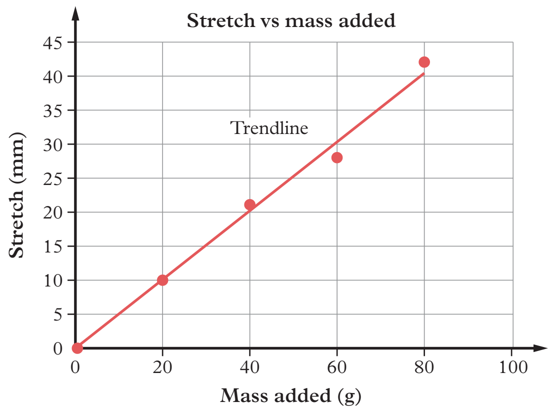


FIGURE 3 Graph showing a directly proportional relationship between stretch and mass added

Any individual outlier or anomaly should be noted and the reasons for its existence can be discussed – but it should not be used for the trendline. If the trendline is straight and goes through the origin (as in Figure 3), it takes the general form of $y \propto x$. The proportional sign ($\propto$) can be replaced by an equals sign and a constant (m) to give:

$$y = mx \text{ or } y = mx + c$$

gradient
the slope of a graph

where x and y are the variables, m is the **gradient** or slope of the line, and c is the y-intercept or point where the line cuts the y-axis when $x = 0$.

In the graph of stretch versus mass (Figure 3), the intercept c is zero. The gradient is found by dividing the change in the y value by the change in the x value for the same section of the line. This can be written as:

$$\begin{aligned} m &= \frac{\text{change in } y}{\text{change in } x} \\ &= \frac{\Delta y}{\Delta x} \\ &= \frac{y_2 - y_1}{x_2 - x_1} \end{aligned}$$

Study tip
You might find it easier to remember the gradient as "rise over run", where "rise" refers to the change in the y-axis values and "run" refers to the change in the x-axis values.

The gradient of the graph in Figure 3 is given by $m = \frac{40 - 0}{80 - 0} = 0.5\,\text{mm}\,\text{g}^{-1}$, and the intercept c is zero. Thus, for every 1 g change in mass (x-axis), the rubber band changes by 0.5 mm in length (y-axis).

There are four important points to remember:

- Don't force the line to go through the origin; it should go through the middle of the data points, with as many points above it as below it.
- Use the x and y coordinates of points on the trendline to calculate the gradient.
- Use points as widely separated as possible to get the most accurate value for the gradient.
- Gradients have the y-axis unit divided by the x-axis unit.

Worked example 1.7H

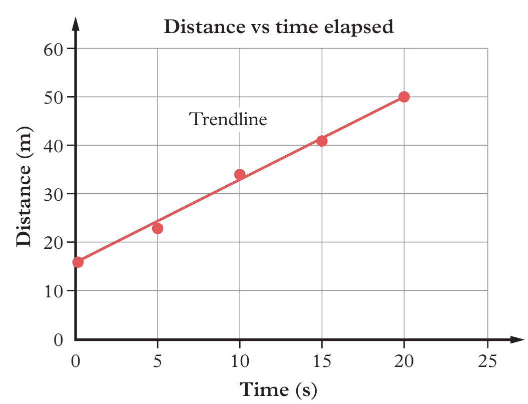
Determining the relationship between variables

The position of a car on a road was noted every 5 seconds and the data in Table 4 was obtained.

TABLE 4 Data obtained from the experiment

Time, t (s)	0	5	10	15	20
Distance, s (m)	16	23	34	41	50

a **Sketch** a graph of the data with the independent variable on the x-axis. (3 marks)
b **Calculate** the average velocity (gradient or slope). (2 marks)
c **Identify** the y-intercept. (1 mark)
d **Derive** the equation for the line. (1 mark)
e **Explain** whether or not the graph is directly proportional. (1 mark)
f **Determine** the distance travelled at 25 s, assuming the velocity is constant. (1 mark)

Think	Do
Step 1: Look at the cognitive verb(s) and mark allocation to determine what the question(s) are asking you to do.	A variety of cognitive verbs are used in this question. "Sketch" means to represent using a diagram or graph. "Calculate" means to determine or find a number or answer by using mathematical processes. "Identify" means to locate or recognise and name. "Derive" means manipulate a mathematical relationship to give a new equation. "Explain" means to describe in more detail. "Determine" means to establish after calculation. These questions are worth a variety of marks.
Step 2: To sketch the graph, draw and label the axes with the IV (time) on the x-axis and DV (distance) on the y-axis. Include units! Plot each data point and draw a trendline.	**a**  (3 marks)
Step 3: To find the gradient, select the appropriate equation. Determine the change in y and change in x for two widely separated points on the line. You can use $x = 0$ as one of the points.	**b** $m = \frac{\Delta y}{\Delta x}$ $\Delta y = 50 - 16$ $= 34$ $\Delta x = 20 - 0$ $= 20$ s (1 mark)
Step 4: Substitute the known values into the formula and solve for the gradient.	$m = \frac{34}{20}$ $= 1.7\,\text{m s}^{-1}$ (1 mark)
Step 5: Read the intercept off the y-axis and include the units. We can also obtain this value from Table 4.	**c** $c = 16$ m (1 mark)
Step 6: To find the equation for the straight line, select the appropriate equation. You can substitute y and x for DV and IV, respectively.	**d** $y = mx + c$ $s = 1.7t + 16$ (1 mark)
Step 7: Directly proportional means the graph has an intercept of zero ($c = 0$) and a relationship $y = mx$.	**e** The graph is linear but not directly proportional as it does not go through (0, 0). The y-intercept occurs at 16 m. (1 mark)
Step 8: Use the equation for the line and substitute in the value for t.	**f** $s = 1.7t + 16$ $= (1.7 \times 25) + 16$ $= 58.5$ m (1 mark)

Your turn

Students performed an experiment in which they connected a power supply across a resistor. As the voltage (V) in volts (V) was increased, they recorded the current (I) in amperes (A) passing through the resistor. Their results are shown in Table 5.

TABLE 5 Data obtained from the experiment

Voltage, V (V)	2.0	4.0	6.0	8.0	10.0
Current, I (A)	7.7	13.6	20.8	26.2	33.0

a **Sketch** a graph of the data with the independent variable on the x-axis. (3 marks)
b **Calculate** the gradient and state its units. (2 marks)
c **Identify** the y-intercept. (1 mark)
d **Derive** the equation for the line using symbols V and I for the variables. (1 mark)
e **Explain** whether or not the graph is directly proportional. (1 mark)
f **Determine** the current at 9.0 V. (1 mark)

How do you graph non-linear relationships?

A non-linear relationship is not a straight line when graphed. The most common non-linear relationships you will meet in physics are power, exponential and logarithmic relationships, as outlined in Table 6.

TABLE 6 Examples of common non-linear relationships

Type of relationship	Equation(s)
Power	$y \propto x^a$ • inverse ($a = -1$): $y \propto x^{-1}$ or $y \propto \frac{1}{x}$ • inverse-square ($a = -2$): $y \propto x^{-2}$ or $y \propto \frac{1}{x^2}$ • square or parabolic ($a = 2$): $y \propto x^2$ • square root ($a = \frac{1}{2}$): $y \propto x^{\frac{1}{2}}$ or $y \propto \sqrt{x}$
Exponential	$y \propto e^{kt}$ or $y = y_0 e^{kt}$ (natural exponential) where y_0 is the y-intercept, e is the "natural" base (2.718) and k is a constant
Logarithmic	$y \propto 10^x$

Power relationships

Inverse relationship

In an inverse relationship, $y \propto x^{-1}$ or $y \propto \frac{1}{x}$, where the power a is –1. Consider a case in which the volume of gas in a syringe is measured as the pressure on the syringe is increased by adding weights to the plunger. This is an inverse relationship (also called an inversely proportional relationship), shown in Figure 4.

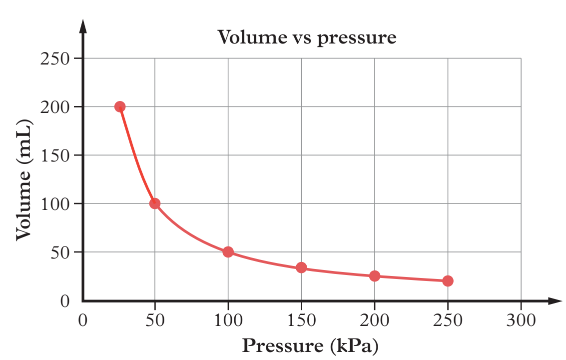


FIGURE 4 Graph showing an inverse relationship

Inverse-square relationship

In an inverse-square relationship, $y \propto x^{-2}$ or $y \propto \frac{1}{x^2}$, where the power a is –2. It looks similar to an inverse relationship but has a much sharper bend. This type of relationship is very common in physics. For example, the variation in gravitational force with distance is given by $F \propto \frac{1}{d^2}$.

There is also the inverse-cube relationship, $y \propto x^{-3}$ or $y \propto \frac{1}{x^3}$, where the power a is –3. This is not as common in physics, but you may find it explains the relationship for force between two magnets at certain distances. Figure 5 shows both the inverse square (solid line), and the inverse cube (dashed line) relationships, so you can see the inverse cube is sharper.

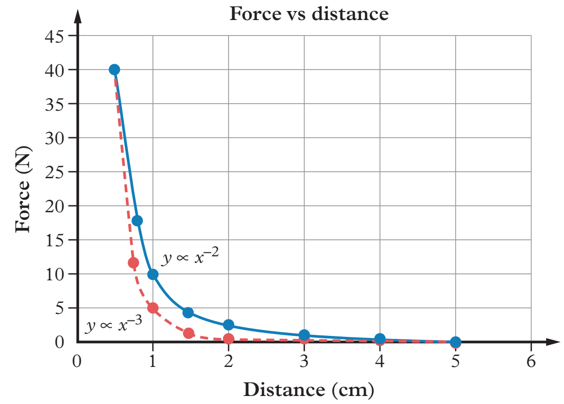


FIGURE 5 Graph showing inverse-square and inverse-cube relationships

Square (parabolic) relationship

In a square or parabolic relationship, $y \propto x^2$, where the power a is 2. It is the most common non-linear relationship you will encounter, along with inverse. An example is the relationship between the distance a rock has fallen from the top of a cliff and the time elapsed. The data in Table 7 shows these variables and Figure 6 shows a graph of the distance against the time.

TABLE 7 Parabolic data

Time, t (s)	0	1	2	3	4	5
Distance, s (m)	0	4	16	36	64	100

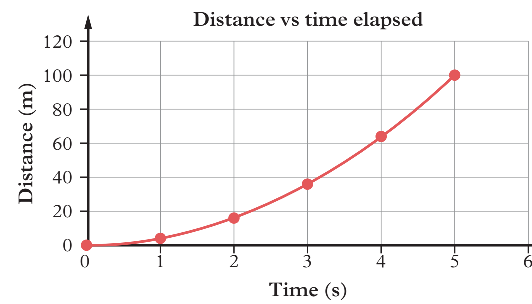


FIGURE 6 Graph showing a parabolic relationship

Other phenomena that exhibit parabolic relationships are the paths of comets (except Halley's Comet, which is elliptical), and the shape of curved mirrors in telescopes and projectiles (e.g. arrows in flight).

Square root relationship

In a square root relationship, $y \propto x^{\frac{1}{2}}$ or $y \propto \sqrt{x}$, where the power a is $\frac{1}{2}$. A square root relationship can be demonstrated by letting a ball roll down a ramp. The speed at the bottom of the ramp, v, varies with the square root of the height, h, of the ramp ($v \propto \sqrt{h}$), as shown in Figure 7.

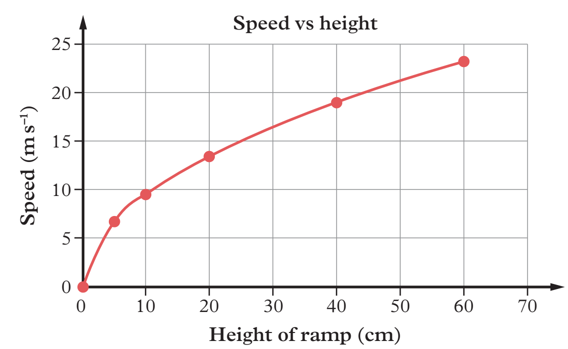


FIGURE 7 Graph showing a square root relationship

Exponential relationships

The exponential relationship is given by $y = a^x$. The "natural" exponential function is a version of this: $y \propto e^{kt}$ or $y = y_0e^{kt}$, where the a value is e, the "natural" base (2.718), the symbol k is a constant ($-k$ for decay, $+k$ for growth), and t is time elapsed. Physics has some quantities that are related exponentially. For example, in a radioactive substance, the number of radioactive atoms remaining follows natural exponential decay (as long as the remaining number of atoms is large). The breakdown (decay) of a radioactive substance is given by intensity $= e^{-kt}$. This is shown in Figure 8.

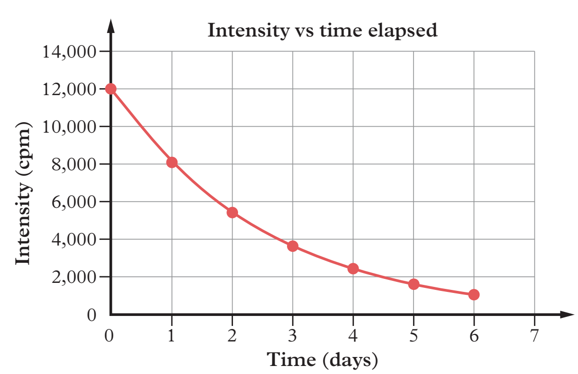


FIGURE 8 Graph showing a natural exponential decay relationship

Study tip

Make simple labelled drawings of each graph shape. This will help you to identify them quickly when you plot your own data or see them in an exam. These can also be found in the summary at the end of this module.

Logarithmic relationships

In a logarithmic relationship, $y \propto 10^x$ or $y = \log_a x$. Let's consider an example. When it is quiet in your laboratory, you could hear a pin drop onto a bench from the other side of the room. The amount of energy released is very small, and human hearing is very sensitive when things are quiet. The human ear can also hear noise, such as an explosion, that could be a trillion (10^{12}) times louder. This is impossible to capture meaningfully with a uniform scale. The sensitivity of human hearing is good for low power sounds but reduced at high power, as shown in Figure 9. Sound intensity (y-axis) is in decibels (dB), which describes the relative intensity of a sound based on a logarithmic scale containing values ranging from 0 to 194. So, the y-axis has intervals of 10^{88}, 10^{89} and so on.

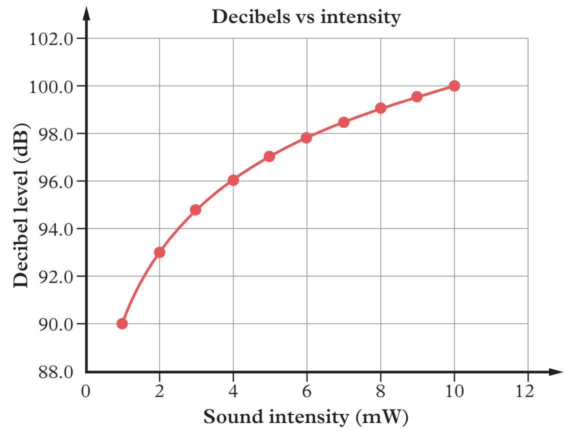


FIGURE 9 Graph showing a logarithmic relationship

How do you linearise a graph?

Even though a graph may have a particular shape, sometimes we cannot be sure of the exact relationship between variables. For example, $y \propto \frac{1}{x}$ and $y \propto \frac{1}{x^2}$ are very similar and therefore hard to distinguish. The relationship could also be in between them, such as $y \propto \frac{1}{x^{1.5}}$. The only way to tell is to plot them in the form of $y = mx$. This is called **linearising** a graph.

linearising
the process of transforming non-linear data by applying a mathematical function to one of the variables so that the relationship between the variables becomes closer to a straight line

Each type of relationship has a different method for linearising. If the linearised graph is indeed linear, then we can say that the relationship has been correctly identified.

Linearising inverse relationships

If you already have a straight-line relationship such as $y \propto x$, then a graph of y versus x is a straight line. However, if you have $y \propto \frac{1}{x}$, then a graph of y versus x is non-linear. Let's look at this using the data in Table 8 and plotting y versus x. The graph of V versus P is non-linear (Figure 10) and instead looks like a $y \propto \frac{1}{x}$ graph.

TABLE 8 Data obtained for change in pressure with volume that has a suspected inverse relationship

Pressure, *P* (kPa)	x	1	2	3	4	5
Volume, *V* (mL)	y	3.0	1.5	1.0	0.8	0.6

You can try to linearise the graph ("undo" the inverse) by calculating $\frac{1}{x}$ (Table 9) and plot y versus $\frac{1}{x}$ (Figure 11). If it is a straight line, then you have confirmed the relationship $y \propto \frac{1}{x}$ (which is $V \propto \frac{1}{P}$ in this case). If the $y \propto \frac{1}{x}$ graph is still curved, then it may be a $y \propto \frac{1}{x^2}$ relationship.

TABLE 9 Data obtained for change in pressure with volume after inverse transformation

Pressure, *P* (kPa)	x	1	2	3	4	5
$\frac{1}{\text{pressure}}$ (kPa^{-1})	$\frac{1}{x}$	1.00	0.50	0.33	0.25	0.20
Volume, *V* (mL)	y	3.0	1.5	1.0	0.8	0.6

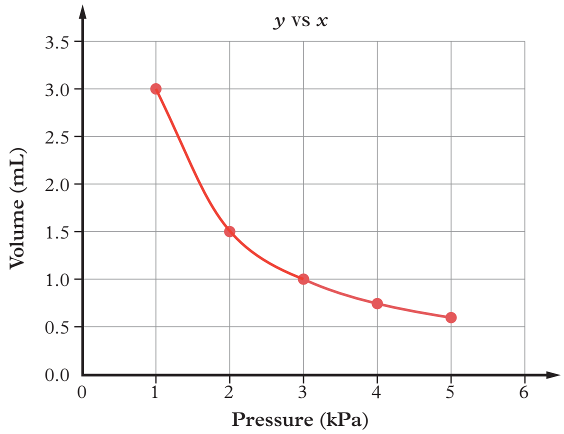


FIGURE 10 The graph of V versus P appears to show an inverse relationship.

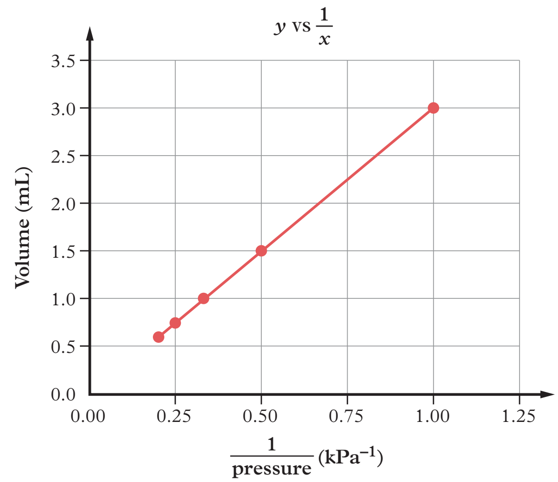


FIGURE 11 The V versus $\frac{1}{P}$ graph of the data gives a straight line, so it is a $y \propto \frac{1}{x}$ relationship.

Linearising inverse-square relationships

Consider the force between two magnets at various distances (Table 10). The graphs of y vs x and y vs $\frac{1}{x^2}$ are shown in Figure 12.

TABLE 10 Data obtained for force and distance between two magnets after inverse-square transformation

Distance (mm)	x	0.5	1.0	2.0	3.0	4.0	5.0
Force (N)	y	12.0	3.0	0.8	0.3	0.2	0.1
$\frac{1}{\text{distance}^2}$	$\frac{1}{x^2}$	4.00	1.00	0.25	0.11	0.06	0.04

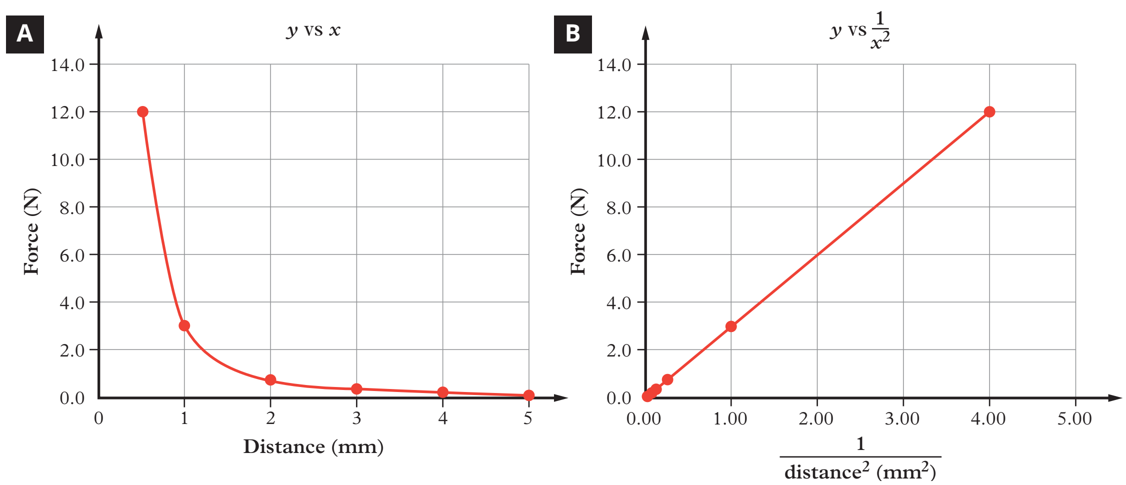


FIGURE 12 (A) A y versus x graph of the data does not give a straight line. (B) The straight line indicates it is a $y \propto \frac{1}{x^2}$ relationship.

A graph of y versus x is non-linear and looks more like a $y \propto \frac{1}{x^2}$ graph. However, a graph of y versus $\frac{1}{x^2}$ is a straight line, so this confirms it is a $y \propto \frac{1}{x^2}$ relationship.

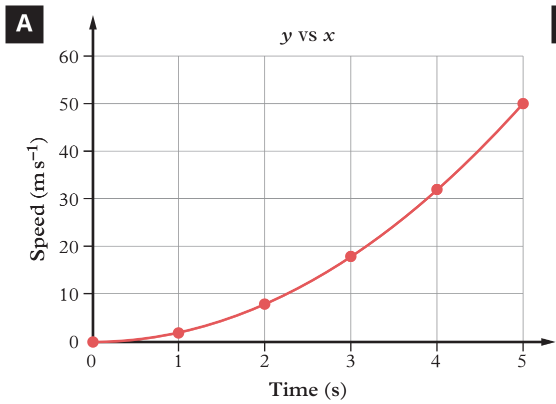
Linearisation of parabolic relationships

Consider the data of a car accelerating from the traffic lights (Table 11).

TABLE 11 Data obtained for the speed of a car over time that has a suspected square relationship

Time (s)	x	0	1	2	3	4	5
Speed (m s⁻¹)	y	0	2	8	18	32	50

The graph of y versus x is shown in Figure 13A. It looks very much like a $y \propto x^2$ relationship. To confirm this, we would linearise the graph by calculating x^2 and plotting y versus x^2 (Figure 13B).



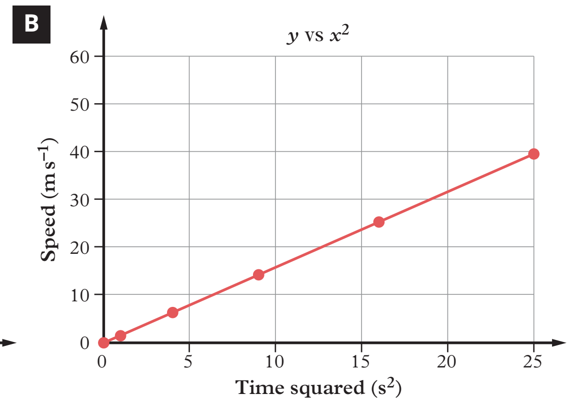


FIGURE 13 (A) The y versus x graph of the data does not give a straight line. (B) The straight line indicates it is a $y \propto x^2$ relationship.

Linearisation of exponential relationships

You will meet exponential relationships in the nuclear physics module. Radioactive substances decay in an exponential fashion, which means the rate of decrease in the y value changes with the x value. The change in y starts off fast at a low value of x but then decreases as x gets larger. Here is an example of a radioactive substance whose radiation intensity was measured over a period of 14 days and plotted in the graph (Figure 14).

Excel suggests it is an exponential relationship by the base e in the equation for the trendline. If we now plot the natural logarithm (ln) of intensity, we get a linearised graph (Figure 15).

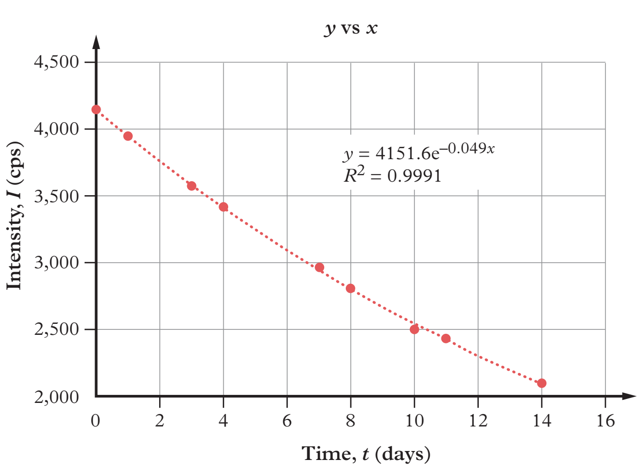


FIGURE 14 Graph of intensity vs time for a radioactive specimen

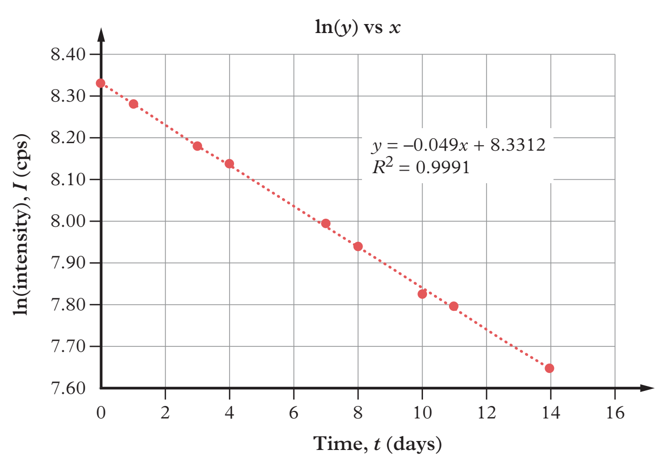


FIGURE 15 Linearised graph of radioactive decay

We can see it is linear because the equation for the trendline is in the pattern $y = mx + c$.

How can you infer data by extrapolation and interpolation?

Extending and reading a graph beyond the last plotted point is called **extrapolation**. Inferring a reading between plotted points is called **interpolation**. Although the data points in Figure 16 are only at 0, 27 kJ, 53 kJ, 81 kJ, 108 kJ and 135 kJ, you can extrapolate the trendline past 135 kJ to 160 kJ and read off the temperature as 66.5°C. You can also interpolate the data to read off values between points. For example, at 100 kJ, the temperature is 51°C. This is commonly done in Physics questions.

extrapolation
the prediction of values beyond the range of data points by extending the trendline

interpolation
the prediction of values between data points using a trendline

Study tip
Be careful not to extrapolate too far beyond the last point. The further out you go, the less reliable the estimate.

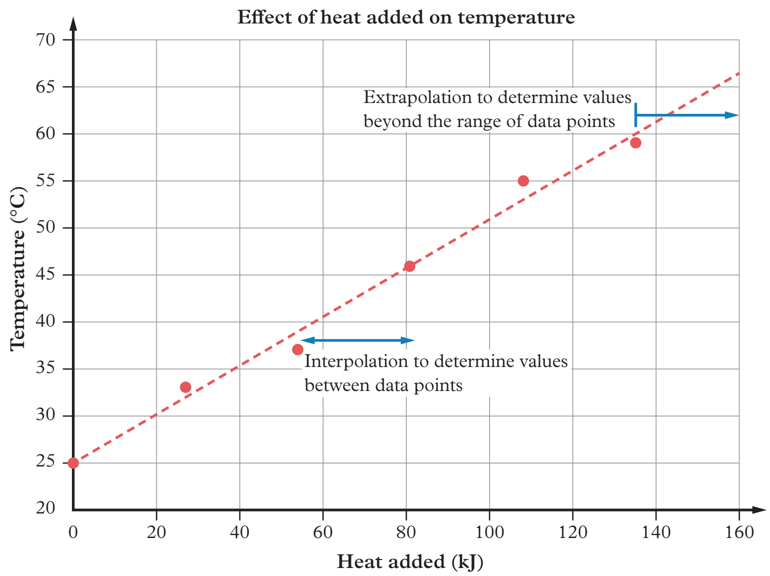


FIGURE 16 The temperature of water vs the amount of heat energy added can be extrapolated or interpolated to infer values.

How are error bars used to represent uncertainty?

The measurement uncertainty associated with a particular mean value can be easily displayed on a graph using error bars. These are vertical or horizontal lines that are added to each data point and represent the absolute uncertainty at that point. For example, an experiment is carried out in which a ball is dropped from a height of 5.0 m, and the displacement recorded every 0.20 s. This was then repeated two more times.

The graph in Figure 17A shows vertical error bars for the measurement of displacement (y-axis). For most experiments, the uncertainty in the IV (x-axis) will be very low and can be neglected. The trendline should be midway between the caps of the error bar. If you use zero as the IV for the first trial, the average would be $\frac{(0+0+0)}{3} = 0$. The uncertainty using the $\frac{(x_{max} - x_{min})}{2}$ formula would be $\frac{(0+0)}{2} = 0$. This says there is no uncertainty. However, there is still the scale reading uncertainty from the measuring instrument and that will be the value of a half-scale division for an analogue device, or the resolution for a digital device. In this experiment, a metre ruler graduated in 1 mm increments was used, so the uncertainty is ± 0.5 mm or ± 0.005 m. This is too small to show up on the error bar for the (0, 0) point.

The graph in Figure 17B shows a graph of the velocity at each time interval, which was calculated using the formula $v = 2v_{av} = \frac{2s}{t}$. A trendline (red line) has been drawn and its calculated gradient is 9.9 m s^{-2}. Two other trendlines – the maximum and the minimum trendlines – have been added.

maximum trendline
a line of best fit of maximum gradient within the bounds of the error bars

The **maximum trendline** has the highest possible slope. It connects the bottom of the error bar of the first data point (0, 0) with the top of the error bar for the last data point (10.9, 1.00) but must not go beyond any of the error bars in between. It shows the maximum gradient.

The **minimum trendline** has the smallest possible slope. It connects the top of the error bar of the first data point (0, 0) with the bottom of the error bar of the last data point (8.9, 1.00), but must not go beyond any of the error bars in between. It shows the minimum gradient.

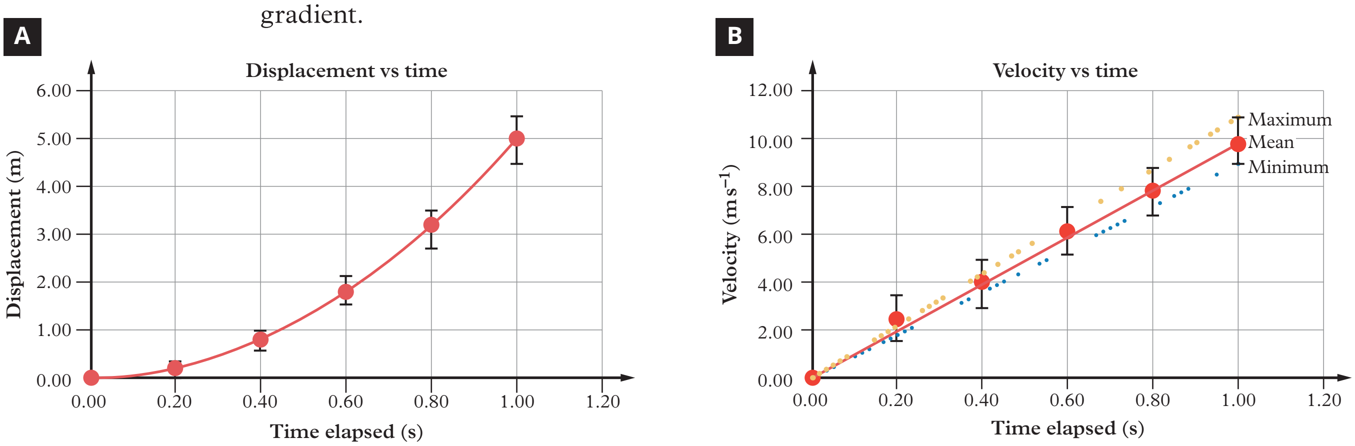


FIGURE 17 (A) Vertical error bars show the zone of uncertainty for the displacement values. (B) Maximum and minimum trendlines can be added to the graph to show the uncertainty in the gradient.

minimum trendline
a line of best fit of minimum gradient within the bounds of the error bars

You can then calculate the maximum and minimum gradients using any part of these trendlines. It is good practice that you use points spaced as widely apart as possible, otherwise you may lose a mark in the external exam. Ideally, try to use the full line between the origin (0 s) and 1.00 s. Remember that the error bar on the (0, 0) point at the origin is too small to be seen.

- The maximum trendline (yellow) gradient is $\frac{(10.9 - 0.0)}{(1.00 - 0.00)} = \frac{10.9}{1.00} = 10.9\,\text{m s}^{-1}$.
- The minimum trendline (red) gradient is $\frac{(8.9 - 0.0)}{(1.00 - 0.00)} = \frac{8.9}{1.00} = 8.9\,\text{m s}^{-1}$.

The uncertainty in the gradient is calculated using the following formula:

$$\begin{aligned}\delta\overline{x} &= \pm\frac{(x_{max} - x_{min})}{2}\\ &= \pm\frac{(10.9 - 8.9)}{2}\\ &= \pm 1.0\,\text{m s}^{-1}\end{aligned}$$

This can also be expressed as percentage uncertainty:

$$\begin{aligned}\delta\% &= \frac{\delta\overline{x}}{x_O} \times 100\\ &= \frac{1.0}{9.90} \times 100\\ &= 10.1\%\end{aligned}$$

Thus, the gradient can be stated using absolute uncertainty as $m = 9.9 \pm 1.0\,\text{m s}^{-2}$. If using percentage uncertainty, $m = 9.9\,\text{m s}^{-2} \pm 10\%$.

The gradient in this case is the experimental value for acceleration due to gravity of $9.9\,\text{m s}^{-2}$ with a minimum of $8.9\,\text{m s}^{-2}$ and a maximum of $10.9\,\text{m s}^{-2}$. We could say that the experiment was accurate, as the accepted value of $9.8\,\text{m s}^{-2}$ is within our experimental range. However, as the range is large, we could also say that there is a lot of uncertainty in the measurements (a lack of precision, or that the data is "imprecise") that detracts from the result. It is thus better to rely on absolute and percentage error to determine accuracy.

Check your learning 1.7

Check your learning 1.7: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the following terms: absolute uncertainty, percentage uncertainty, precision, accuracy, absolute error, percentage error. (6 marks)

2 A student obtained a value of 9.74 m s^{-2} for the acceleration due to gravity. The accepted value is 9.81 m s^{-2} at that location. **Calculate** the

- **a** absolute error (2 marks)
- **b** percentage error. (2 marks)

3 The period for a simple pendulum of length 80 cm was measured in triplicate and found to be 1.79 s, 1.85 s and 1.72 s. **Calculate** the

- **a** mean value for the period (1 mark)
- **b** absolute uncertainty (2 marks)
- **c** percentage uncertainty. (2 marks)

4 A student carries out an investigation to measure the time taken for 10 complete oscillations (swings) of a pendulum. The following values are obtained: 3.1 s, 3.8 s, 3.3 s, 4.1 s and 3.4 s. **Calculate** the absolute and percentage uncertainty for one swing. (5 marks)

5 **Explain** whether it is usual to plot the independent variable on the vertical axis or the horizontal axis. (2 marks)

6 **Define** the following terms: anomaly, outlier, relationship, trendline, line of best fit. (5 marks)

7 **Explain** what it means to “linearise” a relationship. (2 marks)

8 Students obtained the relationship $y \propto x$. **Explain** whether there is any need to linearise it. (1 mark)

Analytical processes

9 **Compare** “precision” and “accuracy”. (2 marks)

10 A digital ammeter shows the current in a circuit to be 0.10 A. **Determine** the percentage uncertainty in the value of I^2. (2 marks)

11 A Physics textbook measures 1.98 ± 0.01 cm by 28.05 ± 0.05 cm by 21.70 ± 0.05 cm. Its mass is 1.205 ± 0.001 kg and it has 502 pages. Use these measurements to **determine** (including the percentage uncertainty of each result)

- **a** the surface area of the front cover in m^2 (4 marks)
- **b** the total external surface area in m^2 (9 marks)
- **c** the volume in m^3 (3 marks)
- **d** the thickness of one page in mm (2 marks)
- **e** the density in kg m^{-3}. (4 marks)

12 Two groups of students were measuring the acceleration due to gravity by dropping a ball from a measured height and timing how long it took to fall. Their results are shown in the table.

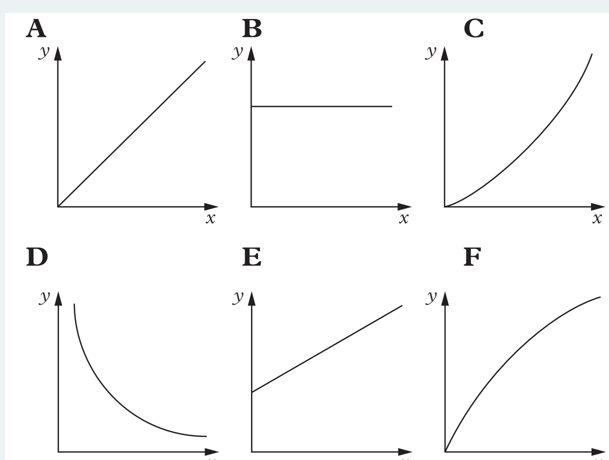
Group	Height, s (m)	Time, t (s)		
		Trial 1	Trial 2	Trial 3
A	0.50	0.37	0.44	0.50
B	2.00	0.75	0.87	0.94

To calculate the acceleration, the students used the formula $a = \frac{2 \times s}{t^2}$, where s is drop height and t is average time. The accepted value for g is 9.81 m s^{-2}. For each group, **use** the average time to **determine** the percentage uncertainty of the acceleration and the percentage error. (4 marks)

13 **Deduce** which of the following voltage measurements is the more precise: $V_1 = 0.55 \pm 0.01$ V or $V_2 = 6.4 \pm 0.1$ V. (3 marks)

14 For the graphs shown, **determine** the graph that best represents the following relationships.

- **a** y is directly proportional to x. (1 mark)
- **b** y is inversely proportional to x. (1 mark)
- **c** y is independent of x. (1 mark)
- **d** y is proportional to x^2. (1 mark)



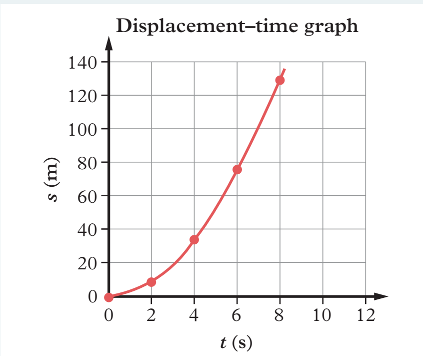
15 a If $W = kV$, **determine** the effect on W of
   i tripling V (1 mark)
   ii halving V. (1 mark)
b **Explain** what a graph of W as a function of V would look like. (2 marks)

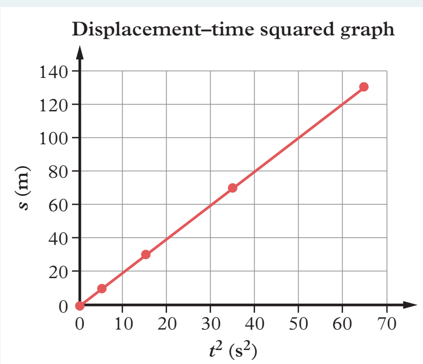
16 A plot of the variables F (vertical axis) and v (horizontal axis) gave a curve in the shape of $y \propto x^2$. **Determine** what you would need to plot to linearise the data. (1 mark)

17 The displacement (s) in metres of a car at various times t (in seconds) is given in the table.

t (s)	0	2	4	6	8
s (m)	0	8	32	72	128

Graphs were drawn to show s vs t and s vs t^2.





Calculate the gradient and **determine** the relationship between s and t. (2 marks)

Knowledge utilisation

18 **Construct** a graph of each set of data in the following questions. For each, draw the trendlines, linearise if non-linear and calculate the gradient. (Note: the independent variable is listed first.)

a Current through a resistor vs voltage applied (4 marks)

Voltage, *V* (volts)	1.0	2.0	3.0	4.0
Current, *I* (A)	0.32	0.66	1.00	1.30

b Diameter vs circumference of a circle (4 marks)

Diameter of circle (cm)	0.0	4.0	8.0	12.0
Circumference of circle (cm)	0.0	12.5	25.4	37.3

19 **Construct** a conclusion about the validity and reliability of an experiment that has a large systematic error but a small random error, with reference to accuracy and precision. (2 marks)

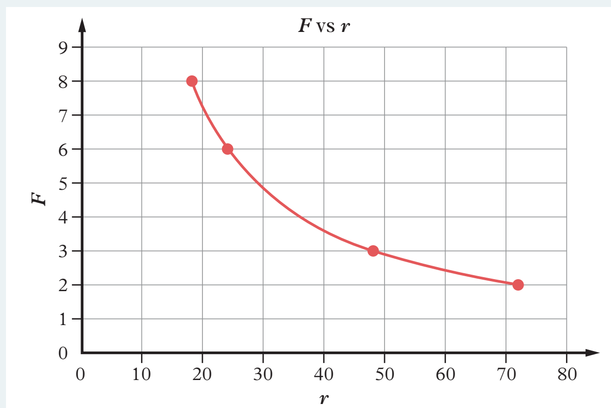
20 "I can't linearise my data." **Discuss** if this means that your experiment was not valid. (3 marks)

21 The table shows data from an experiment where F and r are two related variables.

F	72	48	24	18
r	2	3	6	8

The data was plotted to give the graph shown.

a **Predict** the mathematical relationship suggested by this graph. (1 mark)
b **Sketch** another graph to confirm your prediction. (5 marks)



Lesson 1.8
Evaluating evidence

Key ideas

- → Evidence is evaluated to determine its validity and reliability.
- → Goodness of fit (R^2) provides information about the precision of the data.
- → Random and systematic errors can be identified by assessing the trendline of a graph.
- → Not all secondary sources are reliable; they must be evaluated before use.

Science inquiry skills

Learning intentions and success criteria

This lesson provides support for the following science inquiry skills:

- identify and implement strategies to manage risks, ethics and environmental impact, e.g.
  - acknowledgement of sources and referencing
- use data and reasoning to discuss and evaluate the validity and reliability of evidence, e.g.
  - discuss ways in which measurement error, instrumental uncertainty, the nature of the methodology or other factors influence uncertainty and limitations in the data
  - evaluate information sources and compare ideas, information and opinions presented within and between texts, considering aspects such as acceptance, bias, status, appropriateness and reasonableness
  - compare findings to theoretical models or expected value
- analyse data to identify trends, patterns and relationships; recognising error, uncertainty and limitations of evidence
- appreciate the role of peer review in scientific research.

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Lesson 1.9
Communicating scientifically

Key ideas

- → Different communication conventions are used depending on the target audience.
- → Evidence-based arguments bring together scientific ideas and primary and/or secondary data obtained from scientific investigation.
- → Sources can be acknowledged using in-text referencing and a bibliography.

Learning intentions and success criteria

Science inquiry skills

This lesson provides support for the following science inquiry skills:

- select, synthesise and use evidence to construct scientific arguments and draw conclusions
- communicate to specific audiences and for specific purposes using appropriate language, nomenclature, genres and modes
- acknowledge sources of information and use standard scientific referencing conventions.

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Lesson 1.10
Preparing for your data test

Key ideas

→ The data test is an assessment task in which you respond to items using qualitative data and/or quantitative data derived from practicals, activities or case studies.

→ In your data test, you will apply your understanding, analyse data, and interpret evidence.

Learning intentions and success criteria

Assessment objectives

This lesson provides support for achieving the assessment outcomes for the data test:

Objective 2. Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 3. Analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

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Worked examples

This lesson is supported by the following Worked example:

- **Worked example 1.10A** Responding to the data test

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Lesson 1.11
Conducting your student experiment

Key ideas

→ Your student experiment requires you to modify an experiment you have conducted in Units 1 and 2 to address your own related hypothesis or question.

→ You will research and plan your experiment, analyse, interpret and evaluate your evidence, and communicate your findings.

Assessment objectives

Learning intentions and success criteria

This lesson provides support for achieving the assessment outcomes for the student experiment:

Objective 1. Describe ideas and findings about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 2. Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 3. Analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 5. Evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.

Objective 6. Investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits.

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Lesson 1.12
Conducting your research investigation

Key ideas

→ The research investigation is an assessment task in which students gather evidence related to a research question to evaluate a claim in physics.

Assessment objectives

Learning intentions and success criteria

This lesson provides support for achieving the assessment outcomes for the research investigation:

Objective 1. Describe ideas and findings about linear motion and force, and waves.

Objective 2. Apply understanding of linear motion and force, and waves.

Objective 3. Analyse data about linear motion and force, and waves.

Objective 4. Interpret evidence about linear motion and force, and waves.

Objective 5. Evaluate processes, claims and conclusions about linear motion and force, and waves.

Objective 6. Investigate phenomena associated with linear motion and force, and waves.

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Lesson 1.13
Preparing for your exams

Key ideas

→ Your external exam requires you to demonstrate your understanding of the QCE Physics course by completing multiple-choice and short-answer questions.

→ Exam questions are typically written using cognitive verbs, which tell you what information you need to provide in your answer to the question.

Assessment objectives

Learning intentions and success criteria

This lesson provides support for achieving the assessment outcomes for the examination:

Objective 1. Describe ideas and findings about heating processes, ionising radiation and nuclear reactions, electrical circuits, linear motion and force, and waves.

Objective 2. Apply understanding of heating processes, ionising radiation and nuclear reactions, electrical circuits, linear motion and force, and waves.

Objective 3. Analyse data about heating processes, ionising radiation and nuclear reactions, electrical circuits, linear motion and force, and waves.

Objective 4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, electrical circuits, linear motion and force, and waves.

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MODULE 1

Lesson 1.14
Review: Physics toolkit

Summary

1.1
- In QCE Physics, you will gain a variety of science understanding and inquiry skills that will help you succeed in assessments, as a scientific professional, and as a science citizen.

1.2
- First Nations peoples have longstanding scientific knowledge.
- First Nations peoples have developed knowledge about the world by observing using all the senses, predicting and hypothesising, testing (trial and error), and making generalisations within specific contexts such as the use of food, natural materials, navigation and sustainability of the environment.
- Correctly acknowledging cultural and/or language groups, rejecting deficit discourse, avoiding Eurocentrism and critically evaluating sources of information can help you to respectfully engage with First Nations perspectives in QCE Physics.

1.3
- The scientific method is an iterative and cyclic process.
- Research questions define the scope of an investigation. They can be used to develop hypotheses that predict the outcome of the investigation.

1.4
- A method outlines the steps followed in an experiment and lists all of the materials and equipment used.
- Valid and reliable measurements can be obtained by carefully designing your investigation to collect sufficient data and minimise errors.
- All measurements include errors or uncertainties, either systematic or random. It is important to consider these and implement strategies to minimise their effects when planning your experiments.

1.5
- Laboratory safety is important to prevent harm to yourself and those sharing the lab space with you.
- Safety and ethics extend beyond the lab; you should be considering the broader potential impacts of your experiment.

1.6
- Single experimental measurements are reported using best estimates, indicators of measurement uncertainty and units.
- Scientific notation is used to easily express extremely large or small values.
- Significant figures are digits in a number that are known with certainty and the first digit that is uncertain.
- All measurements, information and observations should be recorded in your logbook.

1.7
- Data is processed and analysed to identify trends, patterns, relationships, limitations and uncertainty.
- Absolute and percentage uncertainty give an idea of the precision of measurements.
- Absolute and percentage error give an idea of the accuracy of measurements.
- Data can be summarised in a variety of ways, such as in a table, a scatterplot, or a scientific diagram.
- Linearising data helps you to identify the exact relationship between variables.

1.8
- Evidence is evaluated to determine its validity and reliability.
- Goodness of fit (R^2) provides information about the precision of the data.
- Random and systematic errors can be identified by assessing the trendline of a graph.
- Not all secondary sources are reliable; they must be evaluated before use.

1.9
- Different communication conventions are used depending on the target audience.
- Evidence-based arguments bring together scientific ideas and primary and/or secondary data obtained from scientific investigation.
- Sources can be acknowledged using in-text referencing and a bibliography.

1.10
- The data test is an assessment task in which you respond to items using qualitative data and/or quantitative data derived from practicals, activities or case studies.
- In your data test, you will apply your understanding, analyse data, and interpret evidence.

1.11
- Your student experiment requires you to modify an experiment you have conducted in Units 1 and 2 to address your own related hypothesis or question.
- You will research and plan your experiment, analyse, interpret and evaluate your evidence, and communicate your findings.

1.12
- The research investigation is an assessment task in which students gather evidence related to a research question to evaluate a claim in physics.

1.13
- Your external exam requires you to demonstrate your understanding of the QCE Physics course by completing multiple-choice and short-answer questions.
- Exam questions are typically written using cognitive verbs, which tell you what information you need to provide in your answer to the question.

Key formulas

Mean (best estimate of repeated single measurements)	$\bar{x} = \frac{\Sigma x}{n}$
Absolute uncertainty	$\delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$
Standard deviation	$\sigma = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n - 1}}$
Percentage uncertainty	$\delta\% = \frac{\delta\bar{x}}{x_O} \times 100$
Absolute error	$E_a = \lvert x_O - x_A \rvert$
Percentage error	$E\% = \frac{E_a}{x_A} \times 100$
Gradient	$m = \frac{\Delta y}{\Delta x}$

Review questions 1.14A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 Select the option that has the smallest magnitude.

A -1×10^2

B 1×10^2

C 10

D 100

2 Which one of the following is closest in area to 2.0 m²?

A 200 cm²

B 20,000 cm²

C 2×10^7 mm²

D 200,000 mm²

3 Calculate the magnitude of the following to the correct number of significant figures: 1.18 cm × 3.1416 cm.

A 3.7

B 3.71

C 3.707

D 3.7071

4 Calculate the following and express in scientific notation to the correct number of significant figures: $(2.0 \times 10^{-3}\,\text{m}) \times (2.00 \times 10^{-4}\,\text{m})$.

A 4.0×10^{-7} m

B 4.0×10^{-7} m²

C 4.00×10^{-7} m

D 4.0×10^{-12} m²

5 Use scientific notation to express the number 0.000552.

A 552×10^{-6}

B 0.552×10^{-3}

C 5.52×10^{-4}

D 5.52×10^{-2}

6 Use the correct scientific notation to express the number 73,000,000.

A 0.73×10^8

B 7.3×10^7

C 73×10^6

D $73 \times (10^3)^2$

7 The resistance of a 20.0 cm length of nichrome wire was measured four times as 15.5, 16.0, 15.7 and 15.9 ohms. Calculate the absolute uncertainty of the mean.

A 0.1

B 0.3

C 0.5

D 15.8

8 The time for a ball to roll down an incline was measured as 1.05 s, 1.20 s, 1.13 s, 1.05 s. Calculate the percentage uncertainty of the mean.

A 0.075

B 1.11

C 6.8

D 7.2

9 An analogue thermometer has a resolution of 1°C. The initial and final temperatures were measured as 24.5°C and 54.0°C respectively. Calculate the change in temperature including the absolute uncertainty.

A 29 ± 0.5°C

B 29.5 ± 0.5°C

C 29.5 ± 1.0°C

D 30 ± 1°C

10 In the analysis of a motion experiment, the equation for the linear line of best fit was $y = 5.0x + 2.5$. The maximum line of best fit was $y = 6.5x$, and the minimum line of best fit was $y = 4.8x + 3.0$. Calculate the absolute uncertainty of the gradient.

A 0.85

B 1.7

C 2.5

D 5.5

11 The formula $\delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$ is used to calculate

A absolute uncertainty.

B best estimate.

C absolute error.

D mean.

12 A strip of copper measures 20.0 ± 0.05 mm by 30.0 ± 0.05 mm. Calculate the area of this face.

A 600 ± 0.0025 mm²

B 600 ± 0.10 mm²

C 600 ± 0.42 mm²

D 600 ± 2.5 mm²

13 The cross-sectional area of a piece of nichrome wire was 0.1 mm². Calculate the area in square metres.

A 1.0×10^{-7} m²

B 1.0×10^{-6} m²

C 1.0×10^{-4} m²

D 1.0×10^{-3} m²

Review questions 1.14B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

14 **Classify** the following units as SI or non-SI: metres, kilograms, pounds, kelvin. (1 mark)

15 In terms of the analysis of data

a **explain** the difference between significant figures and scientific notation. (2 marks)

b **explain** how a “systematic error” differs from a “random error”. (2 marks)

16 **Explain** what is meant by “propagation of errors” when performing a calculation. (3 marks)

17 **Explain** why it may be necessary to calculate percentage error of a result rather than just leave it as absolute error. (3 marks)

18 **Identify** the number of significant figures in each number.

a 83.83 (1 mark)

b 20.0 (1 mark)

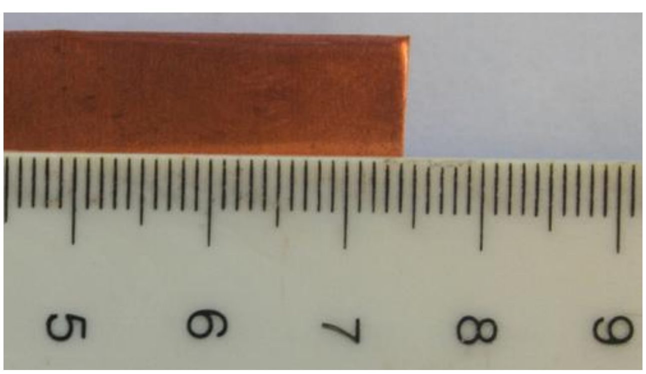
19 **Use** scientific notation to express each number.

a 0.000552 (1 mark)

b 73,000,000 (1 mark)

Analytical processes

20 **Determine** the reading and uncertainty of the measurement on the ruler. The numbers are centimetres and the small divisions are millimetres. (2 marks)



21 Complete the following questions.

a **Sketch** a graph of the data given in the table and draw a line of best fit. (Note: the independent variable is listed first.) (3 marks)

Time, t (s)	0.0	2.0	4.0	6.0
Distance, s (m)	0.0	12	23	37

b For the line plotted on the graph

i **calculate** the gradient (1 mark)

ii **determine** the distance after 8.0 s by extrapolation (1 mark)

iii **determine** the distance after 3.0 s by interpolation. (1 mark)

22 An analogue voltmeter with a scale division of 0.1 V reads 2.4 V when placed across a resistor of 47 Ω ± 5 %.

a **Determine** the absolute uncertainty in the voltage reading. (1 mark)

b If a calculation of $\frac{V^2}{R}$ was made, **calculate** the percentage uncertainty in the result. (2 marks)

23 German physicist Arnd Leike, from the University of Munich, found that the decay of foam height in beer with time was exponential: $y \propto \frac{1}{x^n}$, where y = height of the foam and x = time. He was awarded an “Ig Nobel” Prize by the science humour magazine *Annals of Improbable Research* for one of the world’s most useless pieces of research. **Differentiate** between the shapes of the graphs when n = 3 (Leike’s result) and n = 2 (inverse square). (2 marks)

Knowledge utilisation

24 An experiment using an electric water heater was conducted to test the effect of different currents on the heat added to a cup of water after 10 minutes. The results are shown in the table.

Current, I (A)	0.5	0.8	1.0	1.6	2.4	3.0
Heat, Q (J)	375	960	1,500	3,800	8,640	13,500

a **Construct** a graph to show the relationship between heat Q, in joules, developed in a heater by electric currents of I amperes. (3 marks)

b **Describe** the relationship between Q and I. (1 mark)

c **Construct** a linearised graph to confirm the relationship between Q and I. (4 marks)

25 As part of an investigation into motion of a falling object, a tennis ball was dropped from various heights as shown in the table. The heights were measured with a metre ruler marked in mm and the uncertainty was considered insignificant. Times for three trials were measured with a stopwatch.

Height, s (m)	Drop time, t (s)		
	Trial 1	Trial 2	Trial 3
0.50	0.37	0.44	0.50
1.00	0.62	0.56	0.56
1.50	0.75	0.75	0.69
2.00	0.75	0.87	0.94

a **Calculate** the mean ($\bar{x}$), and the absolute uncertainties of the mean for the times for each height. (8 marks)

b **Construct** a graph with height s on the horizontal axis, and the corresponding mean of the times on the vertical axis. (3 marks)

c **Construct** a linearised graph by plotting $\sqrt{s}$ on the horizontal axis and t on the vertical axis, including vertical error bars. (3 marks)

d **Determine** the gradients of the maximum and minimum trendlines and express these as an absolute uncertainty of the gradient. (4 marks)

26 The following sets of data represent common relationships in physics. **Predict** the relationship by graphical means for each dataset and confirm it where necessary by linearisation.

a Dataset 1 (4 marks)

x	1	2	3	5	6
y	2.00	1.10	0.67	0.41	0.33

b Dataset 2 (4 marks)

x	1	2	4	6	8
y	3.00	0.75	0.19	0.08	0.05

c Dataset 3 (4 marks)

x	0	2	3	5	7
y	0	20	45	125	245

27 The following sets of data represent common relationships in physics. **Predict** the relationship by graphical means for each dataset and confirm it where necessary by linearisation.

a Dataset 1 (4 marks)

x	0.50	1.70	2.10	3.60	7.00
y	0.54	0.99	1.10	1.44	2.01

b Dataset 2 (4 marks)

x	0	1.5	3.4	5.1	7
y	3.2	9.2	16.8	23.6	31.2

28 Students were investigating the swing of a pendulum as a function of the length of the string. Their results are shown in the table. The period is the time for one complete swing.

Length, L (m)	Period, T (s) ± 0.15 s
0.10	0.78
0.20	1.20
0.40	1.42
0.60	1.90
0.80	2.04
1.00	2.16
1.20	2.50
1.40	2.67

a **Construct** a graph with length on the horizontal axis and time on the vertical axis and draw a trendline. (3 marks)

b **Predict** the relationship between T and L. (1 mark)

c **Construct** a linearised graph to confirm the relationship. (3 marks)

d **Determine** the gradient of the trendline (2 s.f.). (1 mark)

e **Construct** error bars on the graph and **determine** the gradient of the maximum and the minimum trendlines. (3 marks)

f **Express** the gradient as a mean value ± absolute uncertainty. (1 mark)

Module 1 checklist: Physics toolkit

Quizlet: Revise key terms online to test your understanding

UNIT 1

Thermal, nuclear and electrical physics

Unit 1 overview

The three seemingly different ideas of heat, nuclear energy and electricity have one thing in common – the pivotal role of energy in modern society. These three topics provide an introduction to the fundamental ideas of energy transfers and transformations, and how global energy needs are met.

As objects are heated, their energy increases, and this means changes to their internal energy – the microscopic kinetic and potential energy of the particles. An understanding of this internal energy forms the basis of modern thermodynamics and the laws that allow us to predict the direction of the flow of energy; deduce the source of energy losses; and calculate the efficiency of energy transfer in devices such as car engines, steam engines and refrigerators. This leads into an examination of matter at the atomic scale, starting with the structure of the nucleus and how the strong nuclear and electrostatic forces compete to keep the nucleus together or let it disintegrate into alpha, beta and nuclear radiation along with neutrinos and antineutrinos. We see how a decaying nucleus converts mass into energy, as described by Einstein's famous equation $E = mc^2$, and how this process is the basis for nuclear reactors, radiopharmaceuticals and the stars. The final topic looks at electricity, beginning with the relationship between voltage, current and resistance. Circuit analysis helps us understand how electrical energy is transferred in wires to be used and controlled in homes and workplaces.

Unit objectives

1. Describe ideas and findings about heating processes, ionising radiation and nuclear reactions, and electrical circuits.
2. Apply understanding of heating processes, ionising radiation and nuclear reactions, and electrical circuits.
3. Analyse data about heating processes, ionising radiation and nuclear reactions, and electrical circuits.
4. Interpret evidence about heating processes, ionising radiation and nuclear reactions, and electrical circuits.
5. Evaluate processes, claims and conclusions about heating processes, ionising radiation and nuclear reactions, and electrical circuits.
6. Investigate phenomena associated with heating processes, ionising radiation and nuclear reactions, and electrical circuits.

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Unit 1 Topics

Topic	Module	
Topic 1 Heating processes	**Module 2**	Kinetic particle model and specific heat capacity
	Module 3	Phase changes and energy conservation
Topic 2 Ionising radiation and nuclear reactions	**Module 4**	Nuclear model and stability
	Module 5	Radioactive decay and half-life
	Module 6	Nuclear energy and mass defect
Topic 3 Electrical circuits	**Module 7**	Current, potential difference and energy flow
	Module 8	Circuit analysis and design

MODULE

2 Kinetic particle model and specific heat capacity

Introduction

Would you rather be too hot or too cold? If you're too hot, you can sit in the shade or wear fewer clothes, but that's about it. If you're too cold, you can add extra layers of clothing. But what is more important to survival: heat, or the lack of heat? The answer to each of these questions has to do with the internal structure of matter and how it responds to heat. It is a subject called "thermodynamics".

The term "thermodynamics" stems from the Greek "therme" = "heat" and "dynamis" = "power". This was appropriate for the 1800s when it was first used, as people were concerned about how to convert heat into power for factories and mines. Today, we say that thermodynamics is concerned with systems involving energy transfer in the form of heat and work. This includes applications such as solar heating and cooling of buildings, refrigeration and air-conditioning, and the design and construction of engines.

The science of heating processes also helps us address contemporary issues through the development of efficient and cost-effective technologies, the use of sustainable and renewable energy sources, and by allowing the prediction of global temperatures and the effects of human activity on climate change.

Prior knowledge

Prior knowledge quiz

Check your understanding of the particle model and energy transfer before you start.

Subject matter

Science understanding

→ Describe the kinetic particle model of matter.

→ Describe the concepts of thermal energy, temperature, kinetic energy, heat and internal energy.

→ Explain heat transfers in terms of conduction, convection and radiation.

→ Use $T_K = T_C + 273$ to convert temperature measurements.

→ Explain that a change in temperature is due to the addition or removal of energy from a system (without phase change).

- → Describe the concept of specific heat capacity.
- → Solve problems involving specific heat capacity using $Q = mc\Delta T$.
- → Interpret data from specific heat capacity experiments.

Science as a human endeavour

- → Explore the development of new technologies and understandings of heating processes as a means to predicting global temperatures and the effects of human-induced climate change.
- → Appreciate that different temperature scales (e.g. Celsius, Fahrenheit, Kelvin) were developed at different times to serve different purposes.

Science inquiry

- → Consider the significance of using common units of measurement internationally.
- → Investigate the precision and accuracy of different temperature measuring devices, such as analogue and digital thermometers, by determining measurement uncertainty.
- → Use digital and other measuring devices to collect data, ensuring measurements are recorded using the correct symbol, SI unit, number of significant figures and associated measurement uncertainty (absolute and percentage); all experimental measurements should be recorded in this way.
- → Consider the energy contained within a cup of coffee versus a swimming pool.
- → Explore the properties of water that makes it ideal for use as a coolant in car engines.
- → Investigate the proportional relationship between heat and temperature change.
- → Investigate specific heat capacity of a substance.
- → Explore why it is possible to boil water in a paper cup on a campfire.

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Practicals

These lessons are available on Oxford Digital.

Lesson 2.2 Heating water on a hotplate – graphing and analysing data
Lesson 2.7 Precision and accuracy of thermometers
Lesson 2.10 Specific heat capacity of liquids – on a hotplate

Lesson 2.1
Heating and cooling

Key ideas

→ Heat is the transfer of energy from a higher temperature object to a lower temperature object.

→ Thermal equilibrium is achieved when two objects that are in contact with one another reach the same temperature.

Learning intentions and success criteria

heat
energy that is spontaneously transferred from one object to another due to a difference in temperature between the objects (symbol: Q; SI unit: joule; unit symbol: J)

energy
a measure of the ability of a system to do work and supply heat; energy is conserved in any interaction (symbol: W; SI unit: joule; unit symbol: J)

Are heat and energy the same thing?

When you add ice to a glass of water, you will notice that the water gets colder, and the ice starts to melt and changes from a solid to a liquid state (or phase). This can be explained using the terms "**heat**" and "**energy**", but we need to be careful about the difference between them.

Heat is energy in the process of being transferred from one object to another due to temperature difference. It is sometimes called "energy in transit". Because heat is a quantity of energy being transferred between two bodies (the water and the ice), neither body has a definite amount of heat. Instead, they each have a definite amount of thermal energy. Thermal energy is sometimes referred to as heat energy, but we should try to use the correct term.

The idea of heat has developed through three different models over time. Thousands of years ago, heat was thought to be something alive and living inside things. This changed 2,000 years ago with the Greek idea that heat was a material substance called "caloric" that was lost or gained as an object was heated or cooled. Our modern view started in the mid-1800s when heat came to be regarded as the transfer of energy related to the movement of microscopic particles (atoms and molecules). The word "energy" was used in 1852 by William Thomson (Lord Kelvin, 1824–1907) from Glasgow, Scotland. This is where we are today: "energy" is not a thing, but a property of an object. We can't really identify what energy is, but we do have formulas to define it and show how it changes in interactions.

A B

FIGURE 1 (A) Heat travels from the water to the ice so the ice warms and the water cools. (B) The spoon and the coffee start off at different temperatures, but as heat flows from the hot coffee to the cool spoon, the coffee loses thermal energy and the spoon gains an equal amount of thermal energy, eventually coming to thermal equilibrium.

Another great example of thermal energy transfer is when you put a spoon into a cup of hot coffee. Although this does not involve a change of phase, the spoon gets hot as heat flows from the coffee into the spoon. Eventually, when the spoon, the coffee and the cup have shared their energy, they come to the same temperature. For the moment, the best we can do is say that "temperature is what you measure with a thermometer". This is an operational definition as it tells you how to measure the quantity in question. Later, we will explain a theoretical definition to do with the motion of the particles. The one thing we do know about temperature is that it will be the same for objects that have been in contact long enough. There is a special term for this, which you will learn more about in Module 3.

What exactly is going on at the very smallest scale when ice melts, or a spoon gets heated by coffee? By the end of this topic, you will be able to answer these questions.

Skill drill

Analysing the relationship between heat and temperature change

Science inquiry skills: Processing and analysing data (Lesson 1.7)

In an experiment, students heated water in an insulated container. The change in temperature at various times is shown in Figure 2.

Practise your skills

1 **Identify** the mathematical relationship between the temperature, T, and the time, t. Express your answer using 2 s.f. Show your working. (3 marks)

2 **Predict**, by extrapolation, the temperature after 700 seconds have elapsed. (1 mark)

3 **Predict**, by interpolation, the temperature after 180 seconds. (1 mark)

4 **Predict**, using the formula developed in question **1**, the time it would take for the water to reach 100°C. (2 marks)

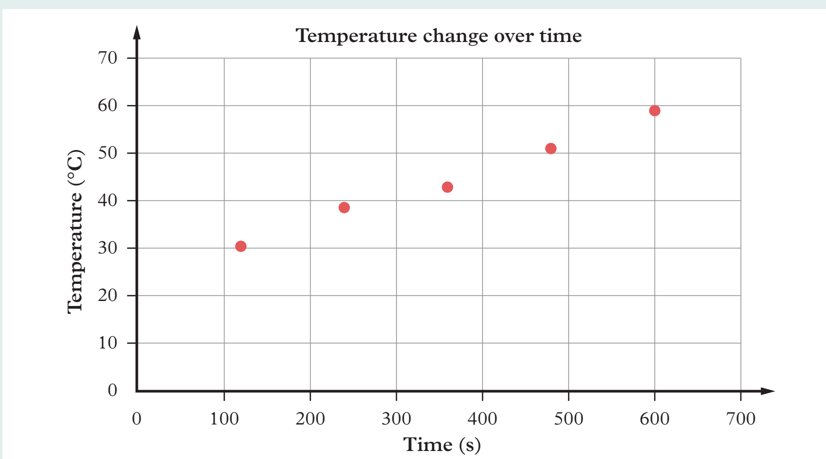


FIGURE 2 Temperature (°C) of water over time (s) during heating in an insulated container

Skill drill

Quantifying uncertainty in a heating process

Science inquiry skills: Processing and analysing data (Lesson 1.7)

A student conducted an experiment to investigate the temperature change of water in a beaker over time. The student used a hotplate that delivered a constant source of heat and measured the temperature of the water every minute for 6 minutes. The data was processed and plotted in Figure 3.

Practise your skills

1 **Identify** a mathematical relationship between the temperature of the water and the time elapsed, including the percentage uncertainty of the gradient (1 s.f.) and the absolute uncertainty of the y-intercept (1 s.f.). (4 marks)

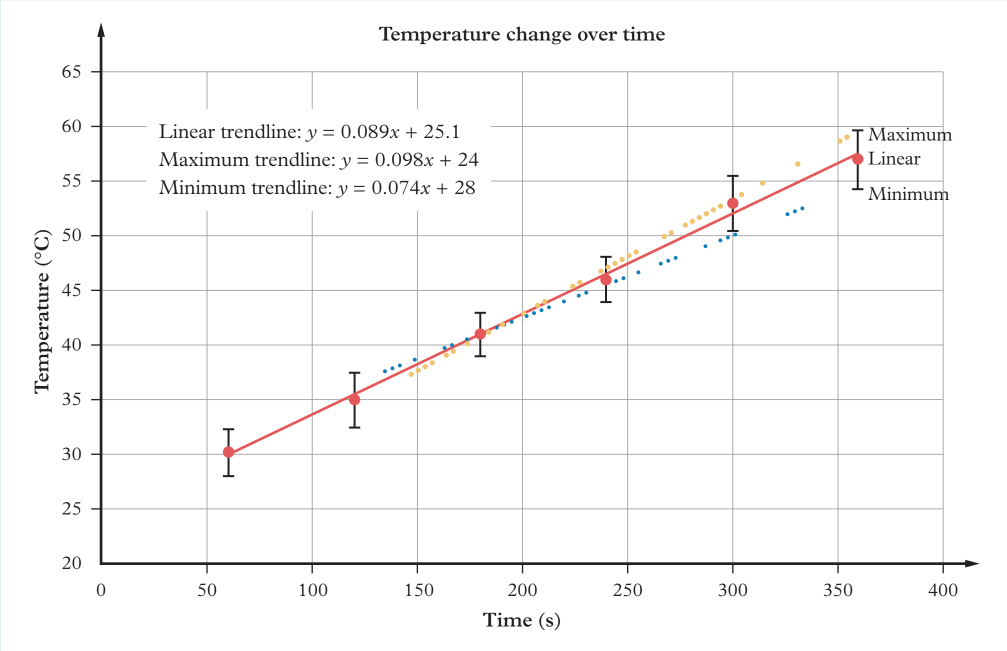


FIGURE 3 Temperature (°C) of water over time (s) during heating in a beaker, including the maximum (orange), linear (dashed) and minimum (blue) trendlines and their mathematical relationships

Check your learning 2.1

Check your learning 2.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the difference between "heat" and "energy". (2 marks)

2 **Explain** why heating is described as a process. (2 marks)

3 **Describe** the direction of heat flow in terms of temperature. (1 mark)

Practical

Lesson 2.2
Heating water on a hotplate – graphing and analysing data

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Lesson 2.3
The kinetic particle model of matter

Key ideas

→ The kinetic particle theory of matter states that all matter is made of particles that are in constant random motion.

→ The behaviour of particles in solids, liquids and gases differs due to their kinetic energy.

What is kinetic theory?

Previously, we looked at how objects lost and gained heat and asked the question: What is happening at the smallest scale? What are these microscopic particles doing when they heat up, or when they lose heat? To answer these questions, we first need to understand how matter behaves at the atomic level.

About 2500 years ago, the Greek philosophers Leucippus and Democritus suggested that matter consisted of small, hard **particles** that couldn't be cut up; they called them **atoms** (Greek "a" = "not", "toma" = "cut"). The behaviour of all particles and atoms can be explained using the kinetic particle model of matter.

The kinetic particle model of matter can be summarised by the following statements:

- Particles of matter are in constant random motion – they have **kinetic energy**.
- There are **intermolecular forces** between the particles.
- Collisions between particles are perfectly elastic, meaning that they do not lose kinetic energy when they collide.

Learning intentions and success criteria

particle
a minute portion of matter, mainly atoms and molecules

atom
the basic unit of matter; the smallest particle of a chemical element that can exist

kinetic energy
the energy due to the motion of an object, including the motion of particles in a substance (symbol: E_k; SI unit: joule; unit symbol: J)

intermolecular force
a force between particles of a substance

What are the phases of matter?

Solids, liquids and gases feel and behave differently. An understanding of how particles are arranged in the phases of matter can help us understand their properties – in this case, what happens when they are heated, or when hot and cold substances are mixed. To make sense of their properties, we need to look at each phase in detail.

Solids

At the lowest possible temperature of −273.15°C, called **absolute zero** (0 K), particles are at their lowest energy state, but they are not still. For example, consider a chair at room temperature that you might be sitting on in your classroom. The chair is not moving but all the particles that make up the chair have a constant, **vibrational motion**. What prevents you from crashing to the floor when you sit on it are the strong intermolecular forces that hold the vibrating particles very closely together. These fix the particles in position and help maintain the shape and volume of your chair (i.e. make it a solid object).

absolute zero
the lowest temperature that is theoretically possible, at which the motion of particles which constitutes heat would be minimal; zero on the Kelvin scale (0 K)

vibrational motion
a form of kinetic energy in which particles vibrate in place

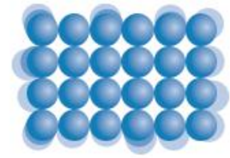


FIGURE 1 Vibrating particles in a solid are held close together in a "lattice" structure and have very limited movement. This allows them to keep their own volume and shape.

Liquids

Particles in liquids are also quite close, and the intermolecular forces between them are not as strong as in solids, so they can slide past one another. Particles in liquids also have more kinetic energy as they can move from place to place – they have **translational motion** (Latin "trans" = "across", "lato" = "to carry"). They may also have **rotational motion**, which means they can spin on their own axes. This allows liquids to maintain their volume, but change shape depending on the container they are placed in.

translational motion
a form of kinetic energy in which a particle moves from place to place

rotational motion
a form of kinetic energy in which a particle spins on its own axis

FIGURE 2 Particles in a liquid are close together and can move around. Liquids keep their own volume but take on the shape of the container they are placed in.

Gases

There is a lot of space between the particles of a gas, and they bounce off each other. The intermolecular forces are quite weak and the particles move at high speeds, with considerable translational, vibrational and rotational motion. This allows gases to change volume and shape to fill the container they are placed in.

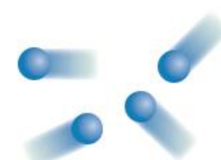


FIGURE 3 Particles in a gas are far apart and can easily move around. Gases take on the volume and shape of the container they are in.

Study tip

Adding heat energy does not always cause a change in phase. For example, there is not enough energy in the cup of coffee to melt the spoon and turn it into a liquid. But there is enough transfer of energy to cause changes in the kinetic energy of the particles within the spoon.

How is energy different in the phases of matter?

When you add enough thermal energy to a solid such as ice, it changes phase to become water, a liquid. If you add even more thermal energy, it eventually changes phase to become steam, a gas. That means steam has more energy than water, which has more energy than ice. You will learn more about phase changes in Module 3.

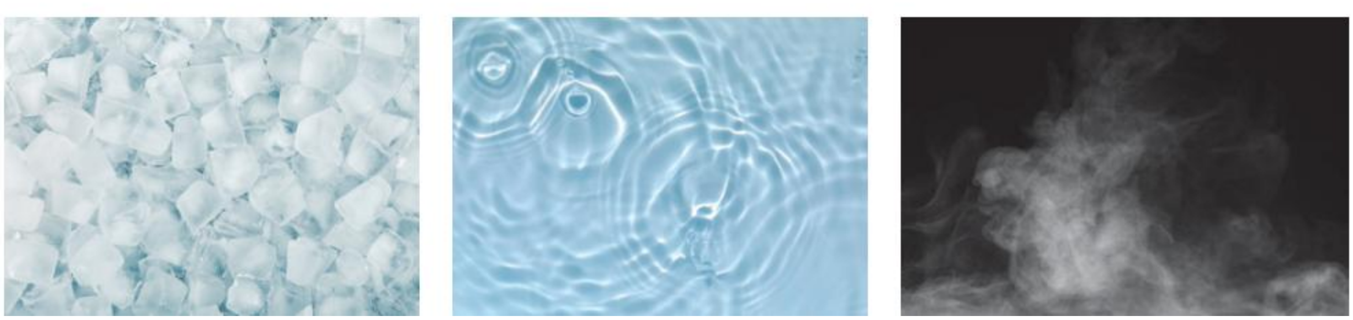


FIGURE 4 Adding or removing thermal energy can allow us to convert between phases of substances such as water.

Consider how the particles in the glass of ice water and cup of coffee are behaving. How do they change as the ice warms and melts, and as the water cools? How do the particles in the spoon change as heat is transferred to them? The summary in Table 1 can help guide you.

TABLE 1 Summary of the three of phases of matter

	Solids	Liquids	Gases
Volume	keep own volume	keep own volume	take volume of container
Shape	keep own shape	take shape of container	take shape of container
Kinetic energy	low	moderate	higher
Intermolecular forces	strong	moderate	weak

Check your learning 2.3

Check your learning 2.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** "kinetic energy". (1 mark)

2 **Describe** the kinetic particle model, using the liquid phase as an example. (2 marks)

3 **Explain** how the kinetic energy of a substance differs when it is a solid compared to when it is a gas. (1 mark)

Analytical processes

4 **Explain** why solids can keep their own shape, while liquids and gases will take the shape of the containers they are placed in. (3 marks)

5 **Compare** the kinetic energy of the ice in the glass of ice water before it melts and after it has completely melted. (2 marks)

Lesson 2.4
Internal and thermal energy

Key ideas

→ Microscopic (or internal) energy is the energy of particles at the atomic level, while macroscopic energy is the energy of the bulk.

→ Thermal energy consists of microscopic kinetic energy and the microscopic potential energy stored within and between bonds.

→ In thermal physics, microscopic energy, internal and thermal energy are the same.

Learning intentions and success criteria

What is microscopic energy?

The kinetic energy of particles in a substance or object is also a type of "microscopic" kinetic energy, but what does this mean?

Imagine a truck full of birds flying about inside. From inside the truck, the birds are in motion, much like particles of matter that have their own energy. This part of the analogy represents the **microscopic energy** of an object or substance on the atomic or particle scale. The motion can be vibrational kinetic energy, or rotational and translational kinetic energy.

microscopic energy
energy of the particles that make up a substance, including microscopic kinetic energy from the motion of particles and microscopic potential energy (symbol E_{micro}; unit: joule; symbol: J)

microscopic potential energy
the energy stored in the bonds within and between particles of a substance (symbol: $E_{p(micro)}$; SI unit: joule; unit symbol: J)

In addition to kinetic energy, the particles of matter also possess **microscopic potential energy** in the form of:

- chemical energy – energy released when chemical bonds (covalent, ionic and metallic) are formed
- nuclear energy – energy that could be released when bonds are formed between particles in the nucleus
- intermolecular bond energy – the energy gained or released when intermolecular bonds between particles are formed.

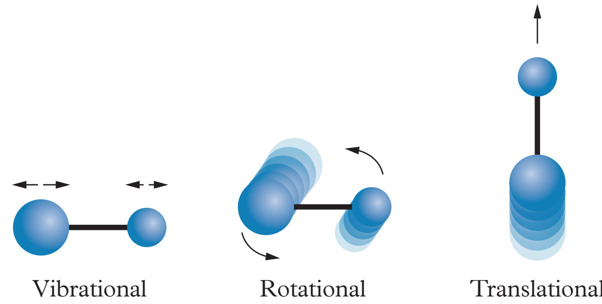


FIGURE 1 Three types of motion in particles

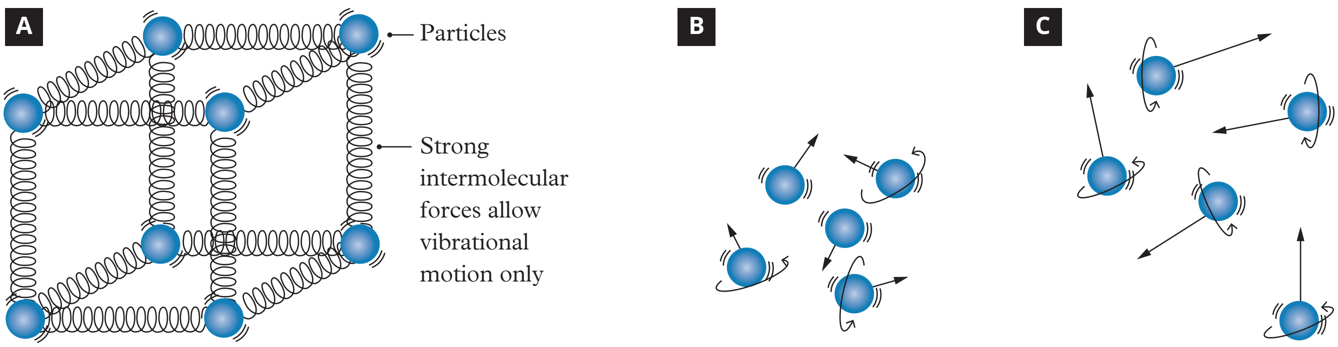


FIGURE 2 The main sources of microscopic potential energy in the three states of matter: (A) vibrational motion in a solid; (B) translational motion in a liquid (plus some vibration and rotation); (C) translational, vibrational and rotational motion in gases. There is also chemical energy and nuclear energy of the molecules.

macroscopic energy
big or bulk forms of energy not at an atomic scale (symbol: E_{macro}; unit: joule; symbol: J)

Now, when you observe the truck from the outside, you cannot see the birds flying about at all and the truck appears stationary. This is one representation of **macroscopic energy**, which is the sort of energy you learnt about in Year 10.

FIGURE 3 The energy of a ball in flight is related to its motion (E_k) and height (E_p), but note the gas molecules shown inside the ball.

What is macroscopic energy?

Macroscopic energy is due to the motion (velocity) or location (height) of an object in a gravitational, electromagnetic or electrostatic field. Consider a student passing a basketball (Figure 3). What macroscopic energy does the ball possess?

You would say the ball has kinetic energy (KE or E_k) because of its motion from being thrown. This means that as the object's velocity increases, its macroscopic kinetic energy increases. There is also gravitational potential energy (GPE or E_p) due to the ball's height above the ground.

Macroscopic energy is the sum of these two forms of energy:

$$E_{macro} = E_{k(macro)} + E_{p(macro)}$$

But the ball possesses more energy than that.

What is internal energy?

Let's consider the motion of the gas particles inside the basketball. The total microscopic energy, E_{micro}, is made up of microscopic kinetic and microscopic potential energy.

$$E_{micro} = E_{k(micro)} + E_{p(micro)}$$

The $E_{k(micro)}$ is made up of the microscopic kinetic energy due to translation, rotation and vibration. The $E_{p(micro)}$ is the microscopic potential energy associated with chemical bonds between and inside molecules (E_{chem}), and the nuclear energy ($E_{nuclear}$) contained inside the nucleus. The combination of microscopic kinetic and potential energy is called **internal energy**. Internal energy, U, is therefore calculated using the same equation:

$$U = E_{k(micro)} + E_{p(micro)}$$

internal energy
the total microscopic potential energy and microscopic kinetic energy of the particles in a system (symbol: U; units: joules; symbol: J)

What is thermal energy?

In thermal physics, E_{chem} and $E_{nuclear}$ are not considered to change in heating and cooling. If we leave out these forms of energy, we are left with the microscopic kinetic energy of the particles, and microscopic potential energy stored between bonds. This is **thermal energy**, E_{th}.

Remember the example of a spoon in hot coffee in which there was a transfer of energy from the hotter object (the coffee) to the cooler one (the spoon). We should now be able to recognise the form of energy being transferred as internal energy, specifically thermal energy.

We cannot measure internal energy directly so, instead, we measure the change in internal energy because this is the same as the change in thermal energy.

$$\Delta U = \Delta E_{th}$$

thermal energy
the component of internal energy present in a system that determines its temperature (symbol, E_{th}; unit: joules; symbol: J)

What makes up the energy in a system?

A system is an isolated group of particles, such as in a balloon, an ice cube or a beaker of water.

The **total energy of the system** (such as in the basketball) is the sum of the energy of the object due to the macroscopic energy and microscopic energy:

$$E_{sys} = E_{macro} + E_{micro}$$

$$E_{sys} = E_{k(macro)} + E_{p(macro)} + E_{k(micro)} + E_{p(micro)}$$

We consider objects, such as the bird-filled truck, to be stationary systems in which there is no change in macroscopic energy. This means that the change in energy of the whole system during heating or cooling is due purely to change in internal energy:

$$\Delta E_{sys} = \Delta U$$

total energy of the system
the sum of the energy present in a system, including microscopic and macroscopic kinetic and potential energy (symbol, E_{sys}; unit: joules; symbol: J)

TABLE 1 The forms of energy that make up total (or "system") energy, E_{sys}

	Macroscopic energy		Microscopic energy		
	E_k	E_p	E_k	E_p	E_p
Type	energy due to movement (KE)	gravity, electric fields, magnetic fields	vibrational, rotational, translational energy of particles	intermolecular bonds between the particles	chemical (E_{chem}) and nuclear bonds ($E_{nuclear}$)
System energy, E_{sys}	✓	✓	✓	✓	✓
Internal energy, U			✓	✓	✓
Thermal energy, E_{th}			✓	✓	
Changes during heating and cooling	stationary and doesn't change		increases during heating and decreases during cooling (no change in E_k during a phase change)		doesn't change

FIGURE 4 This netball has both kinetic energy from its motion and gravitational potential energy from its height above the ground.

Study tip

It is important to be able to summarise and distinguish between internal energy, thermal energy and kinetic energy. The statements provided here are a good start.

How are all these terms connected?

- Kinetic energy, E_k, is the energy associated with the motion of the particles in a system.
- Potential energy, E_p, is the energy associated with the bonding forces in a system.
- Internal energy, U, is the total microscopic kinetic energy, $E_{k(micro)}$, and microscopic potential energy, $E_{p(micro)}$, of the particles in a system. It does not include macroscopic energy.

$$U = E_{k(micro)} + E_{p(micro)}$$

- Thermal energy, E_{th}, is the total kinetic and potential energy of the moving atoms and intermolecular bonds inside an object. It does not include chemical or nuclear potential energy.

$$E_{th} = E_{k(micro)} + E_{p(micro, excluding chem and nuclear)}$$

- Thermal energy is the portion of internal energy that changes when the temperature of the system changes. Therefore, a change in thermal energy has the same value as a change in internal energy.
- Heat is the transfer of thermal energy from a hot to a cooler object; that is, from an object of high temperature to one of low temperature.

Check your learning 2.4

Check your learning 2.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Identify** whether the internal energy of a substance is considered macroscopic or microscopic energy. (1 mark)

2 **Describe** the difference between macroscopic and microscopic energy. (2 marks)

3 **Describe** the difference between thermal and internal energy. (2 marks)

4 **Describe** how heat, thermal energy and internal energy are related. (2 marks)

Lesson 2.5
Kinetic energy and temperature

Key ideas

→ The particles in a substance do not all have the same kinetic energy; they fit on a distribution and are discussed as average kinetic energy.

→ When an increase in thermal energy causes an increase in the average kinetic energy, temperature increases (without phase change).

Learning intentions and success criteria

How is kinetic energy distributed?

When you heat up a substance, you are increasing its thermal energy and thus its internal energy. We have seen that heat is the transfer of this thermal energy from a hot object, such as a hotplate or Bunsen burner flame, to a cold one, such as a beaker of water. Earlier, we used the example of hot coffee transferring some of its thermal energy to a metal spoon. We now know that the addition of thermal energy to a substance by heating can increase its temperature. The opposite is also true, where removal of thermal energy by cooling results in a decrease in temperature.

If you increase the thermal energy of a substance, the kinetic energy and hence the speed of the motion increases. Before we explore this further, it is important to understand the distribution of kinetic energy in a substance.

FIGURE 1 Perfume molecules evaporate and travel quickly as liquid droplets and then a gas.

Let's consider the motion of particles in gases. Imagine that someone in your classroom sprayed perfume in the air. Within a minute it would be smelt at the other side of the room. The gas particles actually move at something like a few hundred metres per second, and collide with each other and other gas particles about 6,000 times per second. Thus, they travel a long, long distance to get to the front of the room.

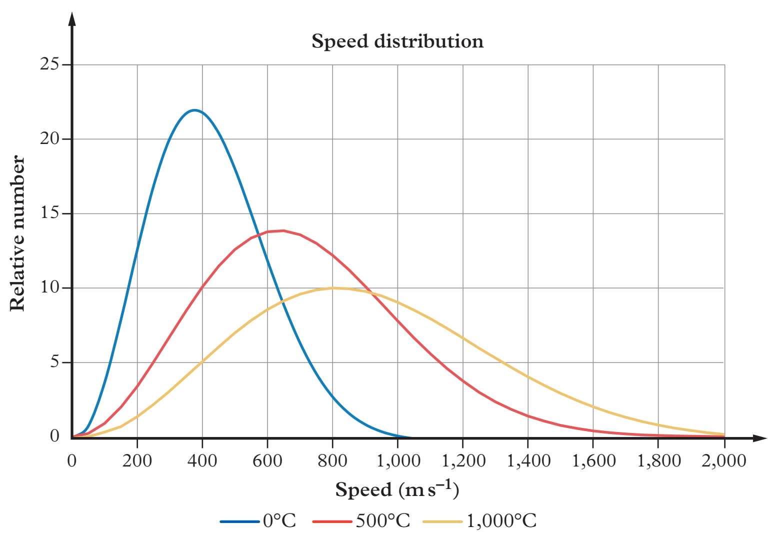


FIGURE 2 The speed of oxygen molecules at different temperatures. The most common speed is shown by the peak of each line. At 0°C (blue), the most common speed for oxygen is about 400 m s^{-1}.

It is impossible to measure the motion of all the particles within a substance because of the number of particles and the great variation in their speeds. Figure 2 indicates the variation of molecular speeds of oxygen gas, O_2, at various temperatures. The hotter the particles become, the more kinetic energy they have. The more kinetic energy they have, the faster they travel.

However, at any one moment in time, there will be some particles that are moving faster and will have more kinetic energy, and some that are moving slower and have less kinetic energy. When these particles collide, they do not lose energy but tend to swap it. If a fast and a slow particle collide, they bounce off each other and the fast one becomes slow, and the slow one becomes fast.

At a temperature of 500°C, the most common speed for oxygen molecules is 650 $m\,s^{-1}$ and at 1,000°C it is 800 $m\,s^{-1}$. Note that as temperature increases, the average increases, and the curve flattens. Physicists call this the Maxwell–Boltzmann distribution. This curve is for the gaseous phase, but is similar for liquids.

When we talk about kinetic energy of a substance or system, it is simpler for us to refer to its average kinetic energy.

Challenge

Air on your skin

Imagine a 1 cm square on your skin. Every second there are 10^{22} "blows" from air molecules. Can you detect them? If you can't, state some reasons why you can't feel these blows. If the blows stopped, predict what you would feel. (4 marks)

How does heating affect kinetic energy and temperature?

Heating causes the average kinetic energy of the particles to increase. For instance, if you heat 100 mL and 200 mL of water in beakers on a hotplate, the particles get faster and faster and their kinetic energy increases. This process involves the absorption of thermal energy. The larger volume needs to absorb more heat for it to reach 100°C than is needed for the smaller volume, so the total kinetic energy is greater for the 200 mL of water. But when the water in each beaker boils, the average kinetic energies of their molecules are the same.

temperature
the average kinetic energy of a system of particles, typically expressed according to a comparative scale such as the Celsius temperature scale; what a thermometer measures

We can now say that **temperature** is a measure of the average kinetic energy of the particles in a system. In other words, "changes in temperature" are due to the addition or removal of thermal energy from a system and will change the average kinetic energy of particles in the system. As more thermal energy is absorbed, kinetic energy increases, and temperature increases; as thermal energy is removed, kinetic energy decreases, and temperature decreases.

Check your learning 2.5

Check your learning 2.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** "temperature" in terms of kinetic energy. (1 mark)

2 **Describe** the relationship between temperature and kinetic energy. (1 mark)

Knowledge utilisation

3 **Analyse** the graph in Figure 2 to **evaluate** the statement: "at higher temperatures, the spread of speeds of oxygen molecule is also greater." (2 marks)

4 **Analyse** the graph in Figure 2 to **evaluate** the statement: "doubling the Celsius temperature of oxygen gas from 500°C to 1,000°C doubles the most common speed of the oxygen molecules." (2 marks)

5 **Evaluate** the following statement: "slow molecules of a gas stay slow unless their temperature is changed". (3 marks)

6 **Propose** why nitrogen does not settle near the ceiling and oxygen near the floor given that air is made up mostly of nitrogen and oxygen, and that nitrogen is lighter than oxygen. (1 mark)

Lesson 2.6
Measuring temperature

Key ideas

→ The thermometer is a good example of thermal expansion as explained by the kinetic particle model of matter.

→ The Fahrenheit, Celsius and Kelvin scales are used to measure temperature.

How do we measure temperature?

Learning intentions and success criteria

Remember at the start of this module that we defined temperature as "what a thermometer measures". That was called an operational definition, as it told us how to measure the physical quantity called temperature. We promised a theoretical definition and in the previous lesson, you saw it defined as a measure of the average kinetic energy of the particles within a system. So how do we measure temperature and what units are used? Why does Australia use Celsius for temperature, but the United States uses Fahrenheit?

Measuring temperature requires the use of some property of a substance that changes proportionally with increase in temperature. Most temperature-measuring instruments (**thermometers**) use the property of expansion and contraction.

thermometer
a device used to measure temperature

Heating causes substances to expand (become less dense). You will have seen hot air balloons; you might have even been in one. A flame is used to heat the gas. As the temperature increases, the average kinetic energy of the gas increases and so the average speed of gas molecules inside the balloon increases. Gas thus expands and pours out from under the balloon, so the balloon gets lighter and rises.

This process, called **thermal expansion**, also occurs in liquids and is what thermometers rely on to function. In schools, the alcohol-in-glass thermometer is most common, whereas the mercury-in-glass thermometer is quite common in industry and research where a bigger temperature range is needed.

thermal expansion
the process by which heat causes an increase in the kinetic energy of particles, leading them to spread apart and occupy a larger volume

Thermometers are calibrated to indicate the temperature. As temperature increases, the alcohol or mercury expands up a fine tube in the glass thermometer. The markings on the thermometer depend on the scale used (Figure 1).

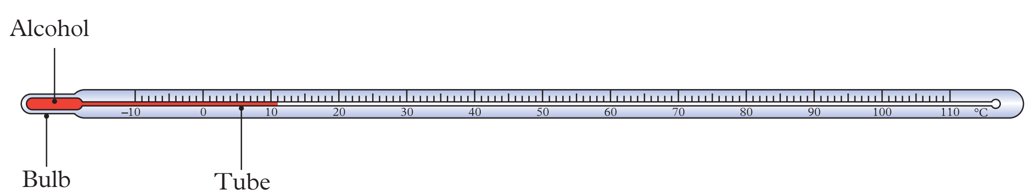


FIGURE 1 A liquid-in-glass thermometer. This one has alcohol with a red dye, which expands more rapidly than the glass containing it. When the temperature of the thermometer increases, the liquid from the bulb is forced into the narrow tube, producing a large change in the length of the column for a small change in temperature.

Real-world physics

Climate change and the kinetic particle model of matter

Meteorologists use the kinetic particle model of matter to model the behaviour of gases in Earth's atmosphere. It helps them make crucial predictions for weather forecasting and modelling of human-induced climate change.

Apply your understanding

1 **Explain** what happens to the average kinetic energy of gas molecules as global temperatures rise. (1 mark)
2 Physicists in the USA have concluded that the number of home runs in baseball has increased because of global warming. They say the thinning air allows the ball to travel further. **Explain** why the air is thinner, in terms of the kinetic particle model of matter. (2 marks)
3 **Reflect on** one other unforeseen consequence of global warming, with respect to its impact on the behaviour of gases. (1 mark)

FIGURE 2 Meteorologists release a weather balloon to collect atmospheric data.

What temperature scales can we use?

Throughout history, scientists have made up their own scales to measure temperature. For example, Sir Isaac Newton made up a temperature scale in which the freezing point of water was 0 degrees and normal body temperature was 12 degrees.

The Fahrenheit scale

Fahrenheit scale a temperature scale that takes the temperature at which a salt–water mixture freezes into ice as 0°F, and Daniel Fahrenheit's body temperature as 100°F

A German physicist, Daniel Fahrenheit (1686–1736), developed a liquid-in-glass thermometer and a temperature scale (now known as the **Fahrenheit scale**) that took the freezing point of an ice and salt mixture to be 0°F and his body temperature as 100°F. He marked those levels on his thermometer and divided the scale into 100 parts, one for each degree. However, Fahrenheit's metabolism was higher than that of most people, so 100°F for him resulted in 98.6°F as the body temperature for the average person. On the Fahrenheit scale, the freezing point for water is 32°F and the boiling point is 212°F. This is an important point of reference later for when we compare to the other temperature scales.

Although the Fahrenheit scale is no longer used in Australia, it is still used in several other countries such as the United States, Liberia, Bahamas, Belize, Palau and the Cayman Islands, but only for day-to-day temperatures – not for science. Scientists in all countries use Celsius for their research as it has become the worldwide standard.

The Celsius scale

Celsius scale a temperature scale that takes the temperature at which pure water freezes as 0°C and its boiling point as 100°C

An easier decimal temperature scale was invented by the Swedish astronomer Anders Celsius (1701–1744). On the **Celsius scale** (also called the centigrade scale), the freezing point of pure water is 0°C and its boiling point is 100°C. Interestingly, Celsius originally took the freezing point to be 100°C and boiling point to be 0°C, but this was changed in the first year. The Celsius scale is the main scale used in measuring body temperature and in all scientific work.

The Kelvin scale

The Fahrenheit and Celsius scales are relative scales – that is, zero degrees on either scale does not mean that this is the lowest temperature obtainable. Since temperature is a measure of the average kinetic energy of the particles, 0°C does not mean that all particle motion has stopped. So, at what temperature does all motion stop?

The graph in Figure 3 shows the relationship between kinetic energy and temperature in degrees Celsius. When we extrapolate this graph to –273°C, the kinetic energy of the gas particles becomes zero (i.e. all particle motion stops). This point is called absolute zero on the **Kelvin scale** of temperature. The Kelvin scale is used by scientists using data from temperature experiments, as it doesn't have negative values, so it makes relationships simpler to express.

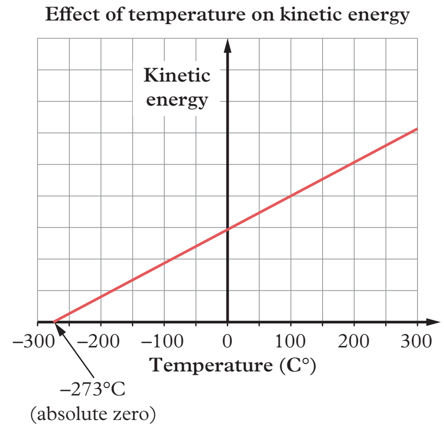


FIGURE 3 The relationship between temperature and kinetic energy, and the establishment of absolute zero. The line cuts the x-axis at –273°C. This point is called "absolute zero" or zero kelvin (0 K). Pressure can also be used on the y-axis for a similar result.

At 0 K, the kinetic energy of the particles should be zero. However, in terms of quantum mechanics (which is beyond what we need to know here), there is said to be some residual energy in the particles. This is called "zero-point energy". In QCE Physics, we will say that, at 0 K, the system is in the lowest energy state rather than the zero energy state.

One degree on the Kelvin scale is equal in magnitude to one degree on the Celsius scale. Therefore, changing Celsius temperature (T_C) to temperature in kelvin (T_K) simply requires the addition of 273 to the Celsius value.

$$T_K = T_C + 273$$

Kelvin scale
a temperature scale that takes absolute zero as 0 K and the melting point of ice as 273 K

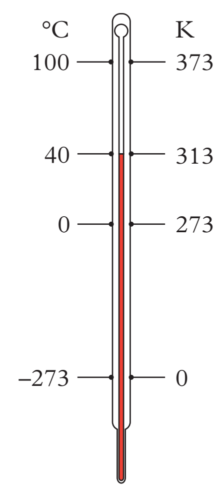


FIGURE 4 A comparison of temperature in degrees Celsius and kelvin

Worked example 2.6A

Converting between temperature scales

Use the correct formula to convert

a 50°C to kelvin (1 mark)

b 486 K to °C. (1 mark)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Use" means to apply knowledge or rules to put theory into practice. We need to use a formula. Each part is worth 1 mark, so we must correctly use a formula and complete a calculation for each.
Step 2: Select the correct formula.	$T_K = T_C + 273$
Step 3: Substitute the known values into the formula and find the unknown.	**a** $T_K = 50 + 273$ $= 323$ **b** $486 = T_C + 273$ $T_C = 486 - 273$ $= 213$
Step 4: Finalise your answer and make sure you have included the correct units.	**a** 323 K (1 mark) **b** 213°C (1 mark)

Your turn

Use the correct formula to convert

a –15°C to K (1 mark)

b 25°C to K (1 mark)

c 100 K to °C. (1 mark)

Study tip

The Celsius and kelvin temperatures differ by 273.15, but we use a rounded value of 273 when converting. Just add or subtract 273.

Table 1 shows you how to correctly represent each temperature.

TABLE 1 How to refer to each temperature scale correctly

Founder	Daniel Gabriel **Fahrenheit**	Anders **Celsius**	William Thomson (Lord **Kelvin**)
Name of scale	Fahrenheit scale	Celsius scale	Kelvin scale
Unit symbol	°F (e.g. 77°F)	°C (e.g. 25°C)	K (e.g. 298 K)
Unit description	77 degrees Fahrenheit	25 degrees Celsius	298 kelvin (note the lowercase "k")

Real-world physics

The development of temperature scales

For a large part of human history, there has been no formal distinction between the concepts of heat and temperature. People spoke of the degrees of hot or cold, but they were not measured – except, perhaps, in a very rough way such as when a physician put their hand on a patient's forehead and diagnosed "fever heat".

Over the past 500 years, numerous temperature scales have been developed. Some of these are outlined in the timeline shown. The various scales were developed to suit different purposes. Isaac Newton, for instance, was the Master of the Royal Mint in England (1699) and oversaw the production of gold coins. He knew that the gold shrank as it cooled, so coins stamped out at the start of a run had less gold than those at the end of the run. He instructed that coins could only be minted at a certain temperature, or, as he called it in Latin, "gradus caloris" ("the same degree of heat") and developed a linseed oil thermometer for this purpose.

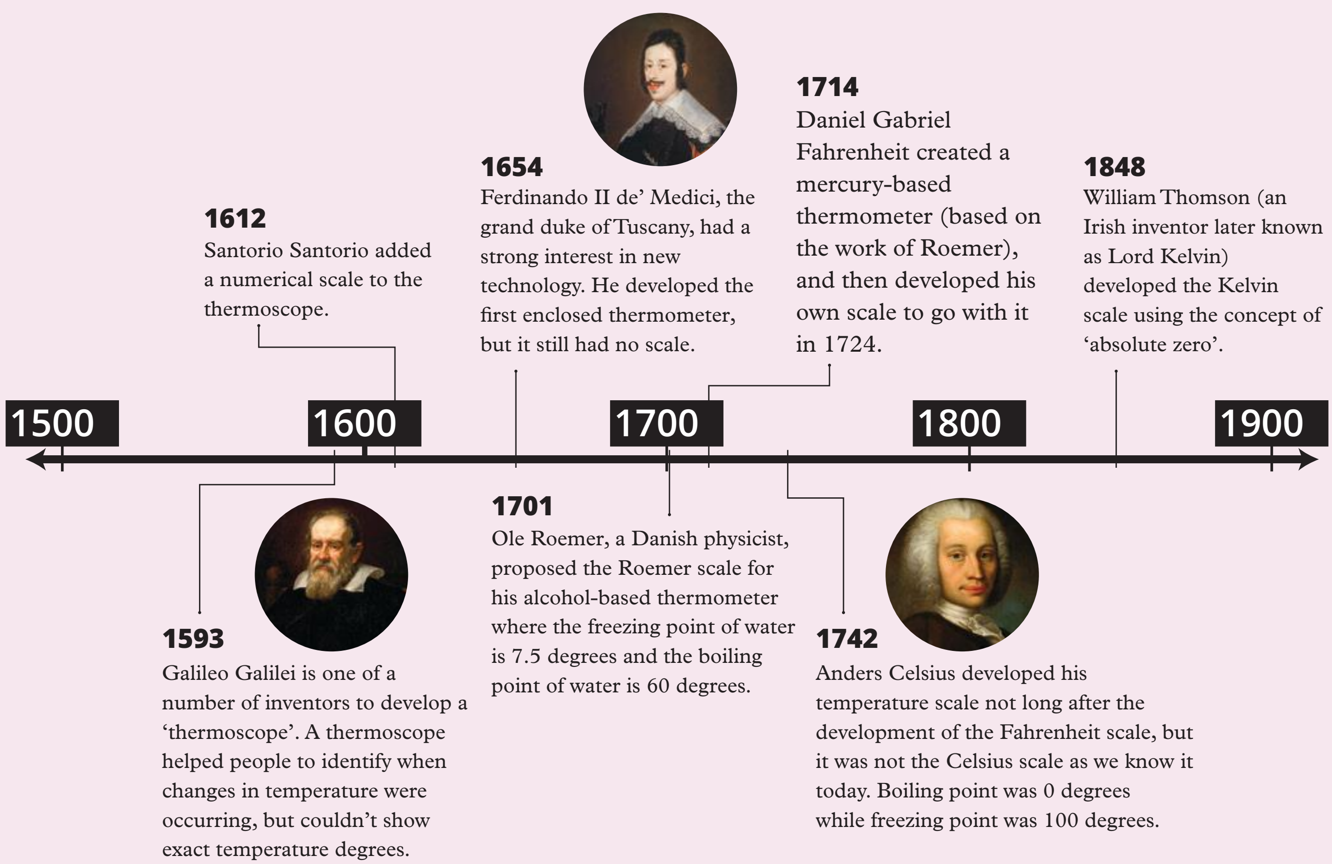


FIGURE 5 Timeline of the development of different temperature scales

Apply your understanding

1 **Describe** the problem with temperature measurement before scales were invented. (1 mark)
2 **Evaluate** the following statement: "The three common temperature scales – Fahrenheit, Celsius and Kelvin – were developed in the order stated. Each was an improvement on the previous scale." (5 marks)
3 The United States is one of the few countries in the world to still use the Fahrenheit scale. **Discuss** the problems associated with using the Fahrenheit scale. (3 marks)

Check your learning 2.6

Check your learning 2.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Identify** the lowest possible temperature on the Kelvin scale. **Explain** why it is called "absolute zero". (2 marks)
2 **Explain** why the liquid in a glass thermometer rises as it heats up. (3 marks)
3 **Use** the correct formula to **convert** the following temperatures to K.
 a 20°C (1 mark)
 b –150°C (1 mark)
 c 520°C (1 mark)
 d –72°C (1 mark)
 e –263°C (1 mark)
4 **Use** the correct formula to convert the following temperatures to °C.
 a 50 K (1 mark)
 b 278 K (1 mark)
 c 1000 K (1 mark)
 d 273 K (1 mark)

Analytical processes

5 **Deduce** the scale an overseas friend is using if they say their child has a temperature of 99 degrees. (1 mark)
6 **Determine** the change in temperature when a thermometer reading goes from 25.0 ± 0.5°C to 42.5 ± 0.5°C (3 s.f.) including the percentage uncertainty for the result (1 s.f.). (2 marks)
7 **Determine** which thermometer reading has the least uncertainty: an alcohol-in-glass thermometer with a resolution of 1°C (scale division), or a digital thermometer that can be read to one decimal place. (2 marks)
8 **Discuss** why the percentage uncertainty for a thermometer reading must be done using kelvin temperatures and not Celsius temperatures. Note: Go to Lesson 1.7 in your Physics toolkit. (3 marks)

Practical

Lesson 2.7
Precision and accuracy of thermometers

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Lesson 2.8
Heat transfer

Key ideas

→ Heat can be transferred by conduction, convection, and radiation.

Learning intentions and success criteria

How is heat transferred?

thermal energy transfer the process of transferring thermal energy from a hot object to a cooler one; also known as heat transfer

Whenever there is a temperature difference, **thermal energy transfer** (or heat transfer) occurs. We know this is called heating or cooling. Heating may occur rapidly, such as through a frypan, or slowly, such as through the walls of a foam or cardboard coffee cup. We can control heat transfer by choosing materials such as thick clothing for winter, by controlling air movement such as through the use of fans, or by choice of colour such as selecting a white car to reflect the Sun's rays. Because so many processes involve heat transfer, it is hard to imagine a situation in which no heating or cooling occurs. However, every transfer takes place by just three processes: conduction, convection and radiation.

What is conduction?

conduction a process in which heat is directly transferred or transmitted through a substance due to a temperature difference between neighbouring regions, without movement of any matter

Conduction (from the Latin word "conducere" meaning "to lead together") is heat transfer through stationary matter by physical contact. Fast-moving particles bump into slow-moving particles and transfer some of their energy in the process. Thus, the direction of transfer is from more energetic to less energetic particles. It can occur within a substance (such as along a metal rod), or from one substance to another (such as from hot coffee to a spoon).

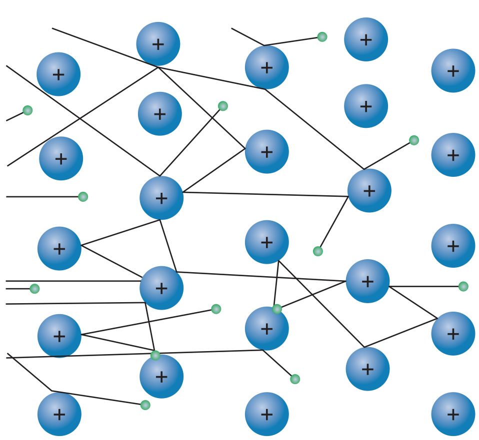


FIGURE 1 Metals have a lot of free-moving electrons that move faster when the metal is heated. The electrons give their energy to neighbouring metal atoms, so they pass the energy on.

Conduction within a substance

Conduction within a substance involves the transfer of thermal energy through a medium by the vibrating particles of the medium, without the particles actually moving from one place to another. The kinetic particle model helps us understand how this works. Particles in a solid are vibrating and are bonded to their neighbours. When a solid is heated, the thermal energy in transferred to the particles and they vibrate faster.

If the solid is a metal, electrons in the lattice structure are freely moving and can transport energy quickly to neighbouring metal atoms. This is heat transfer by mobile electrons.

In non-metals, the atoms are tightly fixed and there are no mobile electrons. For example, in diamond there are strong bonds between carbon atoms, and the electrons are involved in the formation of these bonds. This means that conduction of heat in a non-metal relies on collisions between neighbouring particles. This is a slow process because it relies on the movement of atoms, which are so much heavier than electrons. Hence, diamond and most non-metals are poor conductors of heat.

Conduction from one substance to another

Let's revisit the hot drink example again. In this case, we will use a cup of tea instead of coffee, but the same core principle applies: the heat transfer occurs by conduction from one substance to another.

The particles in the hot drink are moving faster than those of the cold metal teaspoon. When the teaspoon is placed in the drink, the fast-moving particles collide with the particles of the spoon. In this process they transfer some of their thermal energy to those metal particles in the spoon. These particles then vibrate and cause their neighbours to vibrate. Since the teaspoon is metal, the electrons also speed up and transfer this energy to the rest of the metal. This continues until all of the particles in the spoon and liquid have the same thermal energy – that is, they reach thermal equilibrium.

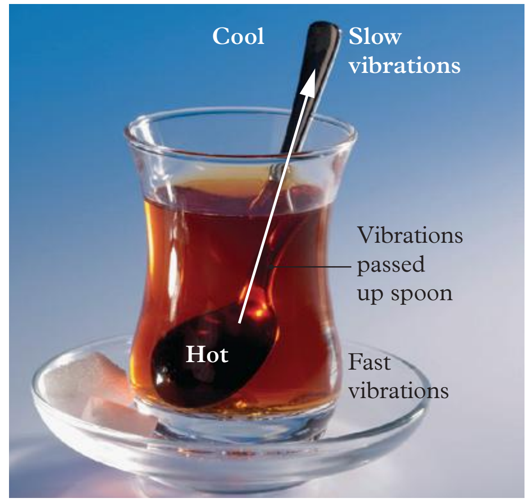


FIGURE 2 Transfer of thermal energy from a hot drink to a metal spoon by conduction

Real-world physics

Watching icebergs melt

Scientists have been researching the factors affecting iceberg melting for at least 60 years. The melting and breaking up of polar ice has become an even more important issue since the effects of climate change were recognised.

The most important factor affecting iceberg melting is the temperature of the surrounding fluid. This fluid can be either the air around the exposed part of the iceberg, or the water around it. But other factors include the volume and shape of the icebergs. The bigger the surface area (and in practice, this also means volume), the faster the rate of melting.

FIGURE 3 It is hard to tell the size of the Antarctic icebergs in this photo, but they are actually the size of office blocks.

When an iceberg melts, it often cracks into two pieces. Depending on the size and shape of these new pieces, it may "roll over" (flip). In Figure 3, you can see icebergs of different sizes – these will melt at different rates.

Apply your understanding

1 **Describe** the change in surface area of an iceberg when it breaks into two pieces. (2 marks)
2 **Explain**, in terms of heat transfer processes, why there is a difference in the rate of melting when an iceberg breaks into two pieces. (3 marks)
3 **Propose** why a "rollover" changes the melting rate of an iceberg if the surface area does not change. (3 marks)

convection
a transfer of heat caused by the movement within a fluid of the hotter and less dense material, which rises, and the colder, more dense material, which sinks under the influence of gravity

convection current
the pathway in which fluid (liquid or gas) particles flow as they heat up (become less dense) and cool down (become more dense)

Study tip

Remember the relationship between kinetic energy and volume (and density). As kinetic energy increases, volume increases and density decreases.

What is convection?

Convection is another method of heat transfer. The word convection comes from the Latin "convehere", meaning "to carry together". Convection is similar to conduction, but in this case the particles of the materials themselves move and carry thermal energy with them. This process is a bulk movement driven by the tendency of hotter and therefore less dense material to rise, and colder, more dense material to sink under the influence of gravity. As solid particles do not move, convection is confined to bulk fluids (i.e. liquids and gases).

For example, when a saucepan of water is placed on a stove, it is heated from the base of the saucepan. The particles in the water that are closest to the stove elements absorb thermal energy and vibrate faster. The fluid becomes less dense, and the particles rise through the saucepan. The cooler water is less dense, so the particles move downwards to replace the hotter particles that rise. The rising hot particles cool as they move higher and therefore a recirculation occurs, as shown in Figure 4A. This is called a **convection current**.

If heat is constantly being applied by the stove, the particles keep getting hotter, and the current helps to warm up all the particles in the saucepan evenly. This only occurs when there are bulk fluids.

A similar process occurs when a pot-belly stove is used in the centre of a room and when onshore breezes are warmed by the land.

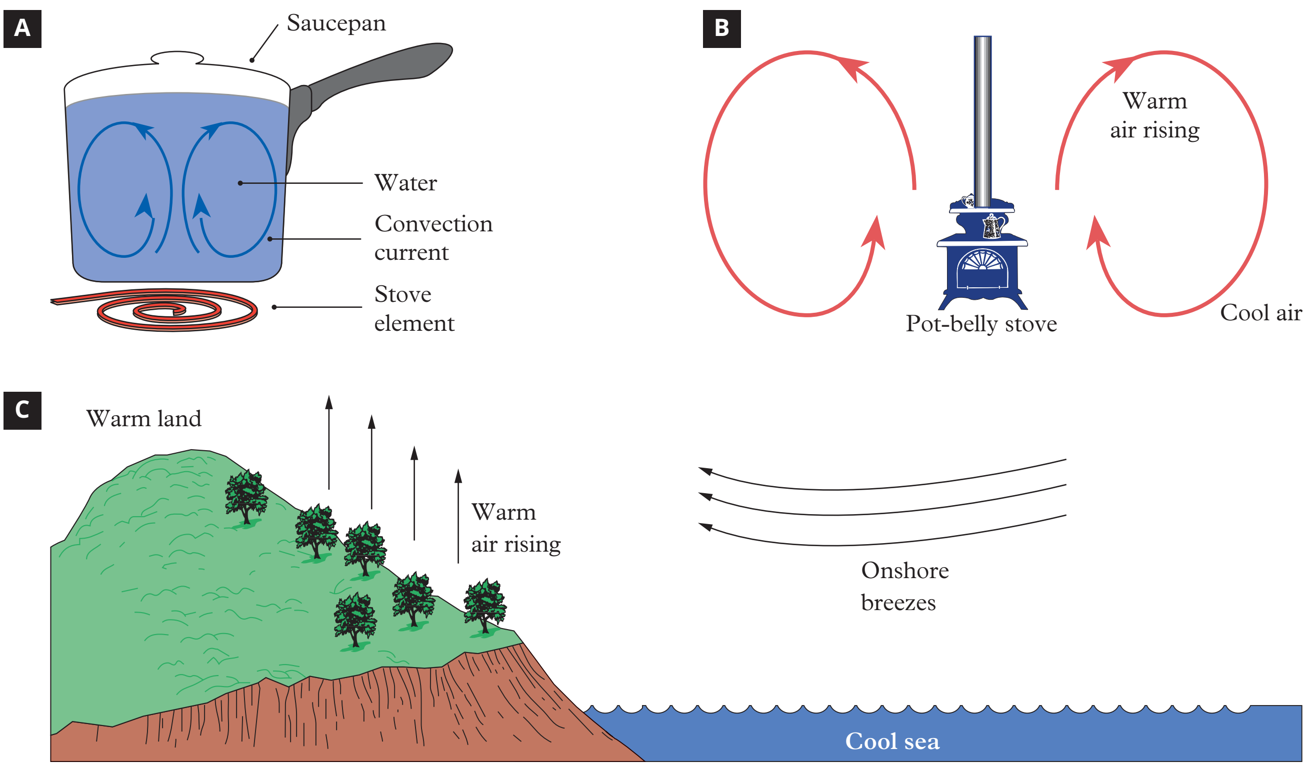


FIGURE 4 (A) Convection currents in a saucepan of water; (B) a pot-belly stove warms a room by setting up convection currents; (C) convection currents arise in the evening of a warm day, because of the difference in temperature between the land and the sea, creating onshore breezes.

Free convection and forced convection

There are two types of convection. **Free convection** (or natural convection) relies on the differences in density due to temperature differences, thus resulting in natural movement of particles. This is assisted by gravity. **Forced convection** involves artificially inducing movement (e.g. by using a fan, wind or a pump).

FIGURE 5 A photo taken from NASA's International Space Station of the sunset over Earth

free convection
the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, more dense material, to sink under the influence of gravity; this consequently results in transfer of heat

forced convection
the movement caused within a fluid generated by an external source such as a pump, fan or suction device

radiation
the transfer of energy in the form of electromagnetic waves or moving subatomic particles

electromagnetic radiation
radiant energy consisting of electromagnetic waves, propagated at the speed of light in a vacuum

thermal radiation
the transfer of thermal energy in the form of electromagnetic waves in the infrared region

What is radiation?

In conduction and convection, the vibration or movement of particles results in heat energy transfer. But how does heat energy move between places where no particles exist? How does heat energy travel between the Sun and Earth through the vacuum of space?

Where no particles exist, heat is transferred by **radiation**. The word "radiation" is from the Latin "radiare" meaning "to emit beams". Radiation involves the movement of heat energy by waves called electromagnetic waves. These waves travel through space at a speed of $3 \times 10^8\,\mathrm{m\,s^{-1}}$. We call this **electromagnetic radiation**.

In thermal physics, we are interested in **thermal** (infrared) **radiation**, which is the electromagnetic radiation emitted by bodies because of their temperature. It differs from visible light, X-rays, radio waves, and microwaves as they are not related to temperature. Objects that are hot emit more infrared radiation than those that are cool. This radiation cannot be seen with the naked eye, so we need the help of technology to see it. You may have seen "heat maps" of suburban areas. The dark roofs and black bitumen roads show up strongly, whereas light-coloured roofs, grass and water show little emission. If you have had your temperature taken with a non-contact heat gun, it is just measuring the emission of infrared radiation from your forehead. The same is true of "night-vision" goggles used by police, the armed forces or night-time photographers.

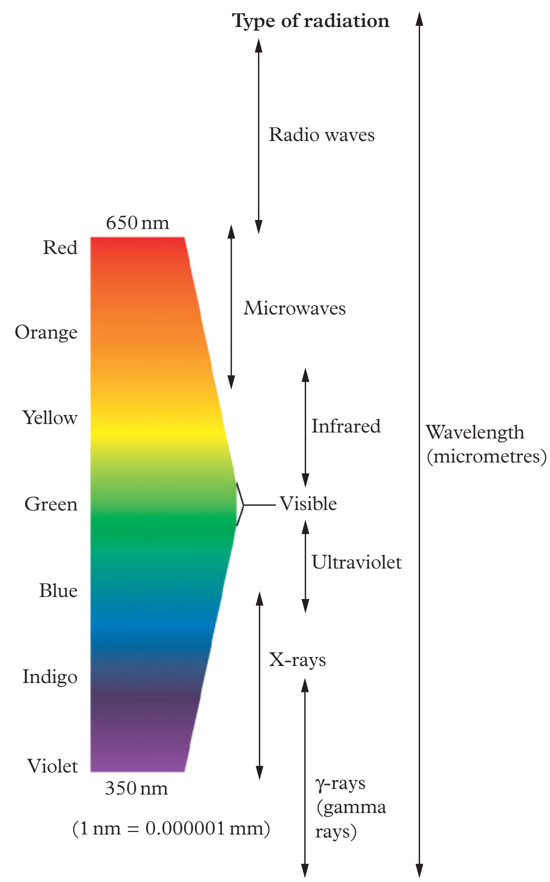


FIGURE 6 Electromagnetic spectrum (note the location of infrared radiation)

Worked example 2.8A

Explaining how heat is transferred in an example

An infrared heater is used to heat some water from room temperature. **Explain** the process by which the water temperature changes. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Explain" means to make an idea or situation clear by describing it in more detail or revealing certain facts. We need to provide more detail about how the water temperature is changing. The question is worth 3 marks, so 3 pieces of information are required.
Step 2: Identify the type of heat transfer.	Radiation, as it is related to infrared energy (1 mark)
Step 3: Outline the effect on the kinetic energy of the particles.	Absorbed by the water particles; kinetic energy increases (1 mark)
Step 4: State the effect on the temperature.	It increases. (1 mark)
Step 5: Finalise your answer.	The infrared heat is transferred to the water through radiation. This energy is then absorbed by the water particles, increasing their kinetic energy. This is shown by an increase in temperature.

Your turn

When a bottle of tap-water is placed in the refrigerator, it cools down. **Explain** the process by which the water temperature changes. (3 marks)

How do convection, conduction and radiation work together?

In a fireplace, heat transfer occurs by all three methods: conduction, convection and radiation. Radiation is responsible for most of the heat transferred into the room. Heat transfer also occurs through conduction into the room, but at a much slower rate. Heat transfer by convection also occurs when cold air enters the room around windows and by the great waste of hot air leaving the room by rising up the chimney. These three processes are summarised in Table 1.

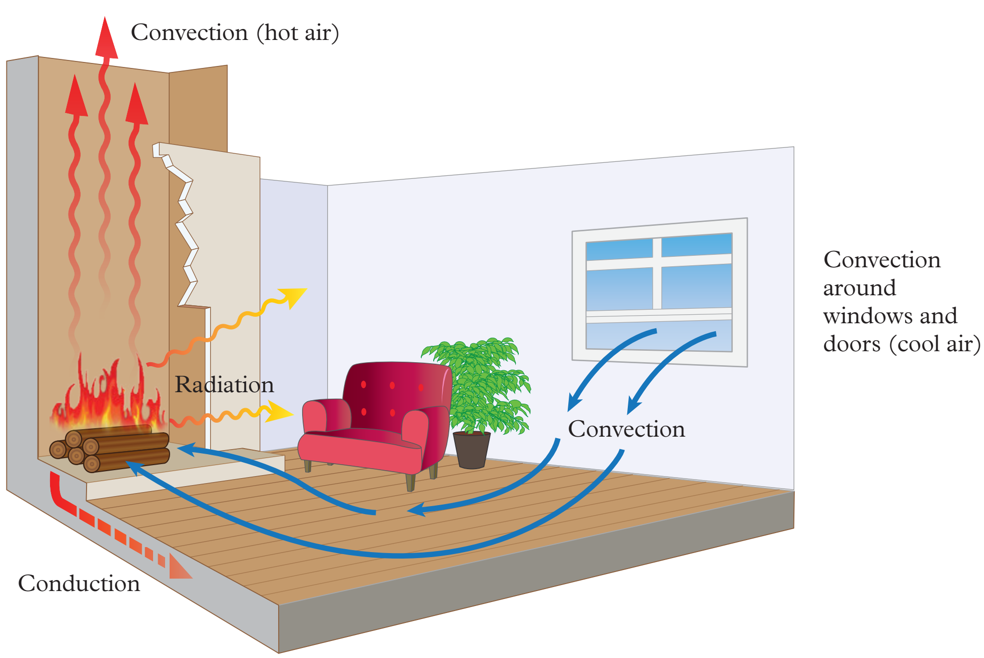


FIGURE 7 Thermal energy transfer in a fireplace

TABLE 1 Summary of conduction, convection and radiation as shown in Figure 7

	Conduction	Convection	Radiation
Heat energy is transferred by …	collisions between vibrating particles	the movement of particles	the absorption of infrared radiation
Requires a medium?	yes	yes	no
Particles travel with heat flow?	no	yes	no
As shown in Figure 7	The floor and walls warm up over a long time, but remain warm for a long time too.	Warm air rises and circulates in the room. Most will be lost up the chimney.	Directly out from the fireplace. You have to be sitting in a direct line to feel it.

Check your learning 2.8

Check your learning 2.8: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** how heat transfer occurs through conduction. (3 marks)

2 **Describe** the advantage of placing the heating element at the bottom of an electric kettle. (1 mark)

3 **Identify** the property that distinguishes radiation from conduction and convection as a means of heat transfer. (2 marks)

4 **Explain** why heat energy from the Sun cannot be transferred to Earth by conduction or convection. (1 mark)

5 Communication satellites in the vacuum of space heat up when exposed to the Sun's rays. **Explain** the process by which their temperatures rise when in a vacuum. (3 marks)

Analytical processes

6 **Contrast** the conduction of heat within and between substances. (2 marks)

7 **Compare** free convection and forced convection. (3 marks)

8 **Differentiate** between infrared radiation and visible light. (2 marks)

Knowledge utilisation

9 When one end of a glass rod is placed in the flame of a Bunsen burner, the other end becomes hot.

a **Infer** how the heat energy travels from one end to the other. (3 marks)

b **Propose** one other laboratory material that would transfer heat faster. **Justify** your decision. (2 marks)

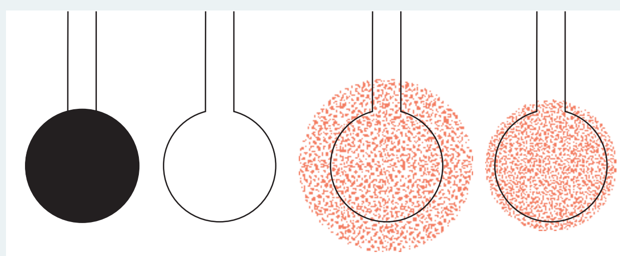
10 **Evaluate** whether thermal energy travels faster by convection or by radiation. (3 marks)

11 **Discuss** why sleeping under the cover of large trees on cold, clear nights helps to keep horses warm. (2 marks)

12 Copper makes a good base for saucepans. **Investigate** why the sides are not also made of copper, in terms of conduction. (3 marks)

13 A student makes the following claim: "You feel colder when you are wearing wet clothes." **Evaluate** this statement, with reference to the relevant heat transfer process(es). (3 marks)

14 Four thermometers are placed in sunlight for 10 minutes. **Predict** the order from highest reading to lowest after this time. **Explain** your thinking. (3 marks)



15 A beaker of tap-water is placed on a hotplate, which is then turned on. The water on the surface begins to feel warm. **Design** an experiment to test if the heat transfer to the surface is by conduction or convection. (3 marks)

Lesson 2.9
Specific heat capacity

Key ideas

→ Specific heat capacity is the amount of energy required to raise the temperature of a specific mass of a substance by one degree.
→ Substances with stronger intermolecular forces can absorb more thermal energy, and thus have a higher specific heat capacity.

Learning intentions and success criteria

What is specific heat capacity?

Have you ever eaten an apple pie and noticed that the inside is very hot and burns your mouth, but the crust does not? Over 200 years ago, physicist Benjamin Thompson complained about exactly the same thing in 1899 with his hot apple pie. The filling burnt his mouth, but the crust was fine to eat. It got him thinking about the way different substances behave when they are heated up.

FIGURE 1 Why does the apple pie filling burn your mouth but the crust does not?

As you add thermal energy to a substance, the particles and the bonds between them absorb more energy. Their average kinetic energy increases and the intermolecular forces between them weaken. When the bonds between particles are strong, it will take more thermal energy to free the particles. This means that more energy is required to achieve the same increase in kinetic energy and, thus, the same increase in temperature.

Because of the great variation in molecular structure and bonds that exist between atoms in different substances, the same amount of energy put into different substances does not result in the same temperature rises. For example, 4,180 J of energy is required to increase the temperature of 1 kg of water by 1°C, but only 2,200 J is required to do the same to paraffin oil. This property is called the **specific heat capacity**, *c*, of the substance. Specific heat capacity is the amount of heat required to raise the temperature of 1 kg of a substance by 1°C.

specific heat capacity
the thermal energy required to raise the temperature of 1 kg of a substance by 1°C or 1 K (symbol: *c*; unit: joules per kilogram per degree; unit symbol: $J\,kg^{-1}\,°C^{-1}$ or $J\,kg^{-1}\,K^{-1}$)

We could also say "by 1 K", as a change of 1°C is equivalent to a change of 1 K. The term "specific" means it is expressed in relation to a given amount of substance – in this case, 1 kg. It is a constant of proportionality that relates the temperature change to the amount of thermal energy transferred for a given mass of a substance.

Note that this only applies if there is no melting or vaporisation (i.e. there is no phase change) involved. Heating water from 98°C to 99°C is very different from heating it from 99.5°C to 100.5°C, as a phase change will then have occurred. You will learn more about this in Module 3. The specific heat capacity of some common substances is given in Table 1.

TABLE 1 Specific heat capacity of some common substances

Substance	Specific heat capacity, c (J kg^{-1} K^{-1})
Gold	129
Lead	130
Mercury	140
Brass	380
Copper	390
Iron and steel	460
Glass	664
Sodium chloride	880
Sand	880
Aluminium	900
Wood	1,700
Water (gas) – steam	2,100
Water (solid) – ice*	2,050
Acetone	2,150
Paraffin	2,200
Honey	2,370
Alcohol	2,450
Methylated spirits	2,500
Water (liquid)	4,180

*Note: the specific heat capacity of ice varies with temperature. At 0°C it is 2,050 J kg^{-1} K^{-1}, and at −100°C it is just 1,389 J kg^{-1} K^{-1}.

Challenge

Boiling water in a paper cup

Paper catches fire at about 250°C and a campfire has an average temperature of about 500°C. **Use** your understanding of specific heat capacity and heat transfer to **explain** how you can boil water in a paper cup over the flames. (4 marks)

Why do ice and liquid water have different specific heat capacities?

It takes, on average, 2050 J to raise the temperature of 1 kg of ice by 1°C, whereas it takes 4180 J to warm the same amount of liquid water by the same amount (1°C). As it is a solid, the particles in ice are only able to vibrate. When they are heated, the kinetic energy (i.e. the vibrations) increases. However, the particles in liquid water move via vibrational, rotational and translational motion. Because liquid water has more freedom of movement, it is able to absorb more thermal energy than ice does. This allows ice to increase in temperature faster than water for the same amount of added energy.

How do we use the specific heat capacity formula?

We have seen from our experiments how temperature change, ΔT, depends on several factors. When we heated different masses of water on a hotplate, the temperature change depended on the amount of heat, Q, added – double the heat and you double the temperature change ($\Delta T \propto Q$). We also saw that double the mass of water required twice as much heat for the same temperature change ($Q \propto m$). In the experiment with water and oil, we found that the amount of heat depended on the nature of the substance, as quantified by its specific heat capacity, c ($Q \propto c$). When we put these three factors together, we get the equation:

$$Q = mc\Delta T$$

where Q is the change in thermal energy (in J), m is the mass of the object (in kg), c is the specific heat capacity (in J kg^{-1} K^{-1}), and ΔT is the change in temperature. You must express ΔT as $T_{final} - T_{initial}$. We use Q as the symbol for "quantity" of thermal energy.

Study tip

If ΔT is negative, thermal energy has been transferred out of an object and it has cooled. If ΔT is positive, thermal energy has been transferred into an object and it has been heated up.

Worked example 2.9A

Calculating energy required to heat different metals

Calculate the amount of thermal energy required to heat the following objects from 30°C to 120°C. Note: the specific heat capacity values can be found in Table 1.

a 2.0 kg steel barbeque plate (2 marks)

b \$2 (brass) coin of mass 6.6 g (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the specific heat capacity formula. Each part is worth 2 marks, so we must correctly apply the formula and complete a calculation for each.
Step 2: Select the correct formula.	$Q = mc\Delta T$
Step 3: Substitute the known values into the formula and find the unknown.	**a** $m = 2.0\,\text{kg}$ $c(\text{steel}) = 460\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$ $\Delta T = 120 - 30 = 90°\text{C}$ $Q = 2.0 \times 460 \times 90$ $= 82{,}800\,\text{J}$ (1 mark) **b** $m = \frac{6.6\,\text{g}}{100} = 0.0066\,\text{kg}$ $c(\text{brass}) = 380\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$ $\Delta T = 120 - 30 = 90°\text{C}$ $Q = 0.0066 \times 460 \times 90$ $= 226\,\text{J}$ (1 mark)
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	**a** 83,000 J (2 s.f.) (1 mark) **b** 230 J (2 s.f.) (1 mark)

Your turn

Calculate the amount of thermal energy required to bring a 750 g aluminium saucepan at 20°C to the boiling point of water. Express your answer to 2 s.f. (2 marks)

Study tip

In chemistry, specific heat capacity is typically expressed as joules per mass in grams. For example, the specific heat capacity of water may be shown as 4,180 J kg^{-1} K^{-1} in your Physics formula book, but as 4.18 J g^{-1} K^{-1} in your Chemistry formula book. Be extra careful of units if you are taking both subjects in QCE.

Challenge

Which has the greater thermal energy: a cup of hot coffee or a swimming pool?

A backyard pool typically contains 40,000 L (1 L = 1 kg) of water at 30°C; a cup of coffee is 200 mL (1 mL = 1 g) at approximately 60°C. The coffee has a higher temperature but a smaller volume, so which has the higher total thermal energy? We rarely work out the total thermal energy of a substance because it is the "change" in thermal energy that is important.

At 0°C, the total thermal energy of water is 9×10^5 J per kg. So, you can work out the total for a pool and for coffee at 0°C. You can then calculate how much extra energy is required to bring them to their final temperature. **Determine** which has the greater thermal energy: water or coffee. (5 marks)

Check your learning 2.9

Check your learning 2.9: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the concept of specific heat capacity, with reference to the three phases of water. (3 marks)

2 **Calculate** the thermal energy, Q, absorbed when the temperature of 1.5 kg of paraffin is raised from 15°C to 50°C. (2 marks)

Analytical processes

3 In an experiment, students placed equal masses of water and paraffin oil in separate beakers on a hotplate. After 2 minutes, the water temperature was measured as 60°C. **Determine** whether the oil would be at a higher or lower temperature at this time. (2 marks)

4 **Determine** how much thermal energy could be absorbed by a 3.0 kg block of ice at –10°C before it reaches its melting point. (2 marks)

5 A liquid is heated in a beaker. It takes 7500 J of thermal energy to increase the temperature of 500 g of the liquid by 6.0°C. **Infer** what the liquid could be. (3 marks)

6 The following table shows the variation in specific heat capacity, c, of ice with temperature, T.

T (K)	173	193	213	233	253	273
c (J kg^{-1} K^{-1})	1,389	1,536	1,681	1,818	1,943	2,050

a **Determine** if there is a linear relationship between the variables. (3 marks)

b **Explain** why the specific heat capacity of frozen water (ice) is lower than for liquid water. (3 marks)

7 For a demonstration to introduce specific heat capacity to a Year 11 Physics class, equal masses of water, ethanol and paraffin were added to separate beakers and placed on a hotplate. After 2 minutes, the water temperature was measured as 60°C. **Calculate** the temperatures of the other two substances and **organise** them from lowest to highest temperature. (5 marks)

8 **Infer** the reason why water is ideal for use as a coolant in car engines. (2 marks)

Practical

Lesson 2.10

Specific heat capacity of liquids – on a hotplate

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

MODULE 2

Lesson 2.11

Review: Kinetic particle model and specific heat capacity

Summary

2.1
- Heat is the transfer of energy from a higher temperature object to a lower temperature object.
- Thermal equilibrium is achieved when two objects that are in contact with one another reach the same temperature.

2.2
- Practical: Heating water on a hotplate – graphing and analysing data

2.3
- The kinetic particle theory of matter states that all matter is made of particles that are in constant random motion.
- The behaviour of particles in solids, liquids and gases differs due to their kinetic energy.

2.4
- Microscopic (or internal) energy is the energy of particles at the atomic level, while macroscopic energy is the energy of the bulk.
- Thermal energy consists of microscopic kinetic energy and the microscopic potential energy stored within and between bonds.
- In thermal physics, microscopic energy, internal and thermal energy are the same.

2.5
- The particles in a substance do not all have the same kinetic energy; they fit on a distribution and are discussed as average kinetic energy.
- When an increase in thermal energy causes an increase in the average kinetic energy, temperature increases (without phase change).

2.6
- The thermometer is a good example of thermal expansion as explained by the kinetic particle model of matter.
- The Fahrenheit, Celsius and Kelvin scales are used to measure temperature.

2.7
- Practical: Precision and accuracy of thermometers

2.8
- Heat can be transferred by conduction, convection, and radiation.

2.9
- Specific heat capacity is the amount of energy required to raise the temperature of a specific mass of a substance by one degree.
- Substances with stronger intermolecular forces can absorb more thermal energy, and thus have a higher specific heat capacity.

2.10
- Practical: Specific heat capacity of liquids – on a hotplate

Key formulas

Temperature conversion	Kelvin temperature = Celsius temperature + 273 $T_K = T_C + 273$
Specific heat capacity	$Q = mc\Delta T$

Review questions 2.11A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 Which one of the following statements about the kinetic theory of gases is correct?
  A All molecules move with the same speed at a given temperature.
  B The average kinetic energy of particles is directly proportional to the Celsius temperature.
  C All molecules make elastic collisions with each other and the walls of the container.
  D The molecules travel in zig-zag lines until they collide.

2 Three sealed flasks each containing 1 g of water, ice or water vapour are at the same temperature. Which of the following is true about the internal energy of the substances?
  A $U_{water} > U_{ice} > U_{vapour}$
  B $U_{water} = U_{ice} = U_{vapour}$
  C $U_{water} < U_{ice} < U_{vapour}$
  D $U_{ice} < U_{water} < U_{vapour}$

3 During an energy transfer process, 1,000 J of heat is added to a gas at constant volume. Which one of the following will remain constant?
  A Internal energy
  B Speed of the molecules
  C Temperature
  D Density

4 A sealed container of air is kept at a constant temperature. What will happen to the speed of the molecules of air in the container as time passes?
  A The molecules will all reach the same speed.
  B Some molecules will speed up and others will slow down, but the average speed will be constant.
  C The molecules will slow down.
  D There will be no change.

5 A scientist is feeling sick and knows that if her temperature is a degree or more above 37.5°C, she should go home from work. But all she has is a thermometer graduated in kelvin. What temperature does the thermometer need to show?
  A 194.5 K **B** 310.5 K
  C 311.5 K **D** 235.5 K

6 Which one of the following shows the relationship between 298 K and the equivalent temperature in °C?
  A $T_C = -298 + 273$ **B** $T_C = 273 + 298$
  C $T_C = 298 - 273$ **D** $T_C = 298 + 273$

7 Which one of the following shows a temperature of –15°C in kelvin?
  A 263 K **B** 273 K
  C 283 K **D** –263 K

8 Convection cannot occur in which one of the following substances?
  A Water **B** Ice
  C Steam **D** Water vapour

9 A metal rod is placed between an object at 200°C and another object at 20°C. An amount of heat, Q, is transferred from the hot to the cold object. If the metal rod is replaced by another made of the same material but twice as thick, determine how much heat will be transferred during the same amount of time, t.
  A Zero
  B Less than Q, but not zero
  C Q
  D More than Q

10 When you stand with one bare foot on a floor tile and the other on carpet, the floor tile feels much colder than the carpet. Which form of heat transfer are you experiencing?
  A Conduction
  B Free convention
  C Forced convection
  D Radiation

11 The specific heat of a liquid is 2,000 J kg^{-1} K^{-1}. What amount of heat in joules is needed to raise the temperature of 500 g of liquid from 30°C to 40°C?
  A 4.0×10^1 **B** 1.0×10^4
  C 4.0×10^4 **D** 1.0×10^7

12 What is the final temperature when 2,090 J of thermal energy is transferred to 500 g of water at 25.0°C?
  A 25.1°C **B** 27.5°C
  C 30.0°C **D** 35.0°C

13 A 150.0 g sample of alcohol in an insulated cup is heated by the addition of 1,920 J of electrical energy. Its temperature rises from 25.0°C to 30.0°C. Which of the following is the experimental value for specific heat capacity of the alcohol in $J\,kg^{-1}\,K^{-1}$, and the percentage error, respectively?

A 1,620, 28%
B 1,620, 63%
C 2,560, 4.3%
D 2,560, 4.5%

14 During a heating experiment, the temperature of a liquid-in-glass thermometer increased from 25.5°C to 32.0°C. The resolution (scale division) of the thermometer scale was 1°C. Which of the following lists the absolute and the percentage uncertainty, respectively, in the change in temperature?

A 0.25°C, ±4%
B 0.5°C, ±7%
C 1.0°C, ±7%
D 1.0°C, ±15%

Review questions 2.11B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

15 **Define** the terms "temperature", "energy" and "heat" in the context of heating water. (3 marks)

16 **Describe** three differences between solids, liquids and gases. (3 marks)

17 You can compress gases easily but not solids. **Explain** whether you can partially compress liquids. (2 marks)

18 **Use** the correct formula to convert the following Celsius temperatures to kelvin.

a –25°C (1 mark)
b 59°C (1 mark)
c 290°C (1 mark)

19 **Use** the correct formula to convert the following kelvin temperatures to °C.

a 150 K (1 mark)
b 378 K (1 mark)
c 6,000 K (1 mark)

20 **Describe** the concept of specific heat capacity, using water as an example. (1 mark)

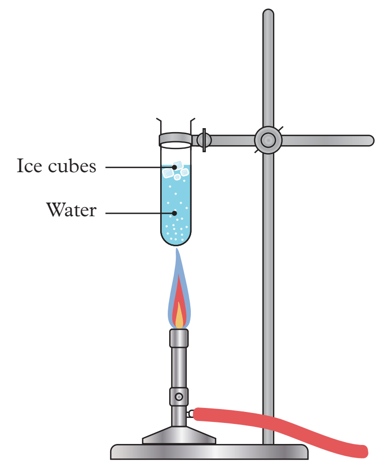
21 **Explain** the main assumptions we make about gases regarding their collisions. (2 marks)

22 **Describe** why knitted woollen jumpers keep you warm in winter, with reference to the heat source and the correct heat transfer terms. (2 marks)

23 **Calculate** the final temperature of the iron when 1,500 J of energy is used to heat a 400 g sample of iron initially at 28°C. (2 marks)

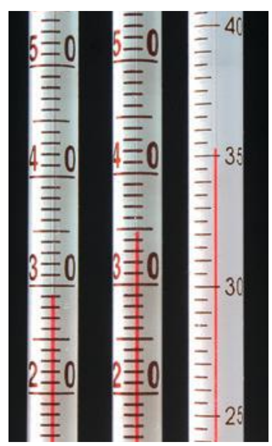
24 **Explain** why salt (NaCl) affects the force of attraction between water molecules given that salty water heats up more quickly than an equal mass of distilled water, when the same amount of thermal energy is added to both. (3 marks)

25 If small blocks of ice are placed in a test tube with water and heated, the ice will float at the top as ice is less dense than water. **Describe** the process by which the ice obtains the heat energy needed to melt. (5 marks)



Analytical processes

26 **Deduce** the temperatures of the three thermometers to the nearest half-scale division. (3 marks)



27 **Determine** the amount of thermal energy needed to raise the temperature of a 250 g piece of copper from −20°C to 25°C. (2 marks)

28 A 2,000 J energy supply was used to heat four different masses of the same metal: 100 g, 200 g, 500 g and 1.00 kg.

a If the temperature of the 100 g mass increased by 5°C, **determine** what the temperature changes of the other three masses would have been. (3 marks)

b **Calculate** the specific heat capacity of the metal. (2 marks)

c **Determine** if the metal is more likely to be copper or aluminium. (1 mark)

Knowledge utilisation

29 **Evaluate** whether heat and temperature are the same thing, by giving an example of two objects that could contain the same heat (thermal) energy but at different temperatures. (5 marks)

30 **Evaluate** the following claim made by an advertisement for insulation: "StayCool Insulation will reduce roof temperatures from 60°C to 30°C – a 50% reduction!" (3 marks)

31 **Evaluate** whether this statement is true or false: "When you double the kelvin temperature of a gas, you double the average speed of the molecules." (3 marks)

32 When you rub your hands together, they begin to warm up. **Predict** how the temperature of your hands will change as you continue rubbing. **Justify** your conclusion in terms of heat transfer processes. (3 marks)

Data drill

Specific heat capacity of a liquid

A student conducted an experiment to investigate the specific heat capacity of paraffin oil in comparison to water. They placed 100.0 g of each liquid in separate beakers and measured the initial temperatures. They placed the samples on a hotplate that delivered a constant and equal amount of energy to each liquid, and measured the temperature of each liquid every minute for 5 minutes. The temperature of the liquids was plotted against the energy added (Figure 1).

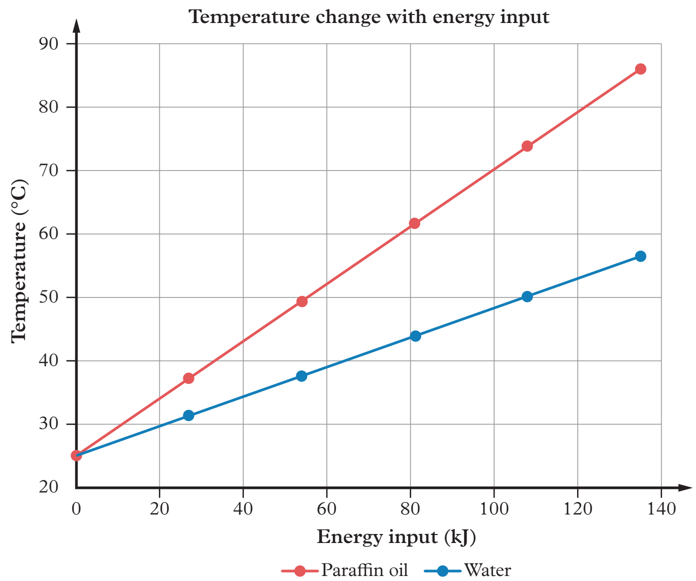


FIGURE 1 Graph of temperature vs energy added

Apply understanding

1 **Calculate** the change in temperature for the water and oil. (2 marks)

Analyse evidence

2 **Identify** which liquid has the higher specific heat capacity. Explain your reasoning. (2 marks)

Interpret evidence

3 **Determine** the specific heat capacity of the oil given that the specific heat capacity of water is 4,180 $J\,kg^{-1}\,K^{-1}$. (3 marks)

4 **Draw a conclusion** about whether this is an accurate method for determining specific heat capacity values for liquids. In your answer, you should refer to the percentage error in the result, given that the accepted value for the oil is 2,210 $J\,kg^{-1}\,K^{-1}$. (4 marks)

Module 2 checklist: Kinetic particle model and specific heat capacity

Quizlet: Revise key terms online to test your understanding

MODULE 3

Phase changes and energy conservation

Introduction

At the start of a lecture in 1761, Scottish scientist Joseph Black showed his audience a bucket of water and a block of ice, both at 0°C. By the end of the lecture, the water had warmed many degrees but the ice remained a solid at 0°C. At this time, heat was still regarded as some sort of invisible fluid that bodies possessed. When a body was warmed, this caloric fluid was transferred to the body. But this did not explain Black's demonstration, or why two ice cubes melted when they were rubbed.

Nevertheless, people were able to harness the energy of heat and turn it into useful work, even if they did not understand the connection. Steam engines were a good example of this. The need to increase the efficiency of these early steam engines led to further technological advancements, such as building the internal combustion engine. More critically, it led to scientists attempting to better understand the mathematical relationship between heating processes and mechanical work. These ideas were eventually brought together in 1843 by James Prescott Joule, and then given a theoretical interpretation in terms of the kinetic particle model of matter in 1857 by Rudolph Clausius.

In this module, we will look at the two ideas: how heat can be transferred from one object or system to another; and how mechanical work and heat can be interchanged.

Prior knowledge

Prior knowledge quiz

Check your understanding of the law of conservation of energy and heat transfer before you start.

Subject matter

Science understanding

→ Explain, in terms of the internal energy of a system and the kinetic particle model of matter, why the temperature of a system remains the same during the process of state change.

- → Describe the concept of specific latent heat.
- → Solve problems involving specific latent heat using $Q = mL$.
- → Describe the concept of thermal equilibrium in terms of the temperature and average kinetic energy of the particles in each of the systems.
- → Explain the process in which thermal energy is transferred between two systems until thermal equilibrium is achieved, and recognise the relevance of this to the laws of thermodynamics.
- → Solve problems involving specific heat capacity, specific latent heat and thermal equilibrium.
- → Explain how a system with thermal energy has the capacity to do mechanical work.
- → Explain that the change in the internal energy of a system is equal to the energy added or removed by heating plus the work done on or by the system, and recognise this as the first law of thermodynamics and as a consequence of the law of conservation of energy.
- → Explain how energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so that the amount of useable energy is reduced.
- → Describe the concept of efficiency.
- → Solve problems involving the efficiency of heat transfers using $\Delta U = Q + W$ and $\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100}{1}\%$.

Science as a human endeavour

- → Recognise that the science of heating processes is of key importance to the development of efficient and cost-effective technologies that use sustainable and renewable energy sources.
- → Explore how the need for increases to the efficiency of early steam engines led to further technological advancements (e.g. the internal combustion engine) and scientific advancements (e.g. an understanding of, and mathematical articulation of, the relationship between heating processes and mechanical work).

Science inquiry

- → Consider why you feel colder when you are wearing wet clothes.
- → Explore the implications on availability of useable energy in the future if useable energy is reduced every time an energy transfer occurs.
- → Investigate percentage error by comparing the theoretical and measured temperatures of a mixture of two liquids.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 3.4 Specific heat capacity of a metal – by calorimetry

Lesson 3.5 Mixture of two liquids – calorimetry

Lesson 3.1
Phase changes and specific latent heat

Key ideas

- → Substances can undergo phase changes, including melting, vaporisation, evaporation, condensation and freezing.
- → Specific latent heat is the energy required for 1 kg of substance to undergo a phase change.

Learning intentions and success criteria

phase change
when a substance changes state, such as from solid to liquid

What happens on the particle level during phase change?

When you eat an icy pole, the ice melts in your mouth and turns from frozen water into liquid water – but it is still made of water molecules (H_2O). Instead of being lumped together in a solid form, the molecules are now free to move. Similarly, when you heat up water in a kettle, the liquid water turns into steam – the molecules are still H_2O molecules, but they are now free to move around even more. These **phase changes** (or state changes) occur with the addition or removal of thermal energy.

Up until now, we have only considered the change in temperature of substances as heat is added or taken away, and can answer the question about what happens on the atomic level to the coffee and the metal spoon. But we are not yet able to explain what is going on with the glass of ice water. Now, we will look at what happens when substances change state. This will allow us to answer the question.

FIGURE 1 What happens on the atomic level when an icy pole melts?

How does heating affect kinetic energy and phase?

In Module 2, the internal energy of a substance was defined as the total microscopic energy possessed by the particles of the substance, including both kinetic and potential energies. We learnt that thermal energy is the portion of internal energy that changes with heating and cooling; that is, it excludes the nuclear and chemical energy of the system.

When you heat a substance up without a phase change, you increase its thermal energy. This increases its average kinetic energy and temperature. When heat is added to cause a phase change, you also increase its thermal energy. However, this increases its potential energy but not its average kinetic energy or its temperature. The changes in energy with heating are summarised in Table 1.

TABLE 1 The effect of heating on energy in a system with and without phase changes

	Effect of heating	
	When there is no phase change	During a phase change
Internal energy, U	increases	increases
Thermal energy, Q	increases	increases
Kinetic energy, E_k	increases	unchanged
Temperature, T	increases	unchanged
Potential energy, E_p	unchanged	increases

In a solid, the particles are held together in a lattice and their strong intermolecular forces mean that they have the least microscopic potential energy. In liquids, particles have a greater freedom of movement and therefore more microscopic potential energy than in solids. The particles in gases have the greatest range of motion, with few intermolecular forces between them, so they have the greatest microscopic potential energy of all three phases of matter. Thus, as a substance changes phases, its microscopic potential energy changes too. Let's explore each phase change in more detail.

What happens during melting – from solid to liquid?

When you heat up ice, it melts. This involves the transfer of thermal energy (Figure 2). However, during the **melting** process, the addition of thermal energy does not go into changing the kinetic energy of the particles but into increasing their potential energy. This is because as the ice absorbs a large amount of thermal energy, the intermolecular bonds between water molecules are broken, increasing the potential energy of the particles.

melting
a physical process in which a solid undergoes a phase change to become a liquid

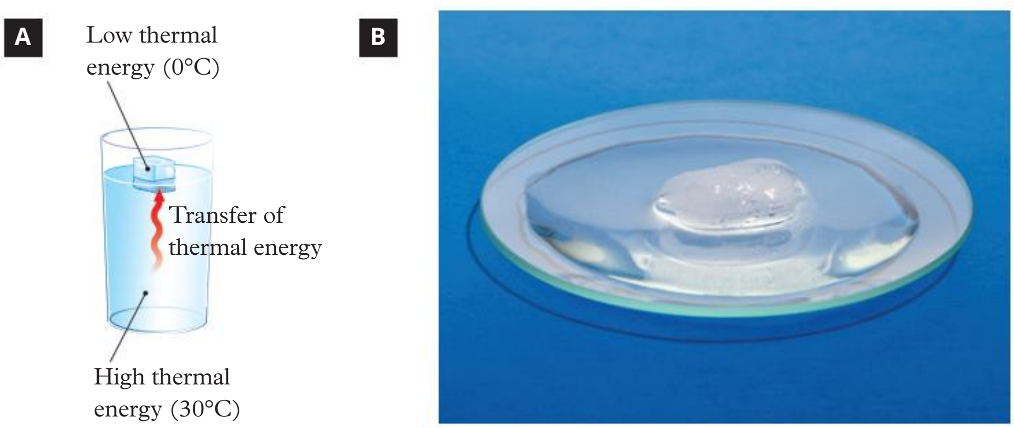


FIGURE 2 (A) Thermal energy is transferred from the water to the ice, causing the ice to melt. (B) Although the liquid water has the same mass as it did as solid ice, it now has higher thermal energy.

Since temperature is a measure of the average kinetic energy of the particles, the temperature does not increase. So, when a solid melts by the addition of heat, the potential energy of the particles increases without a change in temperature. Table 2 shows some real data from a Physics class about the heating of ice. You can see that the temperature remains constant at 0°C for a couple of minutes (t = 3 to 4 minutes) as the ice melts. This is called the **melting point**.

melting point
the temperature at which a solid changes into a liquid

After melting, the addition of heat results in an increase in the kinetic energy (now translational, rotational and vibrational) as well as the potential energies of the liquid. Thus, temperature again rises.

TABLE 2 Data of melting ice

Time, t (min)	0	1	2	3	4	5	6	7	8	9	10
Temperature, T (°C)	−5	−3	−0.5	0	0	2.5	5	15	26	37	48

freezing
a physical process in which a liquid undergoes a phase change to become a solid

The opposite is true in the change from liquid to solid phase (**freezing**). The same quantity of thermal energy required to melt the solid must then be removed from the liquid to cause the required decrease in microscopic potential energy. The substance then freezes.

Study tip

When a change in thermal energy causes a phase change, microscopic potential energy has changed. When a change in thermal energy does not cause a phase change, microscopic kinetic energy has changed.

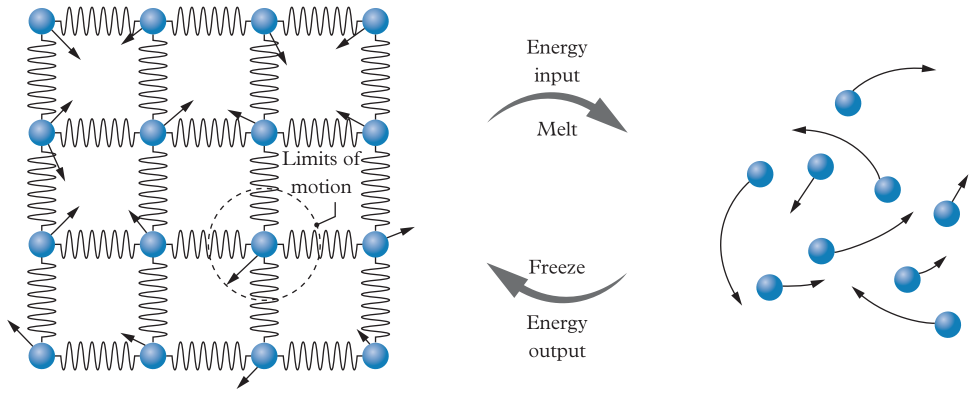


FIGURE 3 Energy is required to partially overcome the attractive forces between particles in a solid to form a liquid. When it does, it melts (top arrow). That same amount of energy must be removed for freezing (solidification) to take place (bottom arrow).

Challenge

What happens when you put a snowman in a coat?

Who would put a coat on a snowman? Wouldn't that make it melt? We wear coats in cold weather to keep our bodies warm, but things must be different for a snowman.

Explain, in terms of thermal energy transfer

a which will melt faster – a snowman with or without a dark coat when the outside air is warm (2 marks)

b which will melt faster if the outside air is colder than the snowman. (2 marks)

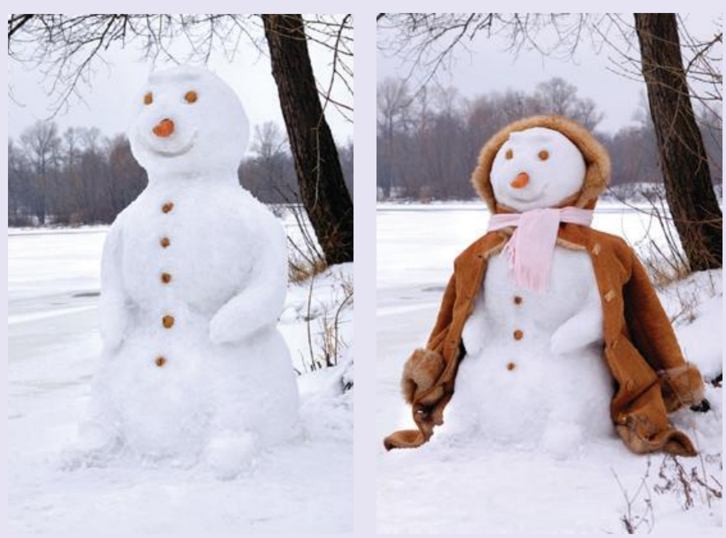


FIGURE 4 This snowman was made in fresh snow. The sun is shining, so why doesn't the snowman melt? Will a dark coat make the snowman melt faster or slower?

What happens during vaporisation – from liquid to gas?

As we continue to heat water, the intermolecular forces between the particles become weaker and the particles move even more freely. Once a liquid reaches a certain temperature, any added thermal energy will go into causing the particles to break apart completely. At this point, the substance starts changing state from a liquid to a gas. This phase change is called **vaporisation**. Again, like during melting, the temperature does not increase during this process as there is no increase in the kinetic energy of the particles. This temperature is called the **boiling point** of the liquid.

The opposite is true in the change from gas to liquid phase (**condensation**). The same quantity of thermal energy must be removed to cause the required decrease in microscopic potential energy, and this then causes the substance to condense.

vaporisation
a physical process in which a liquid undergoes a phase change to become a vapour (it can include evaporation or boiling)

boiling point
the temperature at which a liquid changes into a vapour by boiling

condensation
a physical process in which a gas undergoes a phase change to become a liquid

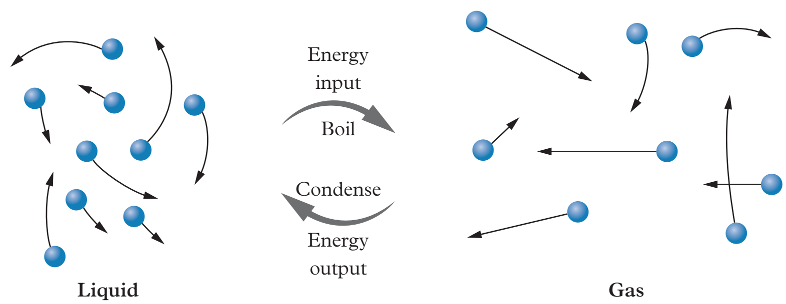


FIGURE 5 As energy is added to a liquid, the particles move faster and eventually break away from each other and leave the surface of the liquid. Similarly, when the gas is cooled, the particles slow down and bonds reform, eventually condensing to form a liquid.

The changes in temperature during heating and phase change are shown in Figure 6.

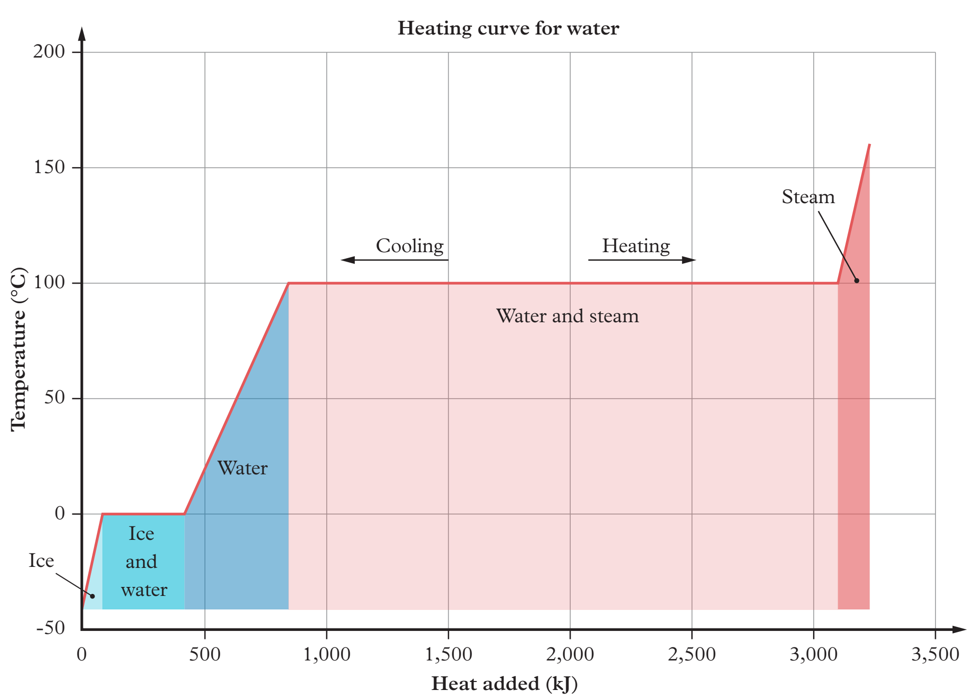


FIGURE 6 Heating curve for 1 kg of water. Adding heat causes a progression through the three states of water, but there are times when the temperature doesn't change.

What is specific latent heat?

You have seen that energy is necessary to change a substance from one phase to another, even when there is no change in temperature. The amount of heat necessary to change the state of 1 kg of a substance with no change in its temperature is called its **specific latent heat**. This can be classified further based on the specific phase change occurring.

specific latent heat
the amount of energy required to change the phase of 1 kg of a substance

Latent heat of fusion

The **specific latent heat of fusion** is the amount of heat required to melt 1 kg of a substance at its melting point. The word "latent'" is Latin for "hidden". It is hidden as potential energy in the bonds between the particles (rather than in the kinetic energy of the particles), and allows a substance to take in heat without the thermometer registering a change. Although it is not the best word to describe the energy, it has stuck for historical reasons. The word "fusion" is from the Latin "fundere", meaning "to melt".

To change 1 kg of ice to water at 0°C requires 3.34×10^5 J of energy. Therefore, ice has a specific latent heat of fusion of 3.34×10^5 J kg^{-1}. This is also the amount of energy that would be released if 1 kg of water was frozen back into ice at 0°C.

specific latent heat of fusion
the amount of energy required to change 1 kg of a substance from solid to liquid at its melting point (symbol: L_{fv}; unit: joules per kilogram; unit symbol: J kg^{-1})

Latent heat of vaporisation

The **specific latent heat of vaporisation** is the thermal energy required to change 1 kg of a liquid into a vapour (gas) at its boiling point.

It takes 2.26×10^6 J of thermal energy to change 1 kg of water at 100°C to steam at 100°C, so the specific latent heat of vaporisation of water is 2.26×10^6 J kg^{-1}. This is also the amount of energy that would be released if 1 kg of steam condensed back into water at 100°C.

Specific latent heats of fusion and vaporisation of other liquids are given in Table 3.

specific latent heat of vaporisation
the thermal energy required to change 1 kg of a liquid into a vapour at its boiling point (symbol: L_v; unit: joules per kilogram; unit symbol: J kg^{-1})

Study tip

Note on spelling: "vapour" is British, "vapor" is American. We tend to use the British spelling "vapour", but the process of changing from a liquid to a vapour is called (and spelt) "vaporisation".

TABLE 3 Specific latent heats of some common substances

Substance	Specific latent heat of fusion L_f (J kg^{-1})	Specific latent heat of vaporisation L_v (J kg^{-1})
Mercury	1.18×10^4	2.90×10^5
Lead	2.30×10^4	8.64×10^5
Gold	6.30×10^4	1.64×10^6
Silver	1.05×10^5	2.36×10^6
Alcohol	1.09×10^5	8.70×10^5
Aluminium	1.80×10^5	1.14×10^7
Copper	2.05×10^5	4.82×10^5
Iron	2.76×10^5	6.29×10^6
Water	3.34×10^5	2.26×10^6

Challenge

How does latent heat protect us from cooking like a steak?

In 1775, British physicist Dr Charles Blagden investigated the effect of extremely high temperatures on humans. During one of these experiments, Dr Blagden took some friends, a dog and a raw beef steak into a room at 127°C for 45 minutes. They all came out unharmed, except for the steak (which was cooked). **Explain**, in terms of latent heat, why this might have happened. Hint: Look at Figure 7. (4 marks)

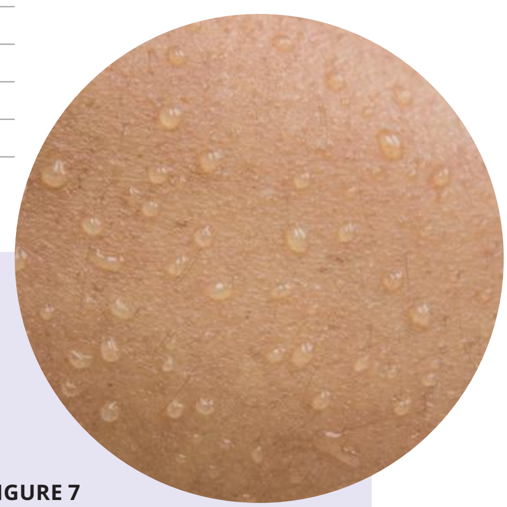


FIGURE 7
When perspiration droplets evaporate, they take the latent heat from the body with them.

How do we use the specific latent heat formulas?

The energy required to change the phase of a substance at its melting or boiling point is Q and this energy is proportional to the mass: $Q \propto m$. The constant of proportionality that links the two is called the specific latent heat L: $Q = mL$.

Latent heat of fusion

The thermal energy required to melt a mass of a substance at its melting (or freezing) point is given by the equation:

$$Q = mL_f$$

where Q is thermal energy (in J), m is the mass of the substance (in kg), and L_f is the specific latent heat of fusion of the substance (in $J\,kg^{-1}$).

Worked example 3.1A

Calculating the energy and time needed to melt lead

a **Calculate** the energy required to change a 2.00 kg block of lead to liquid at its melting point. Express your answer to 3 s.f. (3 marks)

b **Calculate** the time it would take to do this using an electrical heater that produces 1,200 $J\,s^{-1}$. Express your answer to 2 s.f. (3 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the latent heat of fusion formula and find the time required to transfer a given amount of heat. The questions are worth 3 marks each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formula and gather any data required.	**a** $Q = mL_f$ L_f(lead) = $2.30 \times 10^4\,J\,kg^{-1}$ (1 mark)
Step 3: Substitute the known values into the formula and find the unknown.	$Q = 2.00 \times 2.30 \times 10^4$ $= 4.60 \times 10^4$ (1 mark)
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures.	$4.60 \times 10^4\,J$ (3 s.f.) (1 mark)
Step 5: The relationship between rate, energy and time is rate $= \frac{Q}{t}$. Rearrange the equation to find the unknown. Note: the rate of energy output is called power, P, but it is not introduced until the electricity topic, Lesson 7.4.	**b** $1{,}200 = \frac{Q}{t}$ $t = \frac{Q}{1{,}200}$ (1 mark)
Step 6: Substitute the known values into the relationship and find the unknown.	$t = \frac{4.60 \times 10^4}{1{,}200}$ $= 38$ (1 mark)
Step 7: Finalise your answer for part **b** and make sure you have included the correct units and significant figures.	38 s (2 s.f.) (1 mark)

Your turn

Iron has a melting point of 800°C. **Calculate** the amount of heat required to melt 250 g of iron at its melting point (2 s.f.). (2 marks)

Rather than calculating the amount of heat needed to melt a substance at its melting point, we often want to calculate the total heat needed to bring it up from, say, room temperature to its melting point and then melt it. The reverse is also true; we may want to cool a substance down from room temperature to freeze it. This type of question is much harder, but let's look at an example.

Worked example 3.1B

Calculating the energy needed to freeze warm water

A plastic ice cube tray containing 200 g of water at 25.0°C is placed in the freezer. **Calculate** the amount of thermal energy that has to be removed to change the water into ice at −4.0°C. (Note: $c_{water} = 4{,}180\,\mathrm{J\,kg^{-1}\,K^{-1}}$; $c_{ice} = 2{,}050\,\mathrm{J\,kg^{-1}\,K^{-1}}$) (5 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply two different formulas: the specific heat capacity formula and the latent heat of fusion formula. The question is worth 5 marks, so we must correctly apply the formulas and complete the calculations for each.
Step 2: Select the correct formulas and gather any data required.	$Q = mc\Delta T$ and $Q = mL_f$ $L_f(\text{ice}) = 3.34 \times 10^5\,\mathrm{J\,kg^{-1}}$ $c_{water} = 4{,}180\,\mathrm{J\,kg^{-1}\,K^{-1}}$ $c_{ice} = 2{,}050\,\mathrm{J\,kg^{-1}\,K^{-1}}$
Step 3: Identify the stages of cooling that must be considered.	**1** Water is first cooled from 25.0°C to its freezing point. **2** The water is then frozen into ice at 0°C. **3** Finally, the ice is cooled to the final temperature of −4°C. (1 mark)
Step 4: For each stage, identify the correct formula. When there is a change in temperature, use $Q = mc\Delta T$. When the substance is at its melting/freezing point, use $Q = mL_{fv}$. Substitute the known values into the formula and find the unknown.	**1** $Q = \frac{200\,\mathrm{g}}{1{,}000} \times 4{,}180 \times (0 - 25)$ $= -20{,}900\,\mathrm{J}$ (1 mark) **2** $Q = \frac{200\,\mathrm{g}}{1{,}000} \times 3.34 \times 10^5$ $= 66{,}800\,\mathrm{J}$ (1 mark) **3** $Q = \frac{200\,\mathrm{g}}{1{,}000} \times 2{,}050 \times (-4 - 0)$ $= -1{,}640\,\mathrm{J}$ (1 mark)
Step 5: Sum the values for each stage to get the total thermal energy required. Since temperature is decreasing, the thermal energy values are negative. We only need to take the magnitude of the heat transfer, not the direction.	$Q_{total} = \lvert -20{,}900 \rvert + 66{,}800 + \lvert 1{,}640 \rvert$ $= 89{,}340\,\mathrm{J}$
Step 6: Finalise your answer and make sure you have included the correct units and significant figures.	$89{,}000\,\mathrm{J}$ or $8.9 \times 10^4\,\mathrm{J}$ (2 s.f.) (1 mark)

Your turn

A tub contains 1,500 g of water at 30°C. **Calculate** the amount of heat that must be transferred from the water to get it to a freezer temperature of −10°C. (Note: $c_{water} = 4{,}180\,\mathrm{J\,kg^{-1}\,K^{-1}}$, $c_{ice} = 2{,}050\,\mathrm{J\,kg^{-1}\,K^{-1}}$). (5 marks)

Latent heat of vaporisation

The energy required to vaporise a liquid is given by the equation:

$$Q = mL_v$$

where L_v is the specific latent heat of vaporisation (in $J\,kg^{-1}$).

Worked example 3.1C

Vaporising water at its boiling point

A beaker contains 150 g of water. **Calculate** the amount of thermal energy required for the water to vaporise at 100°C. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the latent heat of vaporisation formula. The question is worth 3 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formula and gather any data required.	$Q = mL_v$ L_v(water) = $2.26 \times 10^6\,J\,kg^{-1}$ (1 mark)
Step 3: Substitute the known values into the formula and find the unknown.	$Q = \frac{150\,g}{1{,}000} \times 2.26 \times 10^6$ $= 3.39 \times 10^5$ (1 mark)
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	$3.39 \times 10^5\,J$ (3 s.f.) (1 mark)

Your turn

Ethanol vapour ($L_v = 8.70 \times 10^5\,J\,kg^{-1}$) is condensed to form 16.0 g of liquid at its boiling point of 78.4°C. **Calculate** the amount of heat removed. (2 marks)

Study tip

Here, we make the distinction between specific latent heat of fusion, L_f, and specific latent heat of vaporisation, L_v, but you can also generally use L for specific latent heat and the corresponding formula $Q = mL$.

Challenge

Why do wet clothes make you feel colder?

When you get out of a pool, it feels instantly cold. Similarly, if your clothes get wet under the sprinkler, it feels cold, too. Use latent heat theory to **explain** why your body feels this way. (3 marks)

FIGURE 8 Wet clothes make you feel colder.

Skill drill

Heat, temperature and phase-change data analysis

Science inquiry skills: Processing and analysing data (Lesson 1.7); Evaluating evidence (Lesson 1.8)

An experiment was conducted to address the following research question:

"How does the temperature of a substance change as a function of time when heated at a constant rate?"

A sample of 800 g of benzene was heated by a 1,000 J s^{-1} heater for 10 minutes. The experimental data was collected, processed and presented in Figure 9.

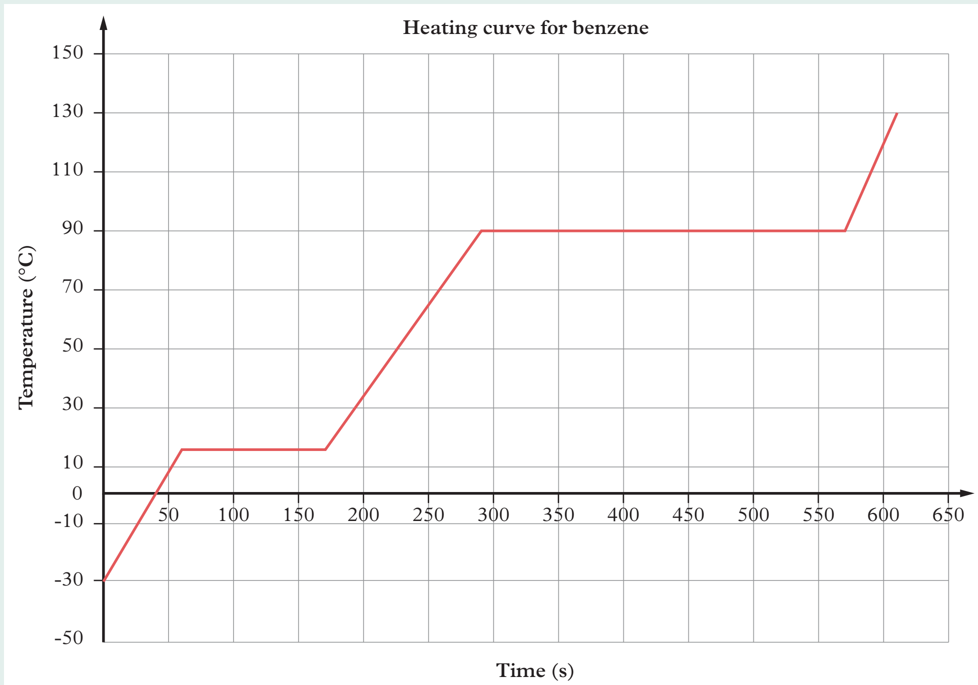


FIGURE 9 The temperature (°C) of a sample of benzene as it is heated over time (s)

Practise your skills

1 **Identify** the melting point temperature of benzene (in °C, 1 d.p.). (1 mark)

2 **Calculate** the minimum amount of energy (in kJ) required for benzene to melt completely (1 d.p.). Show your working. (2 marks)

3 **Calculate** the latent heat of fusion of benzene (in kJ kg^{-1}, 1 d.p.). Show your working. (2 marks)

4 **Predict** the temperature of benzene (in °C) at $t = 400$ s, given that the latent heat of vaporisation is 350,000 J kg^{-1} (1 d.p.). **Justify** your answer. (2 marks)

Check your learning 3.1

Check your learning 3.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the concept of specific latent heat as it applies to water. (2 marks)

2 **Explain** why the temperature of a system remains the same during the process of a change of state. Your answer should refer to the internal energy of the system and the kinetic particle model. (3 marks)

Analytical processes

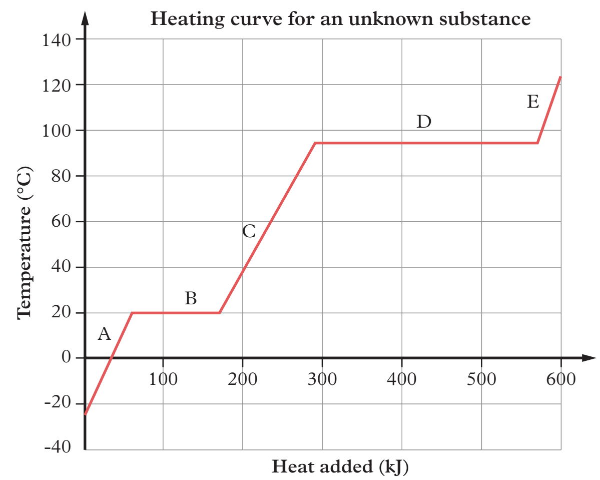
3 **Determine** the energy required to melt 2.50 kg of gold at its melting point. (Refer to Table 3 for specific latent heats of fusion.) (2 marks)

4 Copper has a melting point of 1,083°C. **Determine** the energy required to melt 200.0 g of copper from room temperature (22°C). (4 marks)

5 A 2.0 L bottle of water at 20°C is placed in the freezer compartment of a refrigerator. **Determine** the quantity of thermal energy that must be removed by the refrigerator to freeze the water. (4 marks)

6 **Determine** the mass of acetone that can be vaporised by the addition of 20 kJ of thermal energy at its boiling point of 56°C (acetone $L_v = 5.18 \times 10^5\,\mathrm{J\,kg^{-1}}$). (3 marks)

7 A 700 g sample of an unknown organic compound was heated on a laboratory hotplate that produced 1,000 J of thermal energy per second. The experimental data was collected, processed and presented in a graph.



a **Explain** why the section of the graph labelled B is horizontal. (1 mark)

b **Identify** the melting point of the substance (°C, 2 s.f.). (1 mark)

c **Identify** the boiling point of the substance (°C, 2 s.f.). (1 mark)

d **Calculate** the specific heat capacity of the solid phase ($\mathrm{J\,kg^{-1}\,K^{-1}}$, 3 s.f.). (2 marks)

e **Calculate** the specific heat capacity of the liquid phase ($\mathrm{J\,kg^{-1}\,K^{-1}}$, 3 s.f.). (2 marks)

f **Calculate** the specific latent heat of vaporisation of the compound ($\mathrm{J\,kg^{-1}}$, 3 s.f.). (3 marks)

g **Deduce** whether the molecules in the liquid phase or in the vapour phase have the greater potential energy. **Justify** your answer. (2 marks)

Lesson 3.2
Thermal equilibrium

Key ideas

→ At thermal equilibrium, the components in a system have the same temperature and particles have the same average kinetic energy.

→ The zeroth law of thermodynamics states that energy will transfer from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached.

Learning intentions and success criteria

thermal equilibrium a state in which there is no net exchange of thermal energy between any components of a system; the components have the same temperature and the same average kinetic energy

zeroth law of thermodynamics if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other; energy will transfer from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached

Study tip

The final temperature at which particles have the same average kinetic energy is the equilibrium temperature.

What is thermal equilibrium?

Earlier we said that if you put a spoon in hot coffee and leave it long enough, the coffee and the spoon will come to the same temperature. At this point, we say **thermal equilibrium** has been achieved (Greek "aequi" meaning "equal", "libra" meaning "balance"). At the microscopic level, when the spoon is placed in the coffee, the particles in the hotter substance (coffee) have more kinetic energy than those in the cooler substance (teaspoon). When the two substances are brought into physical contact, the particles collide, and the hot, fast-moving particles transfer heat to the cooler, slow-moving particles. Remember that this process is spontaneous and occurs due to a temperature difference. Once enough thermal energy has been transferred such that they are at the same temperature and their particles have the same average kinetic energy, the two substances will have reached thermal equilibrium.

In Figure 1, the three blocks start at temperatures of 60°C, 50°C and 100°C (from left to right), but soon all end up at 78°C. The brass and aluminium are both in thermal equilibrium with the middle block (iron), so we can say that brass and aluminium must be in thermal equilibrium with each other. This can be explained using the **zeroth law of thermodynamics**.

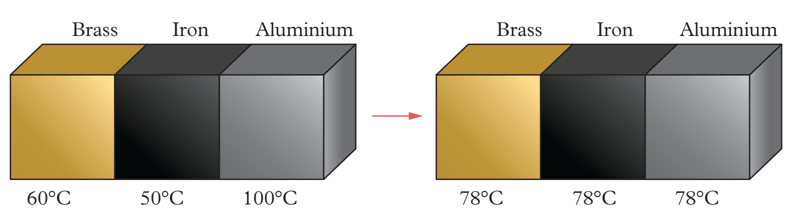


FIGURE 1 Three blocks reach thermal equilibrium

What is the zeroth law of thermodynamics?

The zeroth law of thermodynamics was first proposed by R. H. Fowler in 1931. It was called "zeroth" because, logically, it should have preceded the first and second laws of thermodynamics, but was proposed after them. The zeroth law of thermodynamics states that if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other.

This is the basis on which thermometers work. The zeroth law allows us to say that two bodies (A and B) are in thermal equilibrium if they have the same temperature reading on a thermometer (C), even if A and B are not in contact with each other.

The zeroth law of thermodynamics is sometimes restated as "energy will transfer from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached".

Check your learning 3.2

Check your learning 3.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** how thermal equilibrium is reached when an ice cube is placed in a glass of water. (3 marks)

2 **Compare** the average kinetic energy of the particles for ice and water in thermal equilibrium. (1 mark)

3 **Explain** whether a particle in a cold substance could have a higher kinetic energy than another particle in a hot substance. (2 marks)

Lesson 3.3
Interpreting data in thermal physics experiments

Key ideas

→ Specific heat capacity and specific latent heat can be determined experimentally.

→ In an isolated system, the energy gained is equal to the energy lost. This is the law of conservation of energy.

How do we solve problems about thermal energy transfer?

In this lesson, we will focus on analysing and interpreting data to solve problems involving specific heat capacity, specific latent heat and thermal equilibrium. We can obtain this kind of data through a technique called **calorimetry**. The word comes from Latin "calor" meaning "heat", but originally from the Sanskrit "carad" meaning "harvest" (which is literally "hot time"). The "metry" means "to measure", so calorimetry is about measuring heat.

When it comes to specific heat capacity and thermal equilibrium, we can consider three different scenarios: heat transfer between two solids, two liquids, and between a liquid and a solid.

Learning intentions and success criteria

calorimetry
the science of measuring the amount of heat transferred between objects or in a chemical reaction

FIGURE 1 A calorimeter is a device used in calorimetry. Its key components are an insulated container, lid, stirrer and thermometer.

What happens when a solid and a solid come into contact?

If two substances of different temperatures are placed in contact, they gradually come to the same temperature (Figure 2). The thermal energy transferred ("lost") from the hot substance is equal in size to the thermal energy "gained" by the other. We are assuming this is a closed system – one where no energy can escape to the surroundings and no additional energy is introduced into the system. In simple words, the heat lost equals the heat gained.

For solid–solid systems in thermal equilibrium:

- no heat flows between the objects
- the average kinetic energy of the particles is the same
- the temperatures of the objects are also the same.

Now, imagine the hotter block has a total thermal energy of 10,000J and the cooler block has a thermal energy of 8,000J (Figure 3). If 1,000J is transferred from the hotter block to the cooler block, they will have 9,000J each at thermal equilibrium. The hotter block has lost 1,000J (–1,000J), and the cooler block has gained 1,000J (+1,000J). The net change in thermal energy is (–1,000J) + (+1,000J) = 0J. Energy is conserved – it is the same as it was at the start. This is the **law of conservation of energy**. There is no change to the total thermal energy of the system – it has just been redistributed. You will learn more about this in Lesson 3.6.

law of conservation of energy
a law that states the total energy of an isolated system remains constant

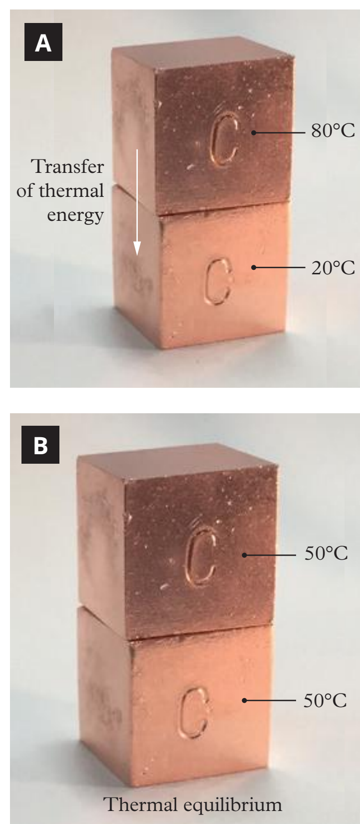


FIGURE 2 (A) Two small cubes of copper at different temperatures are placed in contact. (B) There is a transfer of thermal energy (heat) from hot to cold until thermal equilibrium is reached.

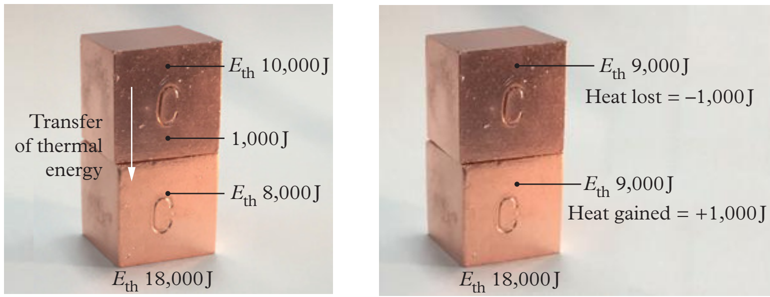


FIGURE 3 The total thermal energy of the system remains the same at 18,000 J. The heat lost (1,000 J) equals the heat gained (1,000 J).

For systems coming to thermal equilibrium, there is a transfer of thermal energy from the hot object to the cooler object. If we assume it is a closed system and no heat is lost to the environment, we can say heat lost, Q_{lost}, plus heat gained, Q_{gained}, equals zero. Using the relationship $Q = mc\Delta T$, we can substitute this into the equation on both sides and expand the terms. Note that the temperature change, ΔT, is always written as $T_f - T_i$:

$$Q_{lost} = Q_{gained}$$

$$(mc\Delta T)_{lost} = (mc\Delta T)_{gained}$$

$$m_{\text{hot copper}} \times c_{\text{copper}} \times \Delta T_{\text{hot copper}} = m_{\text{cool copper}} \times c_{\text{copper}} \times \Delta T_{\text{cool copper}}$$

$$-\left(m_{\text{hot copper}} \times c_{\text{copper}} \times (T_f - T_i)_{\text{hot copper}}\right) = \left(m_{\text{cool copper}} \times c_{\text{copper}} \times (T_f - T_i)_{\text{cool copper}}\right)$$

Study tip

"Sign errors" are the biggest cause of mistakes with these questions. Make sure you use $-Q_{lost} = Q_{gained}$.

Worked example 3.3A

Calculating the equilibrium temperature of solids in contact

A 70.0 g copper block (c = 390 J kg^{-1} K^{-1}) at a temperature of 80.0°C is placed in contact with another copper block of the same mass at a temperature of 20.0°C. Assume no heat is exchanged with the environment. **Determine** the final temperature when the blocks have reached thermal equilibrium. Express your answer to 3 s.f. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both objects. The question is worth 4 marks, so we must gather the correct information, correctly apply the formulas and complete the calculation.
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{lost} = Q_{gained}$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Hot copper block: m = 70.0 g, c = 390 J kg^{-1} K^{-1} T_i = 80.0°C, T_f = ? $Q_{lost} = -(m_{\text{hot copper}} \times c_{\text{copper}} \times (T_f - T_i))$ $= \frac{70.0\text{ g}}{1{,}000} \times 390 \times (T_f - 80.0)$

Think	Do
Step 4: Identify the object(s) gaining heat and substitute the known values into the formula.	Cold copper block: $m = 70.0\,\text{g}$, $c = 390\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$ $T_i = 20.0°\text{C}$, $T_f = ?$ $Q_{\text{gained}} = m_{\text{cool copper}} \times c_{\text{copper}} \times (T_f - T_i)$ $= \frac{70.0\,\text{g}}{1{,}000} \times 390 \times (T_f - 20.0)$
Step 5: Equate the terms and substitute known values.	$Q_{\text{lost}} = Q_{\text{gained}}$ $-\left(\frac{70.0\,\text{g}}{1{,}000} \times 390 \times (T_f - 80.0)\right) = \frac{70.0\,\text{g}}{1{,}000} \times 390 \times (T_f - 20.0)$ (1 mark)
Step 6: Simplify. Remember that two negatives give a positive.	$-(27.3T_f - 2{,}184) = 27.3T_f - 546$ $-27.3T_f + 2{,}184 = 27.3T_f - 546$ (1 mark)
Step 7: Collect terms and solve for the final answer.	$54.6T_f = 2{,}730$ $T_f = \frac{2{,}730}{54.6}$ $= 50$ (1 mark)
Step 8: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the final temperature should be between the high and low initial temperatures.	50.0°C (3 s.f.) (1 mark)

Your turn

A 75 g cube of aluminium at 90°C is brought into contact with a copper cube of mass 50 g at a temperature of 10°C. Assuming there is no transfer of heat with the environment, **determine** the equilibrium temperature of the combined blocks (2 s.f.). (4 marks)

Study tip

Mark allocation can vary for questions in your external exam. To avoid losing marks, make sure to show your full working for all calculation questions.

What happens when a liquid and a liquid come into contact?

In the previous example, you saw that there is thermal energy transfer between two solids in contact until they come to thermal equilibrium. The same is true of two liquids, although thermal equilibrium is reached much faster if they are able to mix freely in each other (i.e. are miscible).

Worked example 3.3B

Calculating error in an experiment where water is mixed

Students mixed 50.0 g of hot water at 80.0°C with 150.0 g of cold water at 5.0°C in an insulated container and let the mixture reach an equilibrium temperature. Their measured temperature was 22.5°C. **Determine** the absolute and percentage errors in their result. Express the answers to 2 s.f. (6 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both substances. The question is worth 6 marks, so we must gather the correct information, correctly apply the formulas, complete the calculations to find the theoretical value, then compare this to the measured value.

Think	Do
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{\text{lost}} = Q_{\text{gained}}$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Hot water: $m = 50.0\,\text{g}$, $c = 4{,}180\,\text{J kg}^{-1}\,\text{K}^{-1}$ $T_i = 80.0°\text{C}$, $T_f = ?$ $Q_{\text{lost}} = -(m_{\text{hot water}} \times c_{\text{water}} \times (T_f - T_i))$ $= -\left(\frac{50.0\,\text{g}}{1{,}000} \times 4{,}180 \times (T_f - 80.0)\right)$
Step 4: Identify the object(s) gaining heat and substitute the known values into the formula.	Cold water: $m = 150.0\,\text{g}$, $c = 4{,}180\,\text{J kg}^{-1}\,\text{K}^{-1}$ $T_i = 5.0°\text{C}$, $T_f = ?$ $Q_{\text{gained}} = m_{\text{cold water}} \times c_{\text{water}} \times (T_f - T_i)$ $= \frac{5.0\,\text{g}}{1{,}000} \times 4{,}180 \times (T_f - 5.0)$
Step 5: Equate the terms and substitute known values.	$Q_{\text{lost}} = Q_{\text{gained}}$ $-\left(\frac{50.0\,\text{g}}{1{,}000} \times 4{,}180 \times (T_f - 80.0)\right) = \frac{5.0\,\text{g}}{1{,}000} \times 4{,}180 \times (T_f - 5.0)$ (1 mark)
Step 6: Simplify. Remember that two negatives give a positive.	$-(209T_f - 16{,}720) = 627T_f - 3{,}135$ $-209T_f + 16{,}720 = 627T_f - 3{,}135$ (1 mark)
Step 7: Collect terms and solve for the answer.	$-836T_f = -19{,}855$ $T_f = 23.75$ (1 mark)
Step 8: Calculate absolute error (E_A). Note: the terms "measured value", "observed value" (x_O) and "experimental value" are the same thing. Likewise, "true value" and "accepted value" (x_A) are the same thing. Finalise your answer and make sure you have included the correct units and significant figures.	$E_A = \lvert x_O - x_A \rvert$ $= \lvert 23.75 - 22.5 \rvert$ $= 1.25°\text{C}$ $= 1.3°\text{C}$ (3 s.f.) (1 mark)
Step 9: Calculate percentage error. Use the unrounded answer in your calculations.	$\%\ \text{error} = \left\lvert \frac{\text{measured value} - \text{true value}}{\text{true value}} \right\rvert \times 100\%$ $\%E = \frac{E_A}{x_A} \times 100$ $= \frac{1.25}{23.75} \times 100$ $= 5.263\%$ (1 mark)
Step 10: Finalise your answer and make sure you have included the correct units and significant figures.	5.3% (2 s.f.) (1 mark)

Your turn

Students mixed 100.0 g of water at 10.0°C with 100.0 g of water at 80.0°C. Their experimental equilibrium temperature was 43.0°C. **Determine** the theoretical equilibrium temperature (3 s.f.) assuming there was no heat exchange with the environment, and the absolute and percentage errors in their result (2 s.f.). (6 marks)

Worked example 3.3C

Calculating the specific heat capacity in an experiment in which different liquids are mixed

In an experiment, students weighed out 100.0 g of ethanol and measured the temperature to be 50.0°C. They weighed out 250.0 g of water, measured the temperature as 20.0°C and mixed the two liquids in an insulated cup. The equilibrium temperature was 25.5°C. **Determine** the experimental value of the specific heat capacity of ethanol and the percentage error in the result. The accepted (true) value is 2,450 J kg^{-1} K^{-1}. Express your answer to 2 s.f. (6 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both substances. The question is worth 6 marks, so we must gather the correct information, correctly apply the formulas, complete the calculations to find the experimental value, then compare this to the true value.
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{lost} = Q_{gained}$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Hot ethanol: $m = 100.0\,g$, $c = ?$ $T_f = 25.5°C$, $T_i = 50.0°C$ $Q_{lost} = -(m_{ethanol} \times c_{ethanol} \times (T_f - T_i))$ $= -\left(\frac{100.0\,g}{1{,}000} \times c_{ethanol} \times (25.5 - 50.0)\right)$
Step 4: Identify the object(s) gaining heat and substitute the known values into the formula.	Cold water: $m = 250.0\,g$, $c = 4{,}180\,J\,kg^{-1}\,K^{-1}$ $T_f = 25.5°C$, $T_i = 20.0°C$ $Q_{gained} = m_{cold\ water} \times c_{water} \times (T_f - T_i)$ $= \frac{250.0\,g}{1{,}000} \times 4{,}180 \times (25.5 - 20.0)$
Step 5: Equate the terms and substitute known values.	$Q_{lost} = Q_{gained}$ $-\left(\frac{100.0\,g}{1{,}000} \times c_{ethanol} \times (25.5 - 50.0)\right) = \frac{250.0\,g}{1{,}000} \times 4{,}180 \times (25.5 - 20.0)$ (1 mark)
Step 6: Simplify. Remember that two negatives give a positive.	$-(0.1 \times c_{ethanol} \times (-24.5)) = 5{,}745.5$ (1 mark)
Step 7: Collect terms and solve for the answer.	$2.45\,c_{ethanol} = 5{,}747.5$ $c_{ethanol} = 2{,}345.91\,J\,kg^{-1}\,K^{-1}$ (1 mark)
Step 8: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the value should be somewhat close to 2,450 J kg^{-1} K^{-1}.	2,350 J kg^{-1} K^{-1} (3 s.f.) (1 mark)
Step 9: Calculate absolute error (E_a). Use the unrounded answer in your calculations. Finalise your answer and make sure you have included the correct units and significant figures.	$E_a = \lvert x_O - x_A \rvert$ $= \lvert 2{,}345.91 - 2{,}450 \rvert$ $= 104.1\,J\,kg^{-1}\,K^{-1}$ $= 104\,J\,kg^{-1}\,K^{-1}$ (3 s.f.) (1 mark)
Step 10: Calculate percentage error. Use the unrounded answer in your calculations.	$\%E = \frac{E_a}{x_A} \times 100$ $= \frac{104.1}{2{,}450} \times 100$ $= 4.25\%$ (3 s.f.) (1 mark)

Your turn

A sample of 50.0 g of ethanol at 15.5°C was mixed 80.0 g of water at 45.0°C in an insulated cup. The equilibrium temperature was 37.3°C. **Determine** the experimental value of the specific heat capacity of ethanol and percentage error. Express your answers to 3 s.f. (6 marks)

What happens when a liquid and a solid come into contact?

The specific heat capacity of a solid can also be determined by adding a hot solid to cool water. This is similar to the coffee and metal spoon example from early in Module 2 (Figure 4).

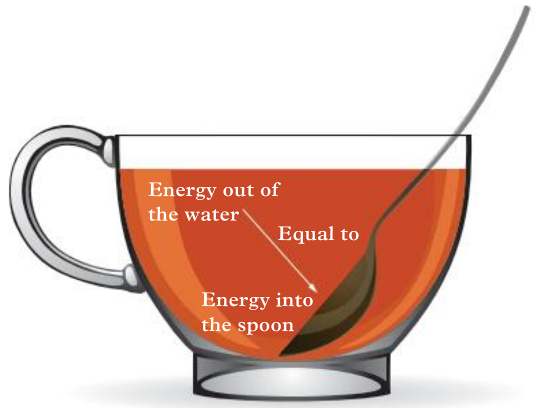


FIGURE 4 The amount of thermal energy transferred out of the hot water equals the thermal energy transferred into the spoon. Both eventually reach an equilibrium temperature somewhere in between the two temperatures.

Study tip

You will need to conduct an extended student experiment as part of your Physics course. A good one to consider is the specific heat capacity of a metal by calorimetry.

Worked example 3.3D

Calculating the equilibrium temperature when a solid is mixed with a liquid

A 20 g stainless steel spoon at room temperature at 20.0°C is placed in 200.0 g of black coffee at 70.0°C in a foam cup. Assume the foam cup doesn't absorb any energy and that the specific heat capacity of coffee is the same as that of water. **Determine** the temperature when thermal equilibrium is established (2 s.f.). The specific heat capacity of stainless steel is 500 J kg^{-1} K^{-1}. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both substances. The question is worth 4 marks, so we must gather the correct information, correctly apply the formulas and complete the calculation.
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{lost} = Q_{gained}$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Hot coffee: $m = 200.0\,\text{g}$, $c = 4{,}180\,\text{J kg}^{-1}\text{K}^{-1}$ $T_i = 70.0°\text{C}$, $T_f = ?$ $Q_{lost} = -(m_{\text{hot coffee}} \times c_{\text{water}} \times (T_f - T_i))$ $= -\left(\frac{200.0\,\text{g}}{1{,}000} \times 4{,}180 \times (T_f - 70.0)\right)$
Step 4: Identify the object(s) gaining heat and substitute the known values into the formula.	Cold spoon: $m = 20\,\text{g}$, $c = 500\,\text{J kg}^{-1}\text{K}^{-1}$ $T_i = 20.0°\text{C}$, $T_f = ?$ $Q_{gained} = m_{\text{cold spoon}} \times c_{\text{steel}} \times (T_f - T_i)$ $= \frac{20\,\text{g}}{1{,}000} \times 500 \times (T_f - 20.0)$

Think	Do
Step 5: Equate the terms and substitute known values.	$Q_{lost} = Q_{gained}$ $-\left(\frac{200.0\,g}{1{,}000} \times 4{,}180 \times (T_f - 70.0)\right) = \frac{20\,g}{1{,}000} \times 500 \times (T_f - 20.0)$ (1 mark)
Step 6: Simplify. Remember that two negatives give a positive.	$-(836T_f - 58{,}520) = 10T_f - 200$ $-836T_f + 58{,}520 = 10T_f - 200$ (1 mark)
Step 7: Collect terms and solve for the final answer.	$846T_f = 58{,}720$ $T_f = 69.4$ (1 mark)
Step 8: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the final temperature should be between the high and low initial temperatures.	69°C (2 s.f.) (1 mark)

Your turn

Students placed a 100.0 g brass mass into a beaker of boiling water at 100.0°C for 5 minutes. They removed it and quickly placed it in a prepared insulated cup containing 50.0 g water at 5.0°C. They measured the temperature and it peaked at 20.0°C, which was considered to be thermal equilibrium. **Determine** the experimental value for the specific heat capacity of brass (3 s.f.) and the absolute and percentage errors (2 s.f.). (6 marks)

Challenge

Adding volume, not temperature

A common mistake among lower primary students is to say that when two identical glasses of water, both at 40°C, are mixed, the final temperature will be 80°C. **Construct** an explanation suitable for a Year 3 student about why this is not true. In your explanation, refer to why you add the volumes together (1 cup + 1 cup = 2 cups), but you do not add the temperatures together. (3 marks)

How do we experimentally determine latent heat of fusion?

We've used the example of adding ice cubes to water to describe the transfer of thermal energy and temperature change. When ice is placed in water, many things happen: the ice has to warm up from its below-freezing temperature to its melting point, then it has to melt, and finally the icy water has to warm up to its final temperature somewhere above 0°C. At the same time, the room temperature water has to cool down as it transfers heat to the ice. So, there are four separate stages in this process and each one has its own formula and data. We will start with a simple example.

In calculations involving latent heat we need to be mindful of the sign (+/–) for the expression for latent heat (mL_f). When a substance such as ice gains heat and melts, the mL_f is a positive value as heat flows into the solid. It appears on the right-hand side of the equation under Q_{gained}, which is positive. If we are considering a case where a liquid freezes to form a solid, such as liquid water changing to ice, heat is lost from the water and the mL_f term under Q_{lost} on the left-hand side will be negative.

Worked example 3.3E

Calculating the temperature of ice melting in water

A 15 g ice cube at −10°C is placed in 250 g of tap water at 25°C in an insulated cup. Assuming there is no heat transfer with the environment, **determine** the equilibrium temperature (2 s.f.). (6 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both substances. We also expect a phase change, so the latent heat equation is required. The question is worth 6 marks, so we must gather the correct information, correctly apply the formulas and complete the calculation.
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{lost} = Q_{gained}$, $Q = mL_f$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Tap water: $m = 250\,g$, $c = 4{,}180\,J\,kg^{-1}\,K^{-1}$ $T_f = ?$, $T_i = 25°C$ $Q_{lost} = -(m_{water} \times c_{water} \times (T_f - T_i))$ $= -\left(\frac{250\,g}{1{,}000} \times 4{,}180 \times (T_f - 25)\right)$ $= -1{,}045T_f + 26{,}125$ (1 mark)
Step 4: Identify the object(s) gaining heat. Note that ice will undergo a phase change, so you will need to consider the three stages it goes through, and sum the energy.	Ice cube: $m = 15\,g$, $c_{ice} = 2{,}050\,J\,kg^{-1}\,K^{-1}$, $c_{water} = 4{,}180\,J\,kg^{-1}\,K^{-1}$ $T_f = ?$, $T_i = -10°C$, $L_{f(ice)} = 3.34 \times 10^5\,J\,kg^{-1}$ 1. The ice warms (–10°C to 0°C). 2. The ice melts (0°C). 3. The icy water warms (0°C to T_f).
Step 5: Expand the terms for stage 1 (–10°C to 0°C). Note that the specific heat capacity of ice is only $2{,}050\,J\,kg^{-1}\,K^{-1}$ and be very careful with the signs.	$Q_{gained} = m_{ice} \times c_{ice} \times (T_f - T_i)$ $= \frac{15\,g}{1{,}000} \times 2{,}050 \times (0 - -10)$ $= 307.5\,J$ (1 mark)
Step 6: Calculate the (latent) heat gained in stage 2. It will be positive, as the ice is gaining heat. There is no need to include a positive (+) symbol.	$Q_{gained} = m_{ice} L_{f(ice)}$ $= \frac{15\,g}{1{,}000} \times 3.34 \times 10^5$ $= 5{,}010\,J$ (1 mark)
Step 7: Expand the terms for stage 3 (0°C to T_f). Note that the specific heat capacity of water is $4{,}180\,J\,kg^{-1}\,K^{-1}$.	$Q_{gained} = m_{icy\ water} \times c_{icy\ water} \times (T_f - T_i)$ $= \frac{15\,g}{1{,}000} \times 4{,}180 \times (T_f - 0)$ $= 62.7T_f\,J$ (1 mark)
Step 8: Equate the terms and substitute the known values. The Q_{gained} is the sum of the energy values for stages 1 to 3.	$Q_{lost} = Q_{gained}$ $-1{,}045T_f + 26{,}125 = 307.5 + 5{,}010 + 62.7T_f$ (1 mark)
Step 9: Simplify, collect terms and solve for the answer.	$1{,}107.7T_f = 20{,}807.5$ $T_f = 18.78°C$
Step 10: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the final temperature should be between the high and low initial temperatures.	19°C (2 s.f.) (1 mark)

Your turn

An insulated cup contains 200 g of tap water at 30°C. A 25 g ice cube at −8°C is placed in the water and allowed to come to thermal equilibrium. Assuming there is no heat transfer with the environment, **determine** the equilibrium temperature (2 s.f.). (7 marks)

Worked example 3.3F

Determining the latent heat of fusion experimentally

A 25.0 g ice cube at exactly 0°C was placed into 250.0 g of water at 33.5°C in an insulated cup. After the contents reached thermal equilibrium, the temperature was measured to be 22.1°C.

a **Determine** the specific latent heat of fusion of ice (3 s.f.). (5 marks)

b **Calculate** the percentage error. (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. "Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the specific heat capacity formula to both substances. We also expect a phase change, so the latent heat equation is required. Part **a** is worth 5 marks, so we must gather the correct information, correctly apply the formulas, complete the calculations to find the experimental value. Part **b** is worth 1 mark, so we must compare this to the true value.
Step 2: Select the appropriate equations and gather any data required.	**a** $Q = mc\Delta T$, $Q_{lost} = Q_{gained}$, $Q = mL_f$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula.	Tap water: $m = 25.0\,g$, $c = 4{,}180\,J\,kg^{-1}\,K^{-1}$ $T_f = 22.1°C$, $T_i = 33.5°C$ $Q_{lost} = -(m_{water} \times c_{water} \times (T_f - T_i))$ $= -\left(\frac{25.0\,g}{1{,}000} \times 4{,}180 \times (22.1 - 33.5)\right)$ $= 11{,}913\,J$ (1 mark)
Step 4: Identify the object(s) gaining heat. Note that ice will undergo a phase change. The ice is already at 0°C so you will need to consider the two stages it goes through, and sum the energy.	Ice cube: $m = 25.0\,g$, $c_{water} = 4{,}180\,J\,kg^{-1}\,K^{-1}$ $T_f = 22.1°C$, $T_i = 0°C$, $L_{f(ice)} = ?$ 1. The ice melts (0°C). 2. The icy water warms (0°C to 22.1°C).
Step 5: Calculate the (latent) heat gained in step 1. It will be a positive value as the ice is gaining heat.	$Q_{gained} = m_{ice} L_{f(ice)}$ $= \frac{25.0\,g}{1{,}000} \times L_f$ $= 0.025 L_f\,J$ (1 mark)
Step 6: Expand the terms for stage 2 (0°C to 22.1°C). Note that the specific heat capacity of water is $4{,}180\,J\,kg^{-1}\,K^{-1}$.	$Q_{gained} = m_{icy\ water} \times c_{icy\ water} \times (T_f - T_i)$ $= \frac{25.0\,g}{1{,}000} \times 4{,}180 \times (22.1 - 0)$ $= 2{,}309.45\,J$ (1 mark)
Step 7: Equate the terms and substitute the known values. The Q_{gained} is the sum of the energy values for stages 1 and 2.	$Q_{lost} = Q_{gained}$ $11{,}913 = 0.025L_f + 2{,}309.45$
Step 8: Simplify and solve for the answer.	$0.025L_f = 9{,}603.55$ $L_f = 384{,}142\,J\,kg^{-1}$ (1 mark)

Think	Do
Step 9: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the value should be somewhat close to $3.34 \times 10^5\,\text{J kg}^{-1}$.	$L_f = 384{,}000$ or $3.84 \times 10^5\,\text{J kg}^{-1}$ (3 s.f.) (1 mark)
Step 10: Calculate percentage error. Use the unrounded answer in your calculations.	**b** $\%E = \frac{E_a}{x_A} \times 100$ $= \frac{384{,}142 - 334{,}000}{334{,}000} \times 100$ $= 15.0\%$ (3 s.f.) (1 mark)

Your turn

Students were conducting an experiment to find the latent heat of fusion of ice. They took 30.0 g of ice at exactly 0°C and placed it into 250.0 g of water at 34.0°C in an insulated cup. After the contents reached thermal equilibrium, the temperature was measured to be 21.5°C.

a **Determine** the specific latent heat of fusion of ice (3 s.f.). (7 marks)

b **Calculate** the percentage error (2 s.f.). (1 mark)

How do we experimentally determine latent heat of vaporisation?

We can now take the same approach to latent heats of vaporisation. Instead of the phase change being melting, we will now consider water forming steam, or steam condensing to liquid water.

A great example of this in real-life is a barista making a cappuccino. Steam is bubbled into about 300 g of cold milk at 10°C. After about 40 seconds, the milk rises to a nice smooth and shiny foam. The final temperature of the milk is generally kept below 70°C, typically around 60 to 65°C. About 40 g of steam condenses into the milk during the process.

FIGURE 5 A steam wand is placed into the milk to heat it.

Worked example 3.3G

Calculating the temperature of condensed steam in milk

Steam at 125°C is bubbled into 418 g of milk at 7.0°C. After a good froth has been achieved, the milk mixture is re-weighed and is now 459 g. **Determine** the final temperature of the frothy milk (2 s.f.). Note: the specific heat capacity values: $c_{steam} = 2{,}000\,\text{J kg}^{-1}\,\text{K}^{-1}$, $c_{water} = 4{,}180\,\text{J kg}^{-1}\,\text{K}^{-1}$, $c_{milk} = 3{,}930\,\text{J kg}^{-1}\,\text{K}^{-1}$. (6 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the specific heat capacity formula to both substances. We also expect a phase change, so the latent heat equation is required. The question is worth 6 marks, so we must gather the correct information, correctly apply the formulas and complete the calculation.

Think	Do
Step 2: Select the appropriate equations and gather any data required.	$Q = mc\Delta T$, $Q_{lost} = Q_{gained}$, $Q = mL_v$
Step 3: Identify the object(s) losing heat and substitute the known values into the formula. Note that steam will undergo a phase change, so you will need to consider the three stages it goes through, and sum the energy.	Steam: $m = 459 - 418 = 41\,g$, $c = 2{,}000\,J\,kg^{-1}\,K^{-1}$ $T_f = ?$, $T_i = 125°C$, $L_{v(water)} = 2.26 \times 10^6\,J\,kg^{-1}$ 1. The steam cools (125°C to 100°C). 2. The steam condenses (100°C). 3. The condensed steam cools (100°C t o T_f).
Step 4: Expand the terms for stage 1 (125°C to 100°C).	$Q_{lost} = -(m_{steam} \times c_{steam} \times (T_f - T_i))$ $= -\left(\frac{41\,g}{1{,}000} \times 2{,}000 \times (100 - 125)\right)$ $= 2{,}050\,J$ (1 mark)
Step 5: Calculate the latent lost by steam in stage 2 (100°C). As heat is lost by the steam when it condenses, the value is negative (–).	$Q_{lost} = m_{steam}L_{v(steam)}$ $= \frac{41\,g}{1{,}000} \times 2.26 \times 10^6$ $= 92{,}660\,J$ (1 mark)
Step 6: Expand the terms for stage 3 (100°C to T_f). The specific heat capacity of the condensed steam is $4{,}180\,J\,kg^{-1}\,K^{-1}$.	$Q_{lost} = -(m_{steam} \times c_{water} \times (T_f - T_i))$ $= -\left(\frac{41\,g}{1{,}000} \times 4{,}180 \times (T_f - 100)\right)$ $= -171.38T_f + 17{,}138$ (1 mark)
Step 6: Identify the object(s) gaining heat and substitute the known values into the formula.	Milk: $m = 418\,g$, $c_{milk} = 3{,}930\,J\,kg^{-1}\,K^{-1}$ $T_f = ?$, $T_i = 7.0°C$ $Q_{gained} = m_{milk} \times c_{milk} \times (T_f - T_i)$ $= \frac{418\,g}{1{,}000} \times 3{,}930 \times (T_f - 7.0)$ $=1{,}642.74T_f - 11{,}499.18$ (1 mark)
Step 7: Equate the terms and substitute the known values. The overall $-Q_{lost}$ value is the negative of the sum of the Q_{lost} values for stages 1 to 3.	$Q_{lost} = Q_{gained}$ $2{,}050 + 92{,}660 - 171.38T_f + 17{,}138 = 1{,}642.74T_f - 11{,}499.18$ (1 mark)
Step 8: Simplify, collect terms and solve for the answer.	$1{,}814.12T_f = 123{,}347.18$ $T_f = 67.99°C$
Step 9: Finalise your answer and make sure you have included the correct units and significant figures. It is good practice to sense-check your answer; in this case, the final temperature should be between the high and low initial temperatures.	68°C (2 s.f.) (1 mark)

Your turn

Steam at 130°C is bubbled through 340 g of cold milk at 12°C. When the final mass was measured, it was found to be 368.7 g. **Determine** the equilibrium temperature of the milk mixture (2 s.f.). Note: $c_{milk} = 3{,}930\,J\,kg^{-1}\,K^{-1}$. (8 marks)

Check your learning 3.3

Check your learning 3.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** what happens to the kinetic energy of the particles when two substances at different temperatures come into contact. (2 marks)

Analytical processes

2 100 g of gold at 20.0°C is placed into 200 g of water at 80.0°C.

a **Determine** the specific heat capacity of gold (3 s.f.) if the final temperature is 79.0°C. (4 marks)

b **Determine** the absolute error and percentage error in the experimental value, given the accepted value is 129.0 J kg^{-1} K^{-1}. (3 marks)

3 When a 350 g sample of lead (c_{Pb} = 130 J kg^{-1} K^{-1}) is placed into 100 g of water that is at 30°C, this results in an equilibrium temperature of 15°C. **Determine** the initial temperature of the lead (2 s.f.). (3 marks)

4 250 g of water at 80°C is mixed with 1,000 g of aluminium at 20°C and 500 g of zinc (c_{Zn} = 388 J kg^{-1} K^{-1}), also at 20°C. **Determine** the equilibrium temperature of the mixture (2 s.f.). (3 marks)

5 A 25.0 g piece of ice at 0°C was placed into a foam cup of negligible heat content containing 350.0 mL of water at 18.0°C. The final (equilibrium) temperature was 12.0°C. **Determine** the latent heat of the ice. (3 marks)

6 In an experiment to determine the specific heat capacity of acetone, 100.0 g of water was placed in a copper container (c_{Cu} = 390 J kg^{-1} °C^{-1}) of mass 150.0 g and the temperature was measured to be 40.0°C. Acetone liquid of mass 145.0 g and a temperature 15.0°C was added to the water, and the lid was placed on. A final temperature of 30.0°C was found at equilibrium.

a **Determine** the specific heat capacity of acetone (3 s.f.). (3 marks)

b **Determine** the percentage error, given the accepted value is 2,150 J kg^{-1} K^{-1}. (4 marks)

7 An insulated copper cup of mass 725 g is cooled to a temperature of –196°C. 100.0 g of water at 21.0°C is added to the cup. All of the water freezes to ice and the copper and ice are allowed to reach thermal equilibrium. **Determine** the final temperature, assuming no heat is exchanged with the environment. Hint: the latent heat is on the loss side of the equation. (7 marks)

Knowledge utilisation

8 In an experiment to measure the latent heat of fusion of ice, a 31.0 g piece of ice at 0°C was placed into a foam cup of negligible heat content containing 300.0 mL of water at 28.6°C. The final (equilibrium) temperature was 18.4°C.

a **Determine** the latent heat of the ice and the percentage error. (7 marks)

b **Discuss** whether the final temperature will be different if crushed ice was used. (2 marks)

c **Predict** whether the system will come to the final temperature any quicker if crushed ice was used. (2 marks)

9 A class of Year 11 students (in five groups) conducted a latent heat investigation (similar to Worked example 3.3F). The table shows their results.

Group	m_{ice}	m_{water}	$T_{i\,(water)}$	T_f	L_f	Error (%)
1	19.61	114.16	59.5	39.0	337,433	1.0
2	18.28	94.26	43.0	24.0	310,658	7.0
3	13.96	103.10	58.0	41.0	355,117	6.3
4	21.18	112.44	55.5	35.5		
5	21.23	94.53	52.0	29.0		

a Using the data in the table, **determine** the specific latent heat of fusion found by Groups 4 and 5, and their percentage error. (4 marks)

b **Evaluate** whether the errors for the L_f results are all in one direction; i.e. are they all over or all under the accepted value? (2 marks)

Practical

Lesson 3.4
Specific heat capacity of a metal – by calorimetry

Learning intentions and success criteria

Video demonstration

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Practical

Lesson 3.5
Mixture of two liquids – calorimetry

Learning intentions and success criteria

Video demonstration

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Lesson 3.6
Heat and mechanical work

Key ideas

→ Heat has the capacity to do mechanical work and mechanical work has the capacity to generate heat.

Learning intentions and success criteria

Are heat and mechanical work the same thing?

If you shake a bottle of water lots of times, it gets warmer. Pass it around the class and if everyone shakes it 100 times it gets a degree hotter … if you're lucky! Hammering a nail into wood makes the nail get hot. Heat up a balloon and work is done on the rubber to stretch it. But what is going on here, especially at the particle level? It seems that work done on objects can turn into heat, and vice versa. We know that we can transfer energy to an object by heating it up, and now we see that we can also heat an object by doing mechanical work on it. This is very much the same as firestick developed by Aboriginal and Torres Strait Islander peoples. The mechanical work done by rotating a stick on a piece of wood creates enough heat to raise the temperature to 350°C for the wood to catch on fire.

What did James Prescott Joule find?

Up until the mid-1800s, mechanical work and heat were thought to be separate ideas. However, people were able to harness the energy of heat and turn it into useful work, even if they didn't understand the connection. These ideas were eventually brought together in 1843 by James Prescott Joule. He performed an experiment in which falling lead weights turned paddles in water in a large container (Figure 2). As the paddlewheels were turned by the falling masses, this increased the average kinetic energy of the water particles in the container. Thus, there was a resultant temperature increase. Joule said that mechanical energy had been converted into heat.

Joule also recognised that he could have increased the temperature of the water by heating it with a flame and the result would have been the same. This led him to the idea that heat and mechanical work are essentially equivalent.

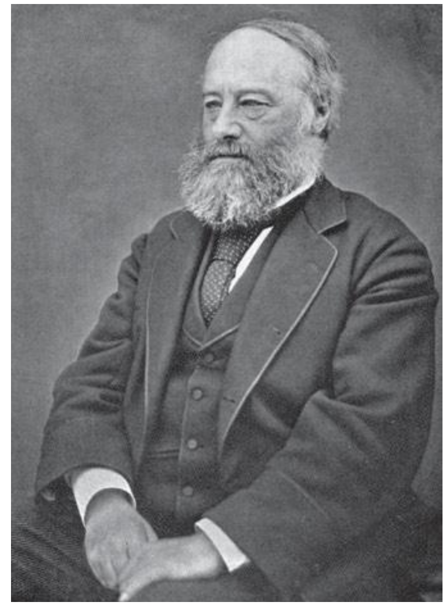


FIGURE 1 James Prescott Joule, an English physicist and mathematician, concluded that mechanical energy can be converted into thermal energy.

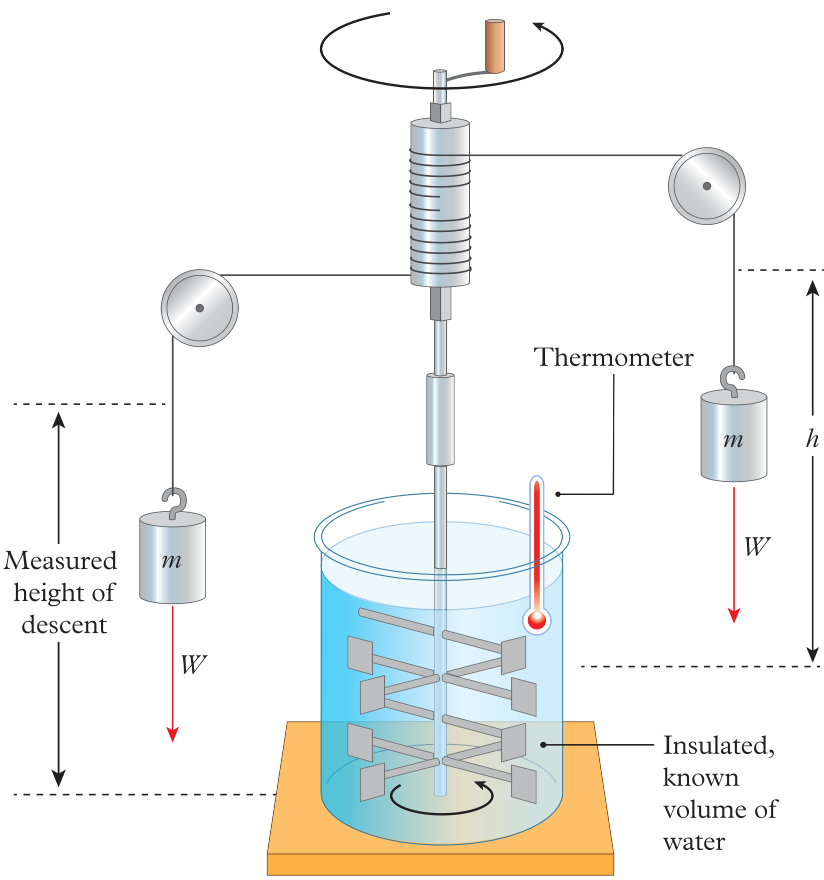


FIGURE 2 A schematic diagram of Joule's apparatus

In the same way, thermal energy can be converted into mechanical energy and do mechanical work. For example, when a car engine burns fuel, the heat generated from the reaction is transferred to a gas (the vapour inside the engine). This expansion of the gas then exerts a force on the pistons to make them move. This movement is relayed to the car's wheels so that the car can travel along the road. From this we can say that a system with thermal energy has the capacity to do mechanical work.

FIGURE 3 A car engine transfers thermal energy to the gas, which expands and exerts force on the pistons, causing them to move.

What did Michael Faraday find?

In 1859, Michael Faraday investigated whether an object dropped from a great height would warm up as it hit the ground. He reasoned that there might be some conversion of energy to heat. He dropped a bag of lead shot (like the lead sinkers used in fishing) but was unable to detect any temperature rise. He tried to publish his "null" results and said that perhaps a height of 36 foot (12 metres) was not enough. Mathematics professor George Stokes convinced Faraday not to publish his report because Stokes believed the theory was wrong. But despite the null result, Faraday's theory wasn't wrong; mechanical energy can be converted into heat. It wasn't the theory that failed Faraday; it was his experiment that wasn't refined enough to detect all of the inputs and outputs of energy to the lead shot "system". Joule, however, saw the limitations of Faraday's work and with meticulous planning was able to show what Faraday couldn't: that mechanical work from a force (gravity) applied over a distance (the fall height) can be converted into thermal energy, and vice-versa – that a system with thermal energy can do work. We can therefore define **mechanical work** as the transfer of energy to or from an object by the action of a force over a distance; it is the capacity of a system with thermal energy.

mechanical work
the transfer of energy to or from an object by the action of a force over a distance; the capacity of a system with thermal energy

Check your learning 3.6

Check your learning 3.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** how Joule was able to claim that heat and work had the same effect on objects, namely an increase in temperature. (3 marks)

Analytical processes

2 Scientists carried out an experiment in which they let a sample of lead shot fall from a large height and crash to a stop on impact. The gravitational potential energy of the lead shot (at the top) was transformed to kinetic energy (at the bottom) and then thermal energy (on impact).

a **Determine** the change in gravitational potential of the lead shot (E_p) from release to reaching the ground, and the change in thermal energy in the lead (Q) after impact. Data: mass of lead, $m = 500.0\,\text{g}$; fall height, $h = 200.0\,\text{m}$; temperature change, $\Delta T = 22.9°\text{C}$ to $26.0°\text{C}$; specific heat capacity of lead $130\,\text{J kg}^{-1}\,\text{K}^{-1}$; $g = 9.8\,\text{m s}^{-2}$. (4 marks)

b **Determine** the change in thermal energy in the lead to gravitational potential energy of the lead, as a percentage. (2 marks)

Knowledge utilisation

3 Joule tried to make the friction between the string and the pulleys as small as possible. **Explain** how reducing friction would have affected his result. (2 marks)

4 Joule used an insulated bucket for his experiment, but there were still heat losses to the atmosphere. **Propose** whether the heat losses would make his experimental value for Q higher or lower than the true value. **Justify** your response. (2 marks)

5 Joule knew there was friction in the pulley wheel. **Propose** whether the energy losses due to friction would make his experimental value for the mechanical work done on the system higher or lower than the true value. (2 marks)

Lesson 3.7
Conservation of energy

Key ideas

→ The temperature of a system can be raised by the addition of heat energy or by doing mechanical work on the system.

→ The first law of thermodynamics states that the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings.

What is the first law of thermodynamics?

Learning intentions and success criteria

Imagine you are pumping up the tyres on a bicycle or a ball. Your arm muscles provide a force to do mechanical work to compress the gas and the gas inside the pump heats up. If you leave the same pump full of gas lying in sunlight, the gas inside it also gets hot. Heat energy from the Sun is transferred into the gas and heats it up. So, you can heat up the air in the pump in two ways: by doing mechanical work on it (compressing it) and by adding heat (leaving it in the Sun). Does that mean heat and mechanical work are interchangeable? If both cause changes in temperature (internal energy) of the gas in the pump, can one form of energy be transformed into the other?

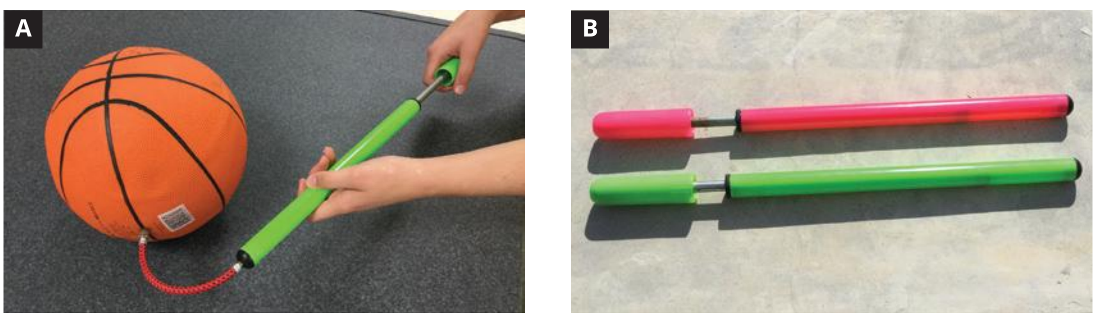


FIGURE 1 (A) Pumping up a ball makes the pump hot. (B) The pump also gets hot if it is left in the Sun.

We can use maths to represent the relationship between heat, mechanical work and internal energy. The bike pump is the "system". We know that the internal energy of the gas in the system has increased because it is hotter; this could have come from heat added from a high temperature source (the Sun), or by mechanical work done by your muscles on the system. In either case, it results in higher internal energy of the gas inside the pump.

To the initial amount of internal energy in the system, U_i, we can add the net amount of heat, Q, and the net amount of mechanical work, W, which gives us the final internal energy, U_f. This can be stated as: $U_i + Q + W = U_f$. This equation can be rearranged to: $U_f - U_i = Q + W$, or, by letting $U_f - U_i = \Delta U$, we can arrive at the formula:

$$\Delta U = Q + W$$

The change in internal energy of a system is therefore equal to the energy added or removed by heating plus the mechanical work done on or by the system. This is an interpretation of the **first law of thermodynamics**. This law states that the total energy of a system remains constant; energy can neither be created nor destroyed. Rather, it transforms from one form to another. The first law of thermodynamics is a consequence of the law of conservation of energy.

first law of thermodynamics
a law that states that during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings; $\Delta U = Q + W$

Study tip

The syllabus requires you to **explain** the first law of thermodynamics and recognise it as a consequence of the law of conservation of energy. This means that, to **define** the two terms, **describe** how they are related, and **elaborate** on what this means in the context of energy transfer processes.

How do we use the thermodynamic energy model to represent energy transfer and transformation?

As discussed in Lesson 3.6, James Joule increased the temperature of water using falling weights to turn a paddlewheel submerged in water. There are four energy transfers and transformations that cause the internal energy of the water to increase:

1 As the weights dropped towards the floor, they gave up some of their gravitational potential energy and did mechanical work on the system (the water). We call that "work in" or W_{in}.
2 The system also needed to do mechanical work to overcome frictional forces – this is "work out", W_{out}. The net energy, W, was transformed into thermal energy of the water.
3 There was no external heating of the water, so "heat in", Q_{in}, was zero.
4 However, there was some loss of heat to the environment. That is the "heat out", Q_{out}.

The diagram in Figure 2 is called the thermodynamic energy model as it shows the two inputs (heat in, and work done on the system) and the two outputs (heat out, and work done by the system).

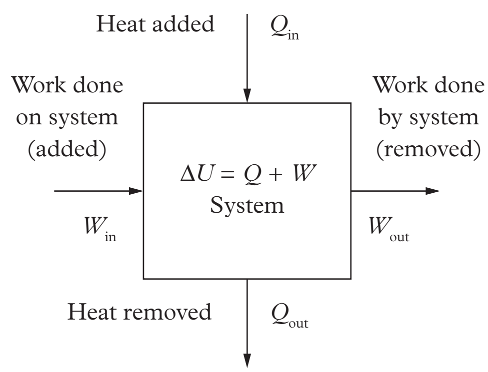


FIGURE 2 Thermodynamic energy model

Conventions

In the thermodynamic energy model:

- Q_{in}, Q_{out}, W_{in}, W_{out} are all positive and the in/out arrows show direction.
- Q_{net} (or Q) = $Q_{in} - Q_{out}$
- W_{net} (or W) = $W_{in} - W_{out}$

It is good practice to include the sign in front of Q and W (+/–). This can help us draw conclusions about what is happening to net heat and net mechanical work. This is summarised in Table 1.

TABLE 1 Summary of Q and W

Sign	Q	W
+	Net heat is in.	Net mechanical work is done on the system.
–	Net heat is out.	Net mechanical work is done by the system.

Worked example 3.7A

Calculating the change in internal energy

Calculate the missing values in Table 2 (all values are in kJ). (1 mark)

TABLE 2 How does the internal energy of the system change?

Q_{in}	Q_{out}	Q	W_{in}	W_{out}	W	ΔU
100	30		10	15		

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the formula for the first law of thermodynamics. The question is worth 1 mark, so we correctly apply the formula and complete the calculations.
Step 2: Select the appropriate equations and gather any data required.	$\Delta U = Q + W$ $Q = Q_{in} - Q_{out}$, $W = W_{in} - W_{out}$ $Q_{in} = 100\,\text{kJ}$, $Q_{out} = 30\,\text{kJ}$ $W_{in} = 10\,\text{kJ}$, $W_{out} = 15\,\text{kJ}$ $Q = ?$, $W = ?$, $\Delta U = ?$
Step 3: Substitute the known values to determine Q. It is good practice to include the sign so that you know very clearly whether there is a net increase or decrease in energy.	$Q = 100 - 30$ $= +70\,\text{kJ}$
Step 4: Substitute the known values to determine W. As above, indicate the sign.	$W = 10 - 15$ $= -5\,\text{kJ}$
Step 5: Substitute the known values to determine ΔU. Indicate the sign here, too.	$\Delta U = +70 + (-5)$ $= +65\,\text{kJ}$ (1 mark)

Your turn

Calculate the missing values in Table 3 (all values are in kJ). (4 marks)

TABLE 3 How does the internal energy of the system change?

	Q_{in}	Q_{out}	Q	W_{in}	W_{out}	W	ΔU
a	120	60		5	40		
b	200	100		0	50		
c	0	500		2,000	0		
d	450		100	400	250		

How do we use the first law of thermodynamics to solve problems?

A practical example of a thermodynamic process is one similar to the paddlewheel described earlier. It shows the conversion of mechanical energy (work) into internal energy. Let's have a look at this in Worked example 3.7B.

Worked example 3.7B

Calculating the heat generated by mechanical work

An insulated cup is filled with hot water and allowed to cool while being stirred by a paddlewheel. No heat is added to the system, but in cooling it loses 150 kJ of heat. The paddlewheel does 250 kJ of work (in) on the water and no work is done (out) by the system. **Calculate** the change in internal energy of the water and **describe** the result. (2 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. "Describe" means to give account of the characteristics or features of something. We need to apply the formula for the first law of thermodynamics, worth 1 mark. Then, we need to state what this means, worth another 1 mark.
Step 2: Select the appropriate equations and gather any data required.	$\Delta U = Q + W$ $Q = Q_{in} - Q_{out}$, $W = W_{in} - W_{out}$ $Q_{in} = 0\,kJ$, $Q_{out} = 150\,kJ$ $W_{in} = 250\,kJ$, $W_{out} = 0\,kJ$
Step 3: Substitute the known values to determine Q. It is good practice to include the sign so that you know very clearly whether there is a net increase or decrease in energy.	$Q = 0 - 150$ $= -150\,kJ$
Step 4: Substitute the known values to determine W. As above, indicate the sign.	$W = 250 - 0$ $= +250\,kJ$
Step 5: Substitute the known values to determine ΔU. Indicate the sign here, too.	$\Delta U = -150 + 250$ $= +100\,kJ$ (1 mark)
Step 6: State the meaning of the result.	A positive value for ΔU means the system has gained internal energy in the process. It would have a higher temperature than at the start. (1 mark)

Your turn

An electric stirrer does a net amount of 80 kJ of mechanical work on a liquid (the system) in the lab. At the same time, the liquid is warmed by the addition of 100 kJ of heat. **Calculate** the change in internal energy and **describe** the result. (2 marks)

Check your learning 3.7

Check your learning 3.7: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** the first law of thermodynamics, using an example. (2 marks)

2 **Describe** the difference between "work done on a system" and "work done by a system". (2 marks)

3 **Explain** whether 100 J of thermal energy could be converted to 100 J of mechanical work. (2 marks)

4 **Calculate** the amount of heat transferred from a system if its internal energy decreased by 220 J while it was doing 100 J of mechanical work. (1 mark)

5 **Calculate** the change in the internal energy of a system that does 1.20 MJ of work (out) while 4.8 MJ of heat is lost to the environment (out). Assume no other changes take place. Note that mega (M) = 10^6. (1 mark)

Analytical processes

6 **Contrast**, using examples, energy transfer and energy transformation in a mechanical system. (2 marks)

7 **Determine** the missing values in the table (all values are in kJ). (6 marks)

	Q_{in}	Q_{out}	Q	W_{in}	W_{out}	W	ΔU
a	100	80		50	30		
b		60	20	80	50		
c		0	150		40	–40	
d	0	20			500	1,500	1,480
e	200		200	0	40		
f		20		0		–10	70

8 **Deduce** how much heat transfer occurs from a system if its internal energy decreased by 350 J while it was doing 50 J of mechanical work. (1 mark)

Lesson 3.8
Heat engines and efficiency

Learning intentions and success criteria

Key ideas

→ Energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so the amount of useable energy is reduced.

→ Efficiency is a measure of the useful work done by a thermal system.

heat engine
a device that receives heat from a high temperature source and converts part of this heat into work, transferring the remaining waste heat to a low temperature "sink"; it works by heating a fluid that turns a rotor or other moving element

What is a heat engine?

While it is fairly easy to produce thermal energy from mechanical work, it is much more difficult to do the reverse – to get usable energy from heat. You may have seen a toy called the Drinking Bird (Figure 1). It is a hollow glass device with a small amount of a low boiling point organic liquid (usually dichloromethane) in the bulb at the lower end. As the warmth of the room causes the liquid to evaporate, it rises up the neck of the Drinking Bird and makes its head heavy. This causes it to tilt over and dip its felt-covered face in the water. The water evaporates into the air in the room and cools the liquid inside the bird. As the liquid cools, it moves back to the bulb and the process cycles over and over again.

What makes the Drinking Bird interesting for our work in physics is that it is an example of a **heat engine**. A heat engine receives heat from a high temperature source and converts part of this heat into mechanical work. The Drinking Bird uses the heat from the environment to produce a small amount of useable, mechanical work (dunking up and down).

FIGURE 1 The Drinking Bird is a device that turns heat into mechanical work. Albert Einstein was fascinated by a toy Drinking Bird he saw when he visited Shanghai, China, in 1922. He puzzled over how it worked.

Study tip

If you see the phrase "heating a fluid that turns a rotor or other moving element", this indicates it is a scenario involving a heat engine.

The remaining waste heat is transferred to a low temperature "sink" – in the case of the Drinking Bird, it is the organic liquid inside the bulb. The waste heat is said to be "rejected" into a low temperature sink – usually the environment. In general, we can say that if a system has thermal energy, then mechanical work can be extracted, provided a lower temperature cold reservoir (heat sink) is available. Heat engines are said to be "open" systems (not "closed") as the waste heat is discharged to the environment (the "heat sink") and does not stay within the system. The main principle is that the engine heats a fluid that turns a rotor or other moving element.

How do we use energy transfer diagrams?

energy transfer diagram
a diagram that summarises all the energy transfers taking place in a process: the thicker the line or arrow, the greater the amount of energy involved

Figure 2 is an **energy transfer diagram** for a heat engine such as the Drinking Bird. The hot (H) reservoir is the warm room at temperature T_H (about 25°C), and the cold (C) reservoir is the cooled liquid inside the bird's head at a temperature T_C (usually several degrees below T_H). The engine is the bird itself. The mechanical work done by the system is the kinetic energy of movement as it bobs up and down. Note that the symbols used earlier for heat in and heat out (Q_{in} and Q_{out}) have been replaced by Q_H (hot) and Q_C (cold), respectively, referring to the reservoirs.

Study tip

Q_{in} / Q_H mean the same thing and have the same sign conventions. The same is true of Q_{out} and Q_C. It is common in university texts to use Q_H and Q_C when discussing heat.

Study tip

A heat engine runs at a constant temperature, so the change in internal energy $\Delta U = 0$. Also, Q_{net} is represented by just Q and equals $Q_H - Q_C$.

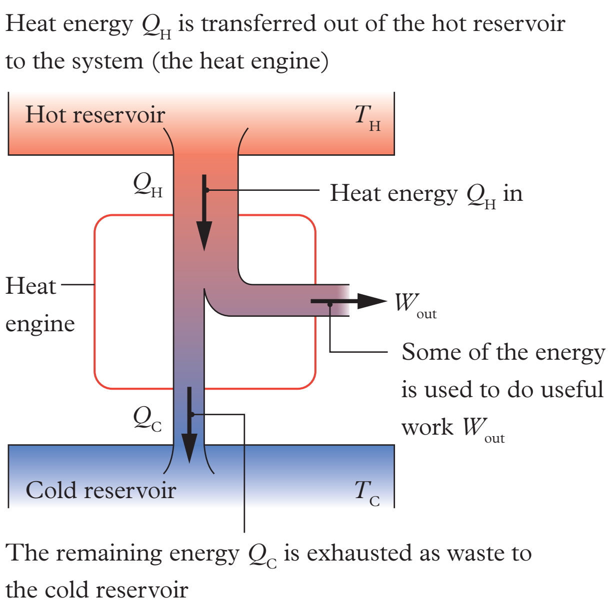


FIGURE 2 Energy transfer diagram for a heat engine such as the Drinking Bird

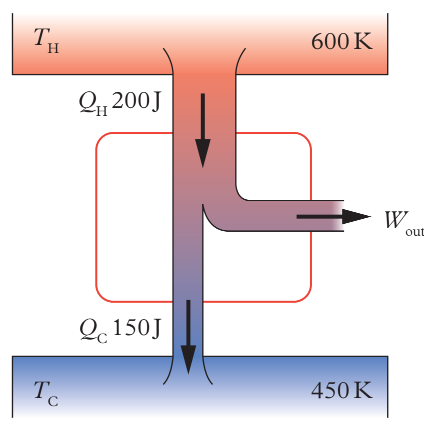


FIGURE 3 An energy transfer diagram that shows specific energy values (energy per unit of mass)

Figure 3 is another energy transfer diagram for a heat engine. It shows a hot reservoir at the top (in red), which could be a fire from a fuel such as coal, oil or wood. The heat coming out of the hot reservoir, Q_H, is added to the heat engine "system" (the red box). Some of this is transformed into useful mechanical work that leaves the system, W_{out}. As the system uses this energy to do work on something else (such as moving a piston), we say mechanical work is done "by" the system. At the bottom of Figure 3, we can see the energy that goes into the cold reservoir, Q_C, as waste.

In all of these heat engines, we assume they have reached a stable temperature and thus there is no change in internal energy ($\Delta U = 0$). We can modify our formula by letting $\Delta U = 0$ to give:

$$\Delta U = Q + W$$
$$0 = Q + W$$
$$W = -Q$$

In other words, the work out equals the net heat lost.

The heat coming out of the hot reservoir, Q_H, into the system (red box) is 200J. The work done by the system is labelled W_{out}. The energy that goes out of the system into the cold reservoir, Q_C, is 150J of waste heat. This means 50J was sent out of the system as useful mechanical work.

Calculating mechanical work output, W_{out}, using the data and formula is straightforward:

$$Q_{in} = +200\text{J},\ Q_{out} = +150\text{ J}$$

$$\begin{aligned} Q \text{ (or } Q_{net}) &= Q_H - Q_C \\ &= 200 - 150 \\ &= +50\text{J} \end{aligned}$$

Q is positive, so there is a net gain of heat into the system.

$$\begin{aligned} W &= -Q \\ &= -50\text{J} \end{aligned}$$

W is negative, so work was done by the system, or net work is "out".

For a heat engine, there is no change in temperature and thus no change to internal energy, so ΔU should equal zero (which it does):

$$\begin{aligned} \Delta U &= Q + W \\ &= +50 + -50 \\ &= 0\text{J} \end{aligned}$$

How can we determine the efficiency of a heat engine?

Being efficient is usually regarded as a good thing; it means your energy is not being wasted. The same is true about the efficiency of heat engines. In Figure 3, not all the heat extracted from the hot reservoir (200J) was transformed into work. Only 50J was transformed, and the other 150 J was wasted. In other words, 50J of the 200J that came in was transformed into useful work. This 50J represents 25% of the heat extracted. This 25% is called the heat engine's **efficiency**. It has the symbol η (lower case Greek eta). Every time an energy transfer occurs, there is a loss and thus efficiency is not 100%. One of the implications of this energy loss is that useable energy is reduced with each transfer.

Earlier, we looked at energy transfer diagrams to show the input and output of energy into a mechanical system. They are sometimes called "thermal efficiency diagrams" as they show graphically where non-useful (waste) energy transfers or transformations have taken place. In the case of these diagrams, "transfer" is used conveniently to include transformation. The greater this non-useful transfer of energy, the less efficient is the heat engine. Figure 4 shows the three main components of energy transfer: in, out and waste.

efficiency
the ratio of useful work produced by a machine or in a process compared to total energy expended or heat taken in; often expressed as a percentage (symbol: η)

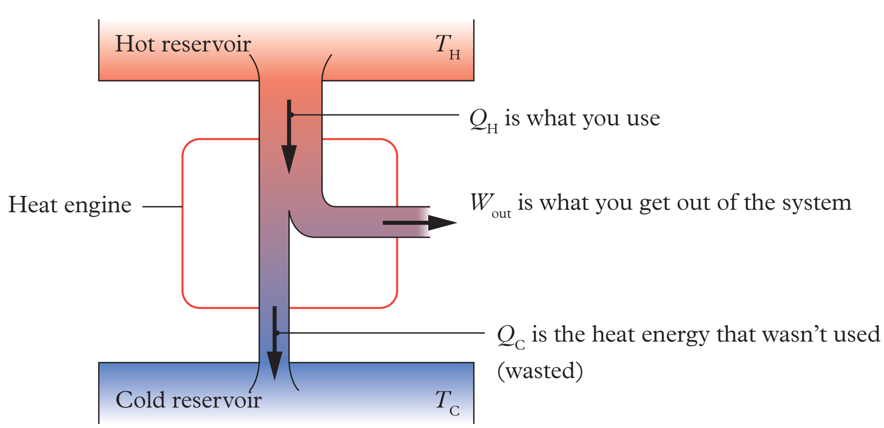


FIGURE 4 The various components of heat in a thermal transfer (energy efficiency) diagram

Thermal efficiency can be determined using the formula:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times 100$$

Let's apply this to the Drinking Bird toy. The heat that flows out of the hot reservoir in the bird is 4.5×10^3 J, and 1.05 J of mechanical work is done. We can calculate the thermal efficiency for the Drinking Bird:

$$\begin{aligned}\eta &= \frac{\text{energy output}}{\text{energy input}} \times 100 \\ &= \frac{1.05}{4.5 \times 10^3} \times 100 \\ &= 0.02\%\end{aligned}$$

The Drinking Bird has very poor thermal efficiency. Compare this with a car engine, which has an efficiency of about 20%.

Worked example 3.8A

Calculating the efficiency of a heat engine

Figure 5 shows the thermal transfers for a heat engine.

a **Calculate** the amount of work out of the system. (2 marks)

b **Calculate** the thermal efficiency (2 s.f.). (1 mark)

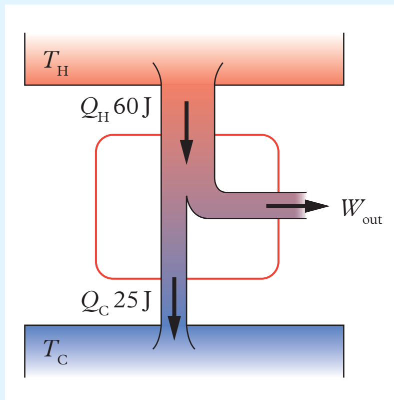


FIGURE 5 A thermal transfer diagram for a heat engine

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. Part **a** is worth 2 marks and part **b** is worth 1 mark so we need to apply heat engine and efficiency equations and complete the calculations.
Step 2: Select the appropriate equations and gather any data required.	$W = -Q$, $Q = Q_H - Q_C$ $\eta = \frac{\text{energy output}}{\text{energy input}} \times 100$ $Q_H = 60\text{J}$, $Q_C = 25\text{J}$
Step 3: Substitute the known values to determine Q, and then W. Make sure the sign is correct (a negative W indicates work "out").	**a** $Q = 60 - 25$ $= +35\text{J}$ (1 mark) $W = -Q$ $= -(+35)$ $= -35\text{J}$ (1 mark) The value of W is negative, so the work is "out"; that is, the work is done by the system. The sign is correct.
Step 4: Substitute the known values to determine efficiency. Check to make sure you have rounded to the correct number of significant figures.	**b** $\eta = \frac{35}{60} \times 100$ $= 58\%$ (2 s.f.) (1 mark)

Your turn

A hot reservoir delivers 200 J to a heat engine system and generates 50 J of work output.

a **Calculate** the heat entering the cold reservoir. (1 mark)

b **Calculate** the efficiency of the process (2 s.f.). (1 mark)

What have we learnt about heat engines?

Heat engines:

- convert heat into usable mechanical work
- require a high temperature source and a low temperature sink
- take in heat, convert some to mechanical work, and dump the rest to a cold sink
- have a constant operating temperature, so $\Delta U = 0$
- are "open" systems, so waste products (such as heat) are lost to the environment
- always lose heat to the environment, so are always less than 100% efficient
- are an example of the first law of thermodynamics.

What are some examples of heat engines?

There are lots of examples of heat engines being used in industry and daily life. They all work on the principle of heating a fluid that turns a rotor or other moving element. Here are two examples to show you what it means.

Real-world physics

Steam engines – heat engines with external combustion

The steam engine is an example of a heat engine that powered the Industrial Revolution. Burning coal or wood in a steam engine turns water into steam, providing the source of thermal energy (T_H). All that is needed is a cold reservoir (T_C, the heat sink).

The high-pressure steam pushes a piston back and forth. In doing so, it gives up some of its thermal energy as useful work (W_{out}). The remainder of the thermal energy (Q_C) is passed on to the cold reservoir (the environment – in this case, the atmosphere – as waste heat). Useful work is produced, but there is always a lot of wasted energy in the form of heat pollution. A steam engine's efficiency (η) is about 8%, which is very low.

Steam has been phased out. However, the need to increase the efficiency of early steam engines led to further technological advancements such as the internal combustion engine. Today, electric and diesel motors are more common for railway engines.

FIGURE 6 A steam train uses the thermal energy produced by the combustion of coal to produce useful work. A steam engine is a good demonstration of the heat engine principles.

Apply your understanding

1. **Explain** how a steam engine heats a fluid that turns a rotor or other moving element. In your answer, **identify** the hot reservoir, the fluid, and the moving element. (3 marks)
2. **Explain** why the steam engine needs an external hot reservoir. (2 marks)

Worked example 3.8B

Explaining a heat engine in terms of the first law of thermodynamics

Engines, such as steam engines and internal combustion engines, work by heating a fluid that turns a rotor or other moving element. **Explain** how this is an application of the first law of thermodynamics and why this process could be considered inefficient. (4 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the question is asking you to do.	"Explain" means to make an idea plain or clear by describing it in more detail or revealing relevant facts. We need to recall the first law of thermodynamics and our understanding of efficiency, and apply it to the heat engine example. This question is worth 4 marks, so we must make 4 key points.
Step 2: Recall and define the first law of thermodynamics.	The first law of thermodynamics recognises that a change in internal energy can be expressed as a change of thermal energy into work being done. (1 mark)
Step 3: Describe how it relates to heat engines.	Engines use this principle by converting the thermal energy of the heated fluid to the kinetic energy of the moving element, such that the internal energy of the system is approximately constant. (1 mark)
Step 4: Define efficiency.	Efficiency is a measure of the useful mechanical work done by a thermal system. (1 mark)
Step 5: Describe the efficiency of heat engines.	The process is inefficient because the system is not closed and heat lost to the environment reduces the total useful energy of the system. (1 mark)

Your turn

Many engines such as the internal combustion engine and the steam engine run at a constant temperature. **Explain** how this relates to changes in internal energy, given that engines are net producers of mechanical energy. (4 marks)

Study tip

Always check that your answer is complete and follows a logical sequence.

Real-world physics

Heat pumps and refrigerators

Refrigerators and air conditioners are just heat engines running in reverse. The engine takes in thermal energy from the cold reservoir (T_C) and expels it to the hot reservoir (T_H). This does not happen spontaneously; it needs an input of work to occur.

Figure 7 shows 400 J of energy being taken from the cold reservoir by the 100 J of work being done on the system (by a motor). The total of this energy (400 + 100 = 500 J) is being transferred to the hot reservoir. It appears to be the output of the system but, in reality, it is the waste. The real output is the 400 J of cooling attained in the process. The cold reservoir (the inside air) gets cooler and the hot reservoir (the outside air) gets hotter. If you've ever stood beside the compressor unit of an air conditioner, you will know how hot the air is. It cools the inside of the house but makes the outside even hotter.

A measure of the effectiveness of the refrigerator is the coefficient of performance (COP). Values of 2 to 5 are common for refrigerators and air conditioners. The refrigeration formula is $\text{COP} = \frac{Q_C}{W}$ where Q_C is the heat taken from the cold reservoir (the room being cooled) and W is the amount of work done by the motor to achieve this. In this case, $\text{COP} = \frac{400}{100} = 4.0$.

Apply your understanding

1 **Calculate** the efficiency of the refrigerator system in Figure 7. (3 marks)

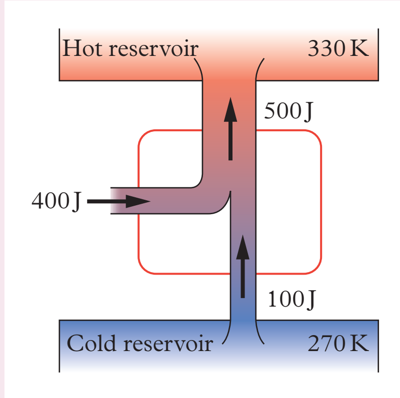


FIGURE 7 Thermal efficiency diagram for a heat pump acting as a refrigerator

Check your learning 3.8

Check your learning 3.8: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** "efficiency" in words, and with a formula. (2 marks)

2 **Identify** an example of a heat engine, and name the heated fluid and one of the moving elements. (3 marks)

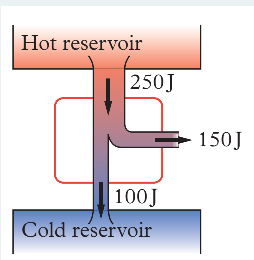
3 **Explain** what is meant by a hot reservoir and cold reservoir. (2 marks)

4 **Identify** an example of a heat sink. (1 mark)

Analytical processes

5 **Determine** the thermal efficiencies of the four systems in each energy transfer diagram. (4 marks)

a



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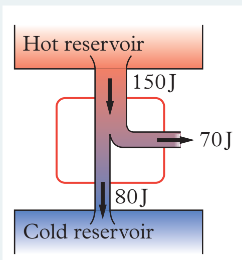

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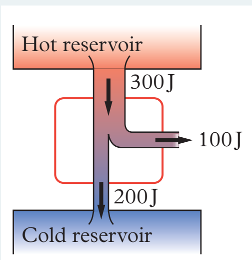
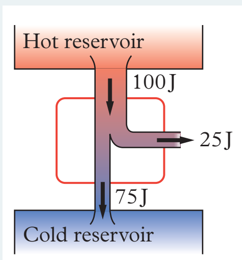


d



6 A car engine with a thermal efficiency of 20% does 2,000 J of work. **Determine** how much heat energy is

a taken from the hot reservoir (2 marks)

b exhausted to the cold reservoir (air). (2 marks)

Knowledge utilisation

7 **Construct** a simple thermal efficiency diagram for an internal combustion engine and state what the arrows represent. Assume the heat input for each cycle is 300 J and that it is 20% efficient. (3 marks)

8 **Discuss** whether the temperature of a can of soft drink would increase as it falls from the top of a tall building and strikes the ground. (3 marks)

9 **Evaluate** the following claim: "A heat engine does 10 kJ of work (out) on an input of 30 kJ, while 40 kJ of heat is transferred to the environment." (4 marks)

10 **Discuss** which room will have the higher temperature in this scenario: there are two identical rooms, one with a refrigerator in it and the other without. In the room with the refrigerator, the refrigerator is left running but with the door open. (3 marks)

MODULE 3

Lesson 3.9
Review: Phase changes and energy conservation

Summary

3.1
- Substances can undergo phase changes, including melting, vaporisation, evaporation, condensation and freezing.
- Specific latent heat is the energy required for 1 kg of substance to undergo a phase change.

3.2
- At thermal equilibrium, the components in a system have the same temperature and particles have the same average kinetic energy.
- The zeroth law of thermodynamics states that energy will transfer from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached.

3.3
- Specific heat capacity and specific latent heat can be determined experimentally.
- In an isolated system, the energy gained is equal to the energy lost. This is the law of conservation of energy.

3.4
- Practical: Specific heat capacity of a metal – by calorimetry

3.5
- Practical: Mixture of two liquids – calorimetry

3.6
- Heat has the capacity to do mechanical work and mechanical work has the capacity to generate heat.

3.7
- The temperature of a system can be raised by the addition of heat energy or by doing mechanical work on the system.
- The first law of thermodynamics states that the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings.

3.8
- Energy transfers and transformations in mechanical systems always result in some heat loss to the environment, so the amount of useable energy is reduced.
- Efficiency is a measure of the useful work done by a thermal system.

Key formulas

Specific heat capacity	$Q = mc\Delta T$
Specific latent heat of fusion	$Q = mL_f$
Specific latent heat of vaporisation	$Q = mL_v$
First law of thermodynamics	$\Delta U = Q + W$
Energy efficiency	$\eta = \frac{\text{energy output}}{\text{energy input}} \times 100$

Review questions 3.9A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 The specific latent heat of fusion is

A the heat required to melt 1 g of substance at its melting point.

B the heat required to melt 1 kg of substance at its melting point.

C the heat required to melt a substance at its melting point.

D the temperature at which heat causes a change of phase.

2 Which one of the following best describes what happens to kinetic energy and potential energy when a substance melts during a phase change?

	Kinetic energy	Potential energy
A	no change	no change
B	no change	increases
C	increases	no change
D	increases	increases

3 Which one of the following best states the zeroth law of thermodynamics?

A Two systems with the same temperature will have the same amount of thermal energy.

B Two systems must be in thermal contact for thermal equilibrium to be achieved.

C Equal amounts of thermal energy will be transferred between two systems.

D Thermal energy will be transferred between two systems until thermal equilibrium is achieved.

4 If two objects labelled B and C are both at thermal equilibrium with object A, which of the following must be true?

A Objects B and C are in thermal equilibrium with each other.

B Object B has a higher temperature than object C.

C Object C has a higher temperature than object B.

D Objects B and C are not in thermal equilibrium with each other.

5 The amount of thermal energy required to melt 500 g of ice at its melting point is

A 1.67×10^5 J.

B 3.34×10^5 J.

C 1.67×10^8 J.

D 3.34×10^8 J.

6 Students were experimentally determining the latent heat of vaporisation of steam. They found that 2.16×10^5 J of heat needed to be removed from the steam to condense 100 g of it at its condensation point. Their percentage error is

A 4.4%.

B 4.6%.

C 4.8%.

D 5.0%.

7 An electrical heater can deliver 1,000 J per second to water contained in it. How many minutes would it take to heat 50 g of water from 25°C to boiling point and then turn 10 g of it into steam at 100°C?

A 0.6 minutes

B 1.2 minutes

C 2.6 minutes

D 3.8 minutes

8 A 70.0 g copper block at a temperature of 80.0°C is placed in contact with another copper block of the same mass at a temperature of 20.0°C. What is the final temperature when they have reached thermal equilibrium?

A 45.0°C

B 50.0°C

C 55.0°C

D 60.0°C

9 A 50.0 g brass mass at 100.0°C is placed in 100.0 mL water at 20.0°C. At equilibrium, the final temperature of water and brass is 23.5°C. The specific heat capacity of brass (in $J\,kg^{-1}\,K^{-1}$) is

A 293.

B 338.

C 365.

D 383.

10 A lead fishing sinker with a mass of 75.0 g and a temperature of 25°C is placed on a block of ice at 0°C, which then melts. If 75.0 g of water at the same temperature was poured on the ice, which of the following is true?

A The water would melt more ice than the lead fishing sinker.

B The water would melt less ice than the lead fishing sinker.

C The water would melt the same amount of ice as the lead fishing sinker.

D Neither the water nor lead fishing sinker would melt any ice.

11 A cube of ice is placed in an insulated cup and it begins to melt. The air temperature is 23°C. Which one of the following best describes the temperature of the water that is formed?

A Less than 0°C

B 0°C

C Room temperature

D Greater than 0°C but less than room temperature

12 Two kilograms of ice at –5.0°C are added to 10 kg of water at 24°C in an insulated cask. What is the temperature of the contents once they have reached thermal equilibrium? Assume there is no heat exchange with the environment or with the cask.

A 6.3°C

B 6.8°C

C 7.7°C

D 19.7°C

13 Steam at 140°C is passed into 340 g of water at 20°C and a final mass of the condensed steam and water was found to be 375 g. The equilibrium temperature of the mixture is

A 43.4°C.

B 53.4°C.

C 79.7°C.

D 98.0°C.

14 During an energy transfer process, 1,000 J of heat is removed from a gas while 100 J of mechanical work is done by the gas. The change in the internal energy of the gas is

A +1,100 J.

B +900 J.

C –900 J.

D –1,100 J.

15 A sample of hydrogen gas is held in a sealed container. The internal energy of the gas is increased by 800 J. If the net amount of mechanical work done on the sample was 500 J, what is the net amount of heat transferred to the gas?

A 300 J added

B 300 J removed

C 1,300 J added

D 1,300 J removed

Review questions 3.9B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

16 A 70.0 g cube of iron at 90.0°C is placed in contact with a block of aluminium of similar mass at room temperature of 23.0°C. **Calculate** the final (equilibrium) temperature. (3 marks)

17 A 70.0 g cube of copper at 100.0°C is placed on a 200.0 g piece of lead at room temperature.

- **a** Assuming no heat is transferred to the environment, **calculate** the final (equilibrium) temperature. (3 marks)
- **b** **Calculate** the temperature the copper would have to be raised to so that the final (equilibrium) temperature was 70.0°C. (3 marks)

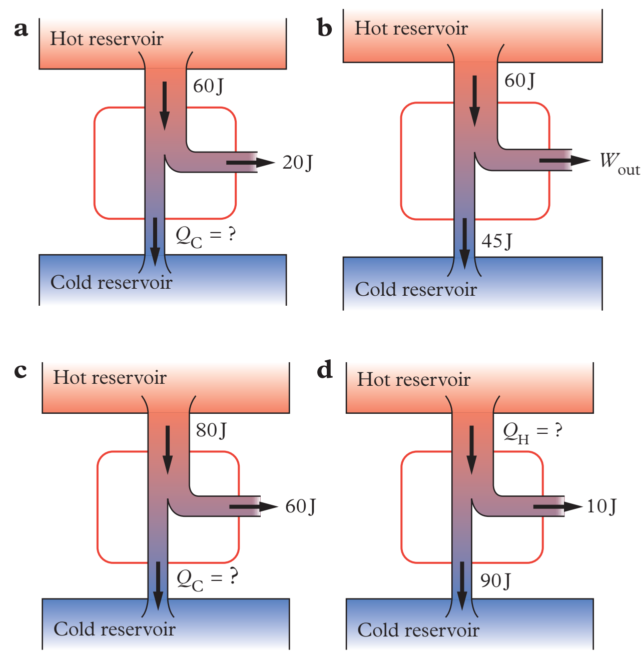
18 **Calculate** the mass of steam initially at 130°C that is needed to warm 200 g of water in a 150 g glass container from 20°C to 50°C. (4 marks)

19 **Calculate** the missing values in the following table which shows the change in internal energy of various systems (all values are in kJ). (4 marks)

	Q_{in}	Q_{out}	Q	W_{in}	W_{out}	W	ΔU	η (%)
a	240	120		5	40	–35		
b	400	200		0	50	–50		
c	0	1,000		3,000		3,000		
d	850		100	400			250	

20 A student investigates thermal efficiency by heating water in a microwave oven and comparing the electrical energy input to the heat energy output. The student reports the energy input as 227,700 J and heats up 1.0 L of water in a plastic ice cream bucket from 26.3°C to 54.3°C. **Calculate** the energy efficiency of the microwave oven. (3 marks)

21 **Calculate** the missing quantities in each of the energy transfer diagrams. (4 marks)



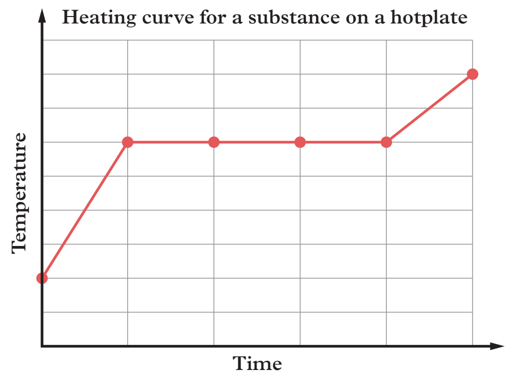
Analytical processes

22 Steam at 100°C will cause much more severe burns than water at 100°C.

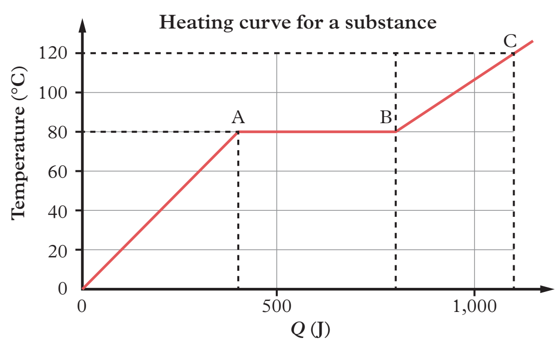
- **a** **Explain** in which state (liquid or vapour) the molecules are moving faster. (1 mark)
- **b** **Identify** in which state the molecules have greater potential energy. (1 mark)
- **c** **Infer** why steam burns are more severe than those from water at the same temperature. (1 mark)

23 A child wanting to make a cordial ice block places 200 g of cordial at 25°C in the freezer. If the freezer can remove energy at the rate of 25 J s^{-1}, **determine** the time it will it take for the cordial to freeze. (Assume the specific latent heat and specific heat capacity of cordial are the same as those of water.) (4 marks)

24 The graph shows the change in temperature for a solid as it is heated by a 1,000 W (1,000 J s^{-1}) hotplate and turns into a liquid. **Deduce** which phase has the greater specific heat capacity: solid or liquid. **Explain** your answer. (2 marks)



25 A substance is in the solid form at 0°C. The amount of heat added to this substance and its temperature are plotted in the graph. The specific heat capacity of the solid substance is 500 J kg^{-1} K^{-1}. **Determine** the specific latent heat of fusion for the melting process. (4 marks)



26 A 150 g steel spanner is left in the sun and reaches a temperature of 50°C. It is then placed on the lid of an aluminium toolbox of mass 1.1 kg at a temperature of 20°C. **Determine** the final temperature when the spanner and the toolbox have reached thermal equilibrium. (3 marks)

27 90.0 g of molten (liquid) lead at 327.3°C is poured into a 300.0 g casting made of iron initially at 20°C. **Determine** the final temperature of the system. (3 marks)

28 A student likes to mix iced coffee with hot coffee to cool the hot coffee down. If the student added 100 mL of iced coffee at 5°C to 250 mL of hot coffee at 70°C, **determine** the final (equilibrium) temperature of the mix. (c_{coffee} = 3,930 J kg^{-1} K^{-1}) (3 marks)

29 A mechanic was making up a 1:50 fuel mixture for a two-stroke motor mower. The mechanic mixed 100 mL (88.8 g) of oil at 35.0°C with 4.90 L (3.53 kg) of petrol at 20.0°C. Given that the specific heat capacities of oil and petrol are 1,800 J kg^{-1} K^{-1} and 2,130 J kg^{-1} K^{-1}, respectively, **determine** the final temperature of the mixture. (3 marks)

30 200 g of water at 80°C is added to 100 g of gold at 20°C. If the final (equilibrium) temperature is 79°C, **determine** the specific heat capacity of gold. (3 marks)

31 A 59.7 g piece of metal was placed in boiling water and allowed to reach 100.0°C. The metal was quickly transferred into 60.0 mL of water initially at 22.0°C. The final (equilibrium) temperature was 28.5°C. **Deduce** the specific heat capacity of the metal and **identify** the metal from a table of specific heat capacities. (3 marks)

32 To help prevent frost damage, 4.00 kg of 0°C water is sprayed onto a fruit tree, where it stays.

a **Determine** how much heat transfer occurs as the water freezes. (2 marks)

b **Calculate** how much the temperature of the 200 kg tree would decrease if this amount of heat is transferred from the tree. Assume that no phase change occurs. (c_{tree} = 3,350 J kg^{-1} °C^{-1}) (2 marks)

33 In an insulated vessel, 250 g of ice at 0°C is added to 600 g of water at 18°C.

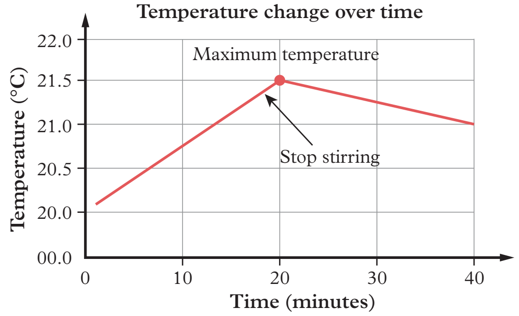
a **Determine** the final temperature of the system. (3 marks)

b **Determine** how much ice remains when the system reaches equilibrium. (1 mark)

34 A block of ice of temperature 0°C and mass 20.0 g was placed in a beaker and weighed. The total mass was 55.0 g. Steam at 110°C was blown onto the ice until the ice completely melted and the water from the ice and steam remained at 0°C. Assuming no loss of heat to the surroundings, **determine** the mass of the beaker and its contents. (4 marks)

Knowledge utilisation

35 Students carried out Joule's experiment in the laboratory using 2.00 kg of water. They stopped stirring with the paddles after 19 minutes. The graph plots their results.



a **Determine** the energy change in the water. (2 marks)

b The mechanical work done on the water by the falling weights was 14,990 J. **Calculate** the percentage efficiency of the energy conversion process from mechanical to thermal energy. (2 marks)

d **Propose** a reason why the water temperature kept increasing after the stirring stopped. (1 mark)

e **Propose** a reason for the cooling of the water after 20 minutes. (1 mark)

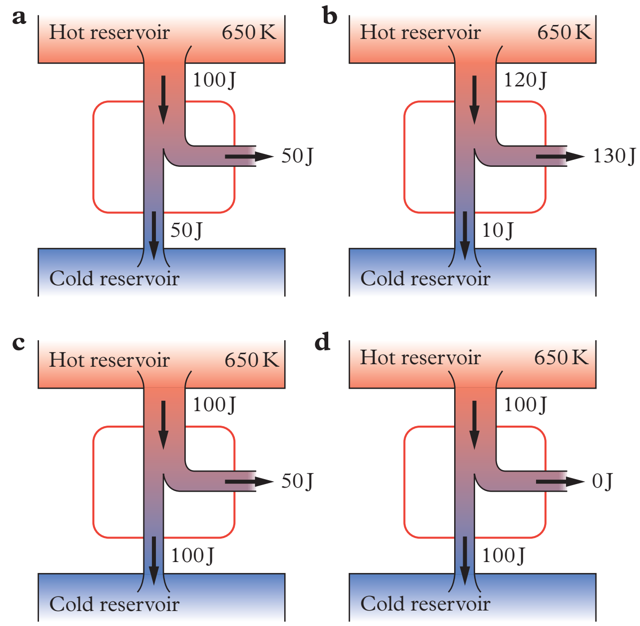
36 **Determine** the change in the internal energy of a system that does 4×10^5 J of work while 3.00×10^6 J of heat transfer occurs into the system, and 3.4×10^6 J of heat transfer occurs to the environment. (2 marks)

37 A system does 30 MJ of work while 12 MJ of heat transfer occurs to the environment.

a **Calculate** the change in the internal energy of the system (assuming no other changes such as in temperature or by the addition of fuel). (2 marks)

b **Determine** the percentage efficiency. (2 marks)

38 **Determine** which (if any) of the four energy transfer diagrams is not possible. **Explain** why. (4 marks)



39 A steam engine does 4,000 J of work while exhausting 1,500 J of waste heat.

a **Calculate** the engine's thermal efficiency. (4 marks)

b **Construct** an energy transfer diagram for this device, showing all inputs and outputs. (2 marks)

Data drill

Specific heat capacity of a metal

A student conducts an experiment to investigate the specific heat capacity of an unknown metal. They heat a 50.0 g mass of the metal in a beaker of water until it boils. They then place this heated metal into another beaker with 50.0 g of water at room temperature and observe the temperature change of this water. A second trial was then undertaken. The results are shown in Table 1.

TABLE 1 Results from student experiment

	Trial 1	Trial 2	Mean
Initial temperature of water, T_i (°C)	24.0	22.5	22.3
Final temperature of water, T_f (°C)	35.5	37.0	

Apply understanding

1 **Calculate** the mean value for the final temperature of the water. (1 mark)

2 **Determine** the specific heat capacity of the metal, given that the specific heat capacity of water is 4,180 $\text{J kg}^{-1}\text{K}^{-1}$. (3 marks)

Analyse evidence

3 **Identify** the greatest source of uncertainty in this experiment: the mass of the metal, the mass of the water, or the temperature change. **Explain** your choice. (3 marks)

Interpret evidence

4 If the accepted value is 905 $\text{J kg}^{-1}\text{K}^{-1}$, **deduce** the range of values for specific heat capacity that would be within 2% of this value. (2 marks)

5 **Determine** whether the method used is a reliable means of determining the specific heat capacity of a metal. **Justify** your answer by referring to the evidence. (2 marks)

Module 3 checklist: Phase changes and energy conservation

Quizlet: Revise key terms online to test your understanding

UNIT 1

Topic 1 review

Multiple choice

(1 mark each)

1 Which of the following is a fundamental SI base quantity?

A Mass
B Force
C Hertz
D Ampere

2 Which is the correct statement about the kinetic model of matter?

A The average kinetic energy of particles is constant.
B There are intermolecular forces within particles.
C Particles of matter are constantly colliding.
D An atom is mostly empty space.

3 The transfer of energy from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached is a statement of the

A kinetic particle model of matter.
B zeroth law of thermodynamics.
C first law of thermodynamics.
D law conservation of energy.

4 When the internal energy of a substance is increased

A the average kinetic energy of its particles always increases.
B there is always a rise in its microscopic energy.
C its temperature always rises.
D heat must have been added.

5 A 40 kg object is heated from 10°C to 25°C, which required 30,000 J of thermal energy. The specific heat capacity of the object is

A 25 $J kg^{-1} K^{-1}$.
B 50 $J kg^{-1} K^{-1}$.
C 75 $J kg^{-1} K^{-1}$.
D 100 $J kg^{-1} K^{-1}$.

6 A substance can be depicted in three different states as shown.

If a substance in state B is cooled down and undergoes a phase change, which of the following occurs?

A It stays as state B.
B It changes to state A.
C It changes to state C.
D It changes to a liquid.

7 An insulated foam cup contains 50.0 g of water at 10°C. A 100 g aluminium cube at a temperature of 100.0°C is added to the cup and stirred gently until it reaches thermal equilibrium. The equilibrium temperature ($c_{Al} = 900\ J kg^{-1} K^{-1}$) is

A 15.4°C.
B 37.1°C.
C 76.5°C.
D 80.5°C.

8 A 50 g sample of a metal was heated to 95°C and then quickly transferred to an insulated container containing 40 g of H_2O at 25°C. The final temperature of the H_2O was 30°C. The specific heat of the metal in $J kg^{-1} K^{-1}$ is

A 257.
B 399.
C 880.
D 2,787.

9 A liquid boils and turns to vapour but it remains at the same temperature. Which of the following states the change of the average potential energy (E_p) and whether there has been a phase change?

A E_p increases, phase change

B E_p no change, phase change

C E_p increases, no phase change

D E_p no change, no phase change

10 The heat required to just melt a 20 g cube of ice at –2°C is

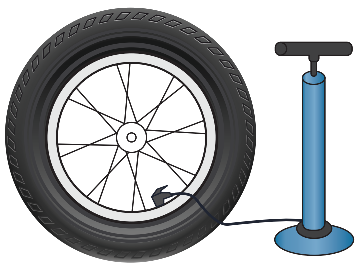
A 6.7×10^3 J.

B 6.8×10^3 J.

C 6.7×10^6 J.

D 6.8×10^6 J.

11 A bicycle pump is being used to pump up a tyre. It consists of a movable piston inside a cylinder.



The gas is compressed rapidly by moving the piston downwards and it gets hot. Which of the following best explains the source of the increased kinetic energy of the gas molecules?

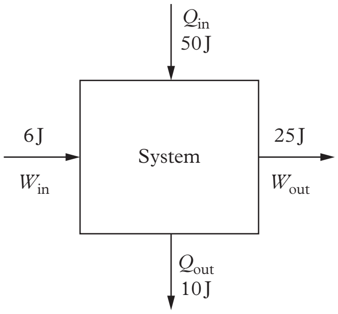
A By being pulled closer together

B From the work done on moving the piston

C By colliding more frequently with each other

D By colliding more frequently with the walls of the cylinder

12 The following thermodynamic efficiency diagram shows the inputs and outputs of a heat engine.



The change in internal energy is

A –69 J.

B –31 J.

C +21 J.

D +69 J.

13 A system receives an input of 200 J of heat and produces 60 J of work. It loses 120 J of heat to the environment. There are no other inputs. The change in internal energy and percentage efficiency of the process is

A +20 J, 30%.

B –20 J, 30%.

C +20 J, 90%.

D –20 J, 90%.

14 An example of a process in which no heat is added to a system but its temperature rises is

A sunlight falling on a rock makes it heat up.

B a block of ice on a kitchen bench warms up.

C pumping air into a tyre makes the pump get hot.

D the element in an electric kettle causes water to boil.

Short response

15 An unopened bottle of water was left in the sun and became hotter as time passed. **Explain** the process of heat transfer in this situation. (3 marks)

16 **Explain** the concept of thermal equilibrium in terms of temperature and particle motion. (3 marks)

17 A 25 g lump of ice at –5°C was placed in an insulated beaker of warm water at 40°C and allowed to melt and reach an equilibrium temperature at 20°C.

- **a** **Determine** the mass of water in the beaker. (4 marks)
- **b** **Explain** how the zeroth law of thermodynamics applies in this situation. (3 marks)

18 A 200 W immersion heater is placed in a beaker containing 0.30 kg of ice at a temperature of −8.0°C. The heater remains switched on until all of the ice has just melted.

- **a** **Determine** the amount of thermal energy needed to take the ice from its initial temperature to the melting point and stay at that temperature until it just finishes melting (2 s.f.). (2 marks)
- **b** **Determine** the time that the heater has to operate for this to be achieved, assuming no energy is lost to the environment (2 s.f.). (2 marks)
- **c** **Explain**, in terms of the energy of the molecules of the water, why the water melts at constant temperature. (2 marks)

19 When you turn on an electric kettle to heat up some water, electricity flows from the power point to the element in the bottom of the kettle and then the water in contact with it gets hot.

- **a** **Identify** whether the flow of energy from the power point to the element is heat or work. (1 mark)
- **b** **Identify** whether the flow of energy from the element to the water is heat or work. (1 mark)

20 The following questions are about an ice cube melting in water.

- **a** **Define** the specific latent heat of fusion of a substance with reference to an ice cube. (1 mark)
- **b** An ice cube with a temperature of 0°C and a mass of 20 g (0.020 kg) is placed in a 0.250 kg beaker of warm water at 80.0°C and melts completely. **Determine** the final temperature of the water (2 s.f.). (3 marks)
- **c** **Explain** two assumptions you made about the data. (2 marks)

21 The following question is about the melting of ice.

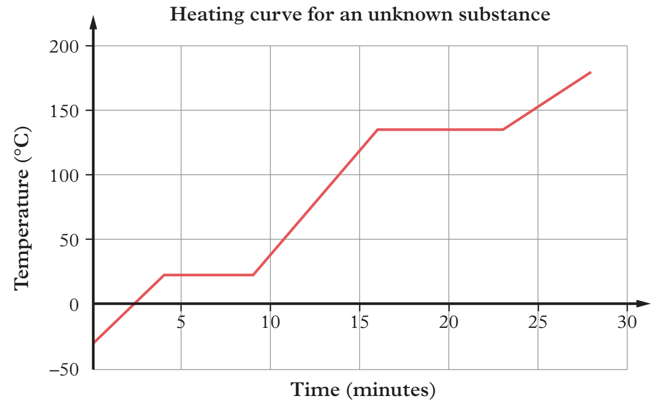
- **a** The specific heat capacity of ice is different from the specific heat capacity of water. **Explain** what this means at a particle level in terms of how ice and water absorb heat differently. (2 marks)
- **b** An experiment was conducted to investigate the temperature changes in the melting of ice. A 25.0 g cube of ice at a temperature of –8.0°C was placed in an insulated foam cup containing 100.00 g of warm water at 60.0°C. The ice was gently stirred until it melted and came to thermal equilibrium. **Determine** the theoretical equilibrium temperature (2 s.f.). (4 marks)
- **c** **Infer** whether your answer to part **b** is an overestimate or underestimate or likely to be an accurate value for the equilibrium temperature of the water. (2 marks)
- **d** **Explain** how the first law of thermodynamics applied to the water when the ice cubes are dropped into it. (2 marks)

22 Fifty millilitres of water was placed in a plastic bottle and shaken hard for 3 minutes. Its temperature was found to have risen. **Explain** the source of this temperature rise. (2 marks)

23 A 300 W electrical heater is placed in a beaker containing 0.25 kg of water at a temperature of 18°C. The heater is switched on for 120 seconds, after which time the temperature of the water is 45°C. The thermal capacity of the beaker is negligible, and the specific heat capacity of water is $4.2 \times 103\,\mathrm{J\,kg^{-1}\,K^{-1}}$. **Determine** the efficiency of the transformation of electrical energy to thermal energy (2 s.f.). (3 marks)

24 An athlete loses 1.8 kg of water evaporating from her skin during a training session that lasts 1 hour. **Determine** the rate of energy loss by the athlete due to sweating. The specific latent heat of vaporisation of water is $2.3 \times 10^6\,\mathrm{J\,kg^{-1}}$ (3 s.f.). (4 marks)

25 An unknown solid of mass 1.45 kg was heated in an insulated cup at a constant rate of $150.0\,\mathrm{J\,s^{-1}}$ and its temperature was recorded as a function of time. This is shown in the graph.



a **Identify** the boiling point of the substance (nearest whole number). (1 mark)

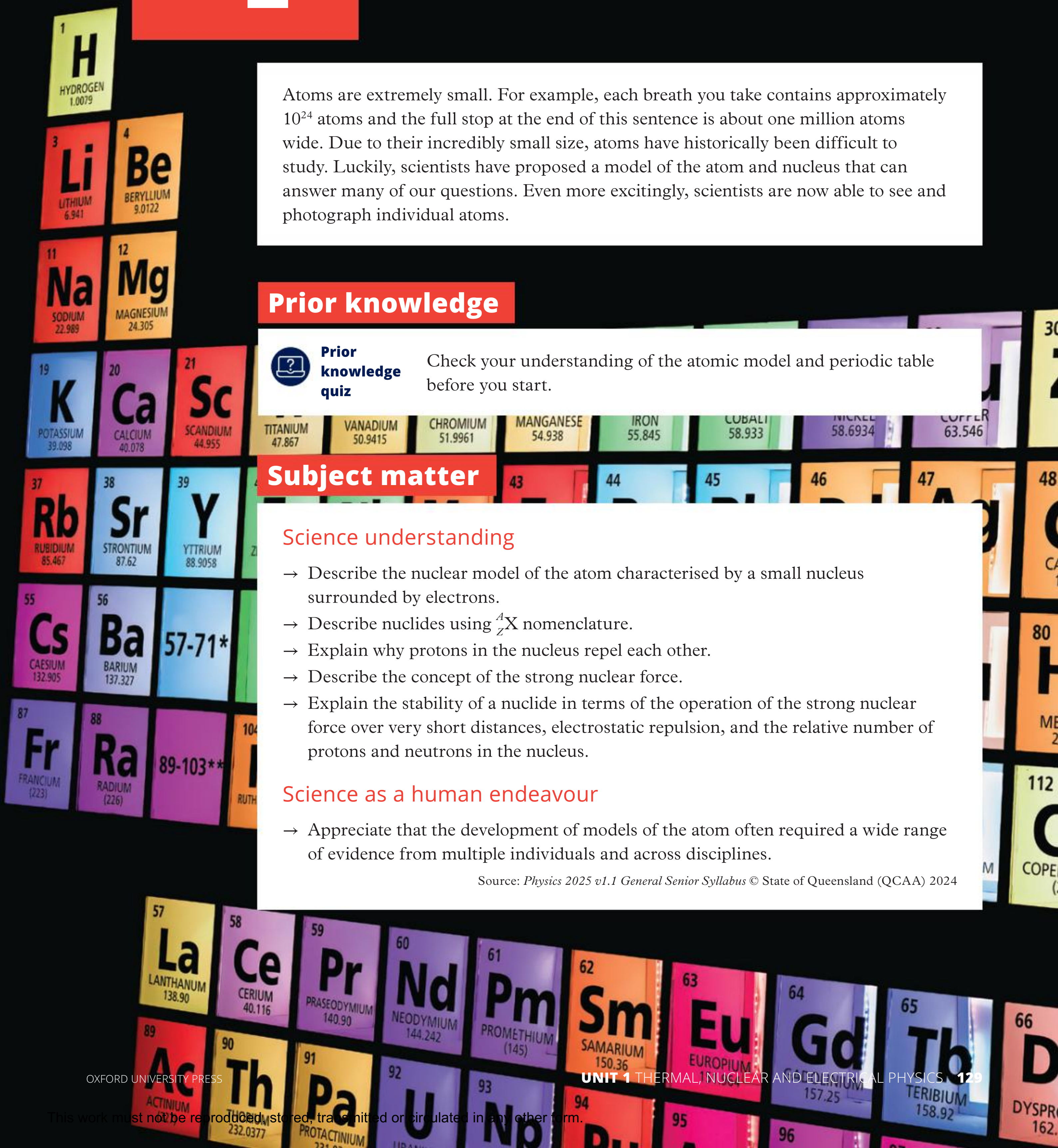
b **Determine** the latent heat of fusion (3 s.f.). (4 marks)

c **Determine** the specific heat capacity of the liquid phase (2 s.f.). (4 marks)

TOTAL MARKS
/69

MODULE 4

Nuclear model and stability



Atoms are extremely small. For example, each breath you take contains approximately 10^{24} atoms and the full stop at the end of this sentence is about one million atoms wide. Due to their incredibly small size, atoms have historically been difficult to study. Luckily, scientists have proposed a model of the atom and nucleus that can answer many of our questions. Even more excitingly, scientists are now able to see and photograph individual atoms.

Prior knowledge

Prior knowledge quiz Check your understanding of the atomic model and periodic table before you start.

Subject matter

Science understanding

→ Describe the nuclear model of the atom characterised by a small nucleus surrounded by electrons.
→ Describe nuclides using $^{A}_{Z}X$ nomenclature.
→ Explain why protons in the nucleus repel each other.
→ Describe the concept of the strong nuclear force.
→ Explain the stability of a nuclide in terms of the operation of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus.

Science as a human endeavour

→ Appreciate that the development of models of the atom often required a wide range of evidence from multiple individuals and across disciplines.

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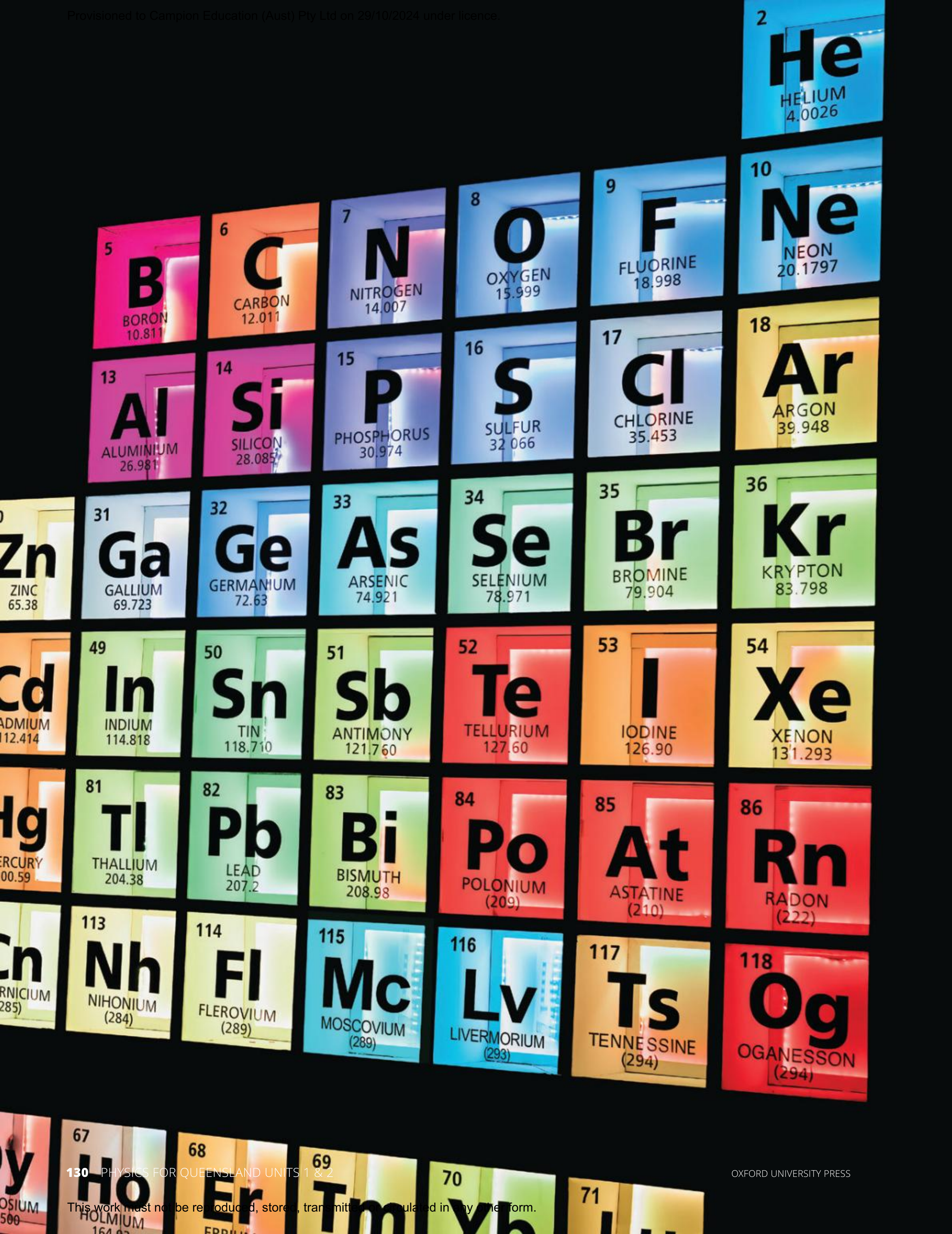
2 He HELIUM 4.0026
5 B BORON 10.811
6 C CARBON 12.011
7 N NITROGEN 14.007
8 O OXYGEN 15.999
9 F FLUORINE 18.998
10 Ne NEON 20.1797
13 Al ALUMINIUM 26.981
14 Si SILICON 28.085
15 P PHOSPHORUS 30.974
16 S SULFUR 32.066
17 Cl CHLORINE 35.453
18 Ar ARGON 39.948
Zn ZINC 65.38
31 Ga GALLIUM 69.723
32 Ge GERMANIUM 72.63
33 As ARSENIC 74.921
34 Se SELENIUM 78.971
35 Br BROMINE 79.904
36 Kr KRYPTON 83.798
49 In INDIUM 114.818
50 Sn TIN 118.710
51 Sb ANTIMONY 121.760
52 Te TELLURIUM 127.60
53 I IODINE 126.90
54 Xe XENON 131.293
81 Tl THALLIUM 204.38
82 Pb LEAD 207.2
83 Bi BISMUTH 208.98
84 Po POLONIUM (209)
85 At ASTATINE (210)
86 Rn RADON (222)
113 Nh NIHONIUM (284)
114 Fl FLEROVIUM (289)
115 Mc MOSCOVIUM (289)
116 Lv LIVERMORIUM (293)
117 Ts TENNESSINE (294)
118 Og OGANESSON (294)
67 Ho HOLMIUM
68 Er
69 Tm
70 Yb
71

Lesson 4.1
Nuclear model of the atom

Key ideas

→ The nuclear model of the atom states that an atom consists of a small nucleus (containing protons and neutrons) surrounded by electrons.

→ Nuclides are represented using $^{A}_{Z}X$ nomenclature.

→ Atomic mass is determined by mass number (number of protons and neutrons).

→ Isotopes of the same element have the same number of protons but a different number of neutrons.

Learning intentions and success criteria

What is the nuclear model of the atom?

Atoms are often referred to as the building blocks of matter because they make up everything that we know, from cats and bananas, to rocks, paper and scissors. Some of these atoms are 14 billion years old.

The **nuclear model of the atom** states that atoms are the basic unit of matter and they consist of a small, central, positively charged **nucleus** made up of **protons** and **neutrons** surrounded by a negatively charged cloud of **electrons**. These electrons are kept there by attractive electrostatic forces between the positive and negative charges.

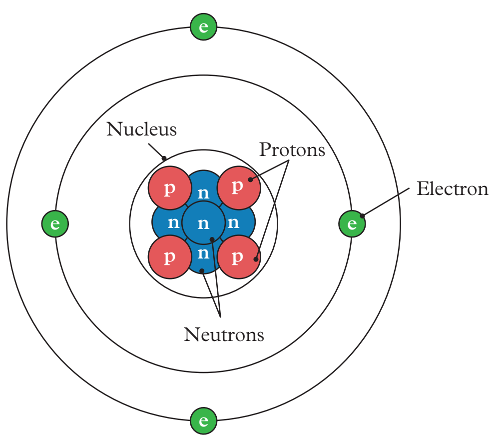

FIGURE 1 The nuclear model of the atom. The electrons are in a cloud surrounding the nucleus. The diagram is not intended to show the electrons as being in circular orbits, but rather in a cloud with shells of different energy levels.

How do you represent atoms?

We refer to the different types of atoms as chemical **elements** using names such as hydrogen, helium, carbon and so on. There are 92 naturally occurring elements and dozens more artificial ones.

nuclear model of the atom
a model that suggests that the atom consists of a small nucleus surrounded by electrons

nucleus
the positively charged central core of an atom, consisting of protons and neutrons and containing nearly all its mass

proton
a subatomic particle of about the same mass as a neutron with a +1 elementary electric charge; present in all atomic nuclei

neutron
a subatomic particle of about the same mass as a proton but without an electric charge; present in all atomic nuclei except those of ordinary hydrogen

electron
a subatomic particle of mass 1,836 times lighter than a proton with a −1 elementary electric charge; present in all atoms

element
a chemical substance that cannot be broken down into other substances by chemical reactions

atomic number
the number of protons in an element's nucleus, Z; in a neutral atom, the number of protons will be equal to the number of electrons surrounding the nucleus

Study tip

Atom diagrams are commonly drawn as shown in Figure 2, but these diagrams can sometimes be a bit misleading. Try to think of electrons in a cloud consisting of imaginary shells of different energies, rather than following a circular path around the nucleus.

nucleon
proton or neutron found in the nucleus of an atom

nuclide
a distinct kind of atom or nucleus characterised by a specific number of protons and neutrons

mass number
the total number of nucleons in an element's nucleus; the number of protons plus the number of neutrons; symbol: A

Study tip

When discussing atoms, protons, neutrons and electrons are often shortened to p, n and e, respectively. Be careful answering questions; the variable *n* (in italics) usually means "number", so make sure you read the information in exam questions carefully.

Study tip

Use of these symbols comes up again in The Standard Model, and Particle Interactions units. Make sure you understand it here first.

The number of protons in an atom determines its position in the periodic table. This is also called the atom's **atomic number**, which has the symbol Z. Hydrogen has one proton, helium has two, uranium has 92 and so on. Figure 2 and the periodic table (Appendix 2) show this clearly.

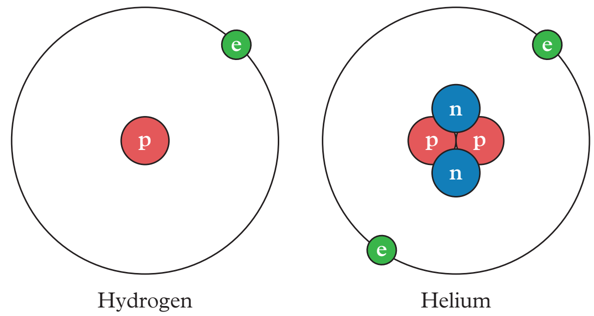

FIGURE 2 Models of hydrogen and helium atoms

After helium (two protons) is lithium with three protons, beryllium with four protons and so on. The number of protons is used to identify the atom. For example, all atoms with eight protons are called oxygen, and oxygen always has eight protons.

In Figure 2, you can also see that as we add protons to our model, we also add more neutrons. Together with the protons, they make up the nucleus; thus, protons and neutrons are called **nucleons**. You can also see that the number of electrons increases.

Using the $^{A}_{Z}X$ nomenclature

Each different type of nucleus is referred to as a **nuclide**; for example, there is a hydrogen nuclide, a helium nuclide and so on. They can be described using shorthand (Figure 3). This is called the $^{A}_{Z}X$ nomenclature (read as the A-Z-X nomenclature). The bottom number (Z) is the atomic number or number of protons, and the top number is the sum of protons and neutrons (p + n) and called the **mass number** (A). The symbol X is determined by the atomic number, not the mass number. In Figure 3, we can see that for carbon with symbol C, $Z = 6$ because carbon has six protons, and $A = 12$, since carbon has 12 nucleons.

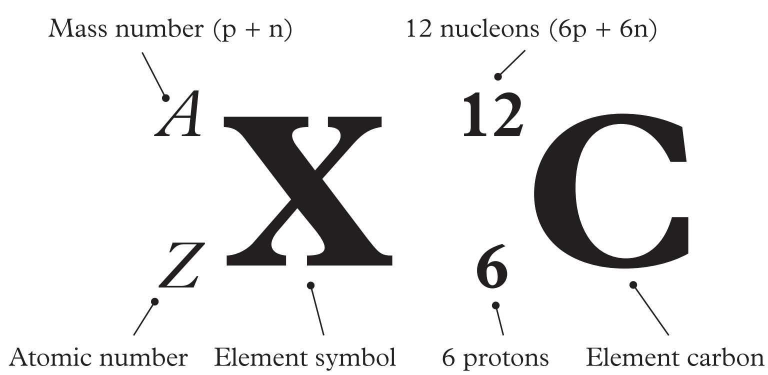

FIGURE 3 Nuclide nomenclature

Worked example 4.1A

Using ${}^A_Z X$ nomenclature

Identify, using the ${}^A_Z X$ nomenclature, the nuclide that has 84 protons and 125 neutrons. (1 mark)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Identify" means to recognise and name. We need to figure out what the nuclide is. The question is worth 1 mark, so we must use the values given and apply the nomenclature.
Step 2: Select the correct formulas and gather any data required.	${}^A_Z X$ $A = Z +$ neutrons $Z = 84$, neutrons = 125
Step 3: Substitute the known values into the formula and find the unknown. Use the atomic number (Z) to find the X value. You can find this in the periodic table in the Appendix or in the QCAA data book.	$A = 84 + 125$ $= 209$ For $Z = 84$, X = Po.
Step 4: Finalise your answer by writing it in the form ${}^A_Z X$.	${}^{209}_{84}Po$ (1 mark)

Your turn

Identify, using the ${}^A_Z X$ nomenclature, the nuclide that has 88 protons and 138 neutrons. (1 mark)

Study tip

Use the bottom number, the atomic number Z (number of protons), to determine which element it is. Don't make the mistake of using the mass number A (top number) to work out the symbol.

Are atomic mass and charge related?

Electrons have a negative charge of –1, and protons have a charge of +1. We can refer to these as **elementary charges**. If the number of positive charges and the number of negative charges is equal, the atom is said to be neutral (from the Latin word meaning "neither one nor the other"). If the atom has more positive than negative charges, the atom is positive overall. Chemists call it a positive **ion** (cation), and it is formed through the loss of one or more electrons. If the atom has more negative than positive charges, it is a negative ion (anion) and it has formed through the gain of one or more electrons. The process of forming an ion is **ionisation**. Ions are represented with the charge as a superscript after the elemental symbol.

Table 1 shows how the charge of oxygen changes with its number of electrons. Oxygen has eight protons, so the nucleus has a +8 charge. If oxygen has eight electrons (–8), it is then a neutral atom (O). If oxygen has more electrons (such as 10), it is a negative ion (O^{2-}). With fewer electrons (such as 7), it will be a positive ion (O^+); however, O^+ does not exist.

elementary charge
the magnitude of the electric charge carried by a single electron or single proton

ion
an atom that has lost or gained electrons

ionisation
the process by which an atom or molecule acquires a negative or positive charge by gaining or losing electrons

TABLE 1 The overall charge of oxygen can vary with the number of electrons.

Atom	Number of protons (+1 charge on each)	Number of electrons (–1 charge on each)	Overall charge	Symbol
Oxygen	8	8	0	O
Oxygen	8	9	–1	O^-
Oxygen	8	10	–2	O^{2-}
Oxygen	8	7	+1	O^+

To determine whether charge affects the atomic mass, we need to consider the masses of each individual particle (Table 2).

TABLE 2 The mass and charge of atomic particles

Particle	Mass (kg)	Elementary charge
Proton	$1.6726219 \times 10^{-27}$	+1
Neutron	1.674925×10^{-27}	0
Electron	$9.1093835 \times 10^{-31}$	–1

The electron is considered to be a charge located at a single point in space, so its size is negligible. About 99% of an atom's mass is concentrated in the nucleus. Thus, charge does not affect atomic mass.

If you had a nucleus the size of a strawberry, it would be so heavy that it would bore its way through the ground. A proton or neutron has a mass 1,836 times that of an electron. In all atoms, nearly all of the mass is contained in the nucleus. However, the nucleus occupies only a tiny volume – about 1 trillionth (10^{-12}) the volume of the atom.

Atomic mass units

Although Table 2 shows the masses of neutrons, protons and electrons in kilograms, this is not a common way to express atomic mass. Instead, mass is expressed as "unified atomic mass units", which are referred to as amu or just u. The amu is equal to one-twelfth of the mass of a ^{12}C atom. The unified mass unit includes the masses of the protons, neutrons and electrons of the carbon atom. The amu is a unit of mass used for very small masses and is equal to 1.66×10^{-27} kg.

The masses of atomic particles are as follows:

- proton (m_p) = 1.007276 amu
- neutron (m_n) = 1.008665 amu
- electron (m_e) = 0.000549 amu.

What are isotopes?

Historically, when scientists were discovering more and more elements, they were struggling to fit them onto the existing structure of the periodic table. This was especially so for the radioactive elements – those between lead (atomic number $Z = 82$) and uranium ($Z = 92$). Cases began to appear in which two radioactive elements, distinctly different in the type of radiation they emitted, were otherwise chemically identical. In 1913, Frederick Soddy found that there were two forms of lead – one was the ordinary sort with a mass number of 207 units, and the other (taken from a uranium deposit in Norway) had a mass of 206 units. Soddy concluded that such inseparable elements must occupy the same place in the periodic table and gave them the name **isotopes** (Greek "iso" = "same", "topos" = "place").

isotope
a form of an element with the same number of protons but different number of neutrons; nuclides with the same atomic number but different mass numbers

Most elements exist as various isotopes. Isotopes of an element have the same number of protons but different numbers of neutrons. So, they are different nuclides of the same element. In the previous example, both isotopes of lead have 82 protons, but one has 124 neutrons (206 – 82) and the other has 125 neutrons (207 – 82). They would be written as $^{206}_{82}Pb$ and $^{207}_{82}Pb$, or simply using their symbol and mass number: Pb-206 and Pb-207.

All isotopes of lead have an atomic number of 82 and all atoms with an atomic number of 82 are lead. There can be other nuclides with a mass number of 206 besides lead (e.g. ${}^{206}_{83}Bi$ and ${}^{206}_{84}Po$).

The chemical properties of isotopes are identical, but the physical properties are different because of the different masses. Figure 4 shows the three isotopes of hydrogen – hydrogen (H), deuterium (D) and tritium (T). They are written as ${}^{1}_{1}H$, ${}^{2}_{1}H$ and ${}^{3}_{1}H$.

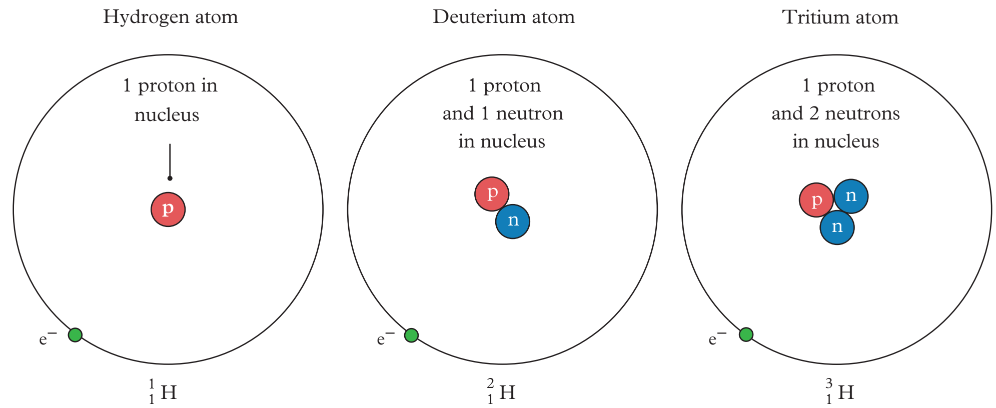

FIGURE 4 The three isotopes of hydrogen – the most abundant is ${}^{1}_{1}H$.

Their composition is shown in Table 3. Water (H_2O) made with ordinary hydrogen, ${}^{1}_{1}H$, has a density of 1.000 g cm^{-3} and boils at 100.00°C, whereas "heavy water" consisting of deuterium oxide (D_2O) has a density of 1.1079 g cm^{-3} and a boiling point of 101.42°C.

TABLE 3 The isotopes of hydrogen

Isotope (nuclide)	Symbol	Protons (atomic number)	Neutrons	Electrons	Protons + neutrons (mass number)	Exact mass (amu)
Hydrogen	${}^{1}_{1}H$	1	0	1	1	1.007825
Deuterium	${}^{2}_{1}H$	1	1	1	2	2.014102
Tritium	${}^{3}_{1}H$	1	2	1	3	3.016049

Challenge

The dense core of the helium atom

The nuclear model of the atom refers to a small nucleus. We know that most of the mass is in the nucleus, so it must be very dense. The radius of a helium nucleus (${}^{4}He$) is 1.9×10^{-15} m and the mass of a helium nucleus (excluding electrons) is 4.001505 amu.

a **Calculate** the volume of the helium nucleus using $V = \frac{4}{3}\pi r^3$. (1 mark)

b **Calculate** the mass of the helium nucleus in kilograms. (1 mark)

c **Calculate** the density (ρ) of the helium nucleus using $\rho = \frac{m}{V}$. (1 mark)

Check your learning 4.1

Check your learning 4.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the structure of an atom in terms of the nuclear model of the atom. (1 mark)

2 **Identify** whether isotopes of a particular substance have the same physical and chemical properties. (1 mark)

3 **Explain** why isotopes of carbon have different masses if they are all carbon atoms. (2 marks)

4 **Identify** the number of protons and neutrons in each of these nuclides.

a ${}^{2}_{1}H$ (2 marks) **b** ${}^{12}_{6}C$ (2 marks)
c ${}^{17}_{8}O$ (2 marks) **d** ${}^{23}_{11}Na$ (2 marks)
e ${}^{32}_{16}S$ (2 marks) **f** ${}^{107}_{47}Ag$ (2 marks)
g ${}^{127}_{53}I$ (2 marks) **h** ${}^{238}_{92}U$ (2 marks)

Analytical processes

5 **Apply** the ${}^{A}_{Z}X$ nomenclature to **distinguish** between the two common isotopes of carbon (atomic masses 12 and 14). (2 marks)

6 **Deduce** the missing values from the table to show the composition of each nuclide. (1 mark per row)

Symbol (${}^{A}_{Z}X$)	Symbol	Number of protons	Number of neutrons	Number of nucleons (protons + neutrons)	*A*	*Z*
${}^{64}_{29}Cu$	Cu-64					
	P-32					
		38	50			
			124			82
	Ra-?			220		
					239	93
${}^{239}_{92}?$						

Lesson 4.2
Nuclear stability

Key ideas

→ Protons in the nucleus repel each other due to electrostatic repulsion.

→ In stable nuclides, the strong nuclear force between neutrons and protons helps to hold protons together.

→ The ratio of neutrons to protons in stable nuclides increases as the size of the atom increases.

Learning intentions and success criteria

What makes a nuclide stable?

You are probably familiar with the idea of "stability". Something stable doesn't fall over and smash into pieces. In this lesson, we look at **nuclear stability**. If a nuclide is **stable**, its nucleons are held together tightly and the nucleus doesn't break up. Nuclear stability depends on the forces present in the nucleus, the ratio of neutrons and protons in the nucleus, and the total number of nucleons present.

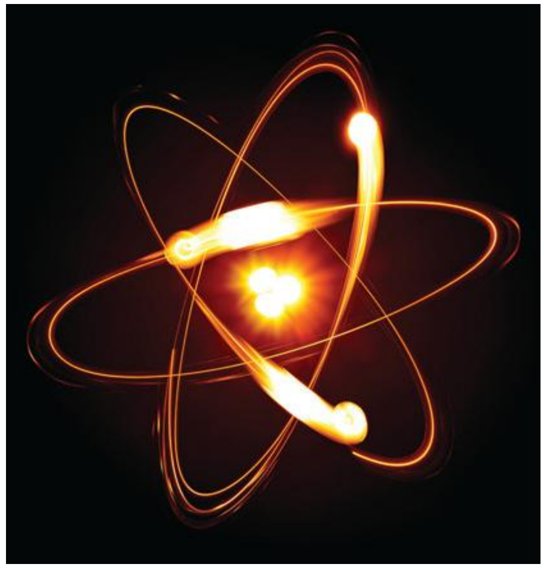

FIGURE 1 What makes a nuclide stable?

nuclear stability
a measure of the stability of an isotope determined from the neutron-to-proton ratio and the total number of nucleons in the nucleus

stable
characteristic of nuclides that are not radioactive and so (unlike radionuclides) do not spontaneously undergo radioactive decay; when such nuclides are referred to in relation to specific elements, they are usually termed stable isotopes

How do forces present in the nucleus affect nuclear stability?

Protons and neutrons form a very dense nucleus. To do this, they must be held together tightly to the point where protons are almost touching. However, as protons are positively charged, and as like charges repel, this means that the force of the **electrostatic repulsion** is enormous.

Electrostatic force varies in an inverse-square relationship with the separation distance (distance between charged particles) – that is, $F \propto \frac{1}{d^2}$. If you halve the separation distance, then the force is multiplied fourfold. So, when protons are close, the force pushing them apart is very large. But why don't the protons fly apart? The answer lies in the role of the neutrons.

Neutrons serve two purposes – to add some distance between the protons to reduce the repulsive force, and to act as a nuclear "glue". This gluing force is called the strong force or, more correctly, the **strong nuclear force**. It holds the nucleons together against the repulsive electrostatic (electromagnetic) forces exerted between the adjacent protons.

electrostatic repulsion
the phenomenon of two like charged particles repelling each other

strong nuclear force
a force that acts over very small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces between the positively charged protons

As the number of protons increases, the number of neutrons must also increase. The strong nuclear force is a very short-range force that decreases rapidly as separation increases, but at very close separation distances becomes repulsive (Figure 2). If it wasn't repulsive at close distances, the particles would merge and collapse to a point.

The strong nuclear force acts between all nucleons whether they are protons or neutrons. Their charge has nothing to do with it.

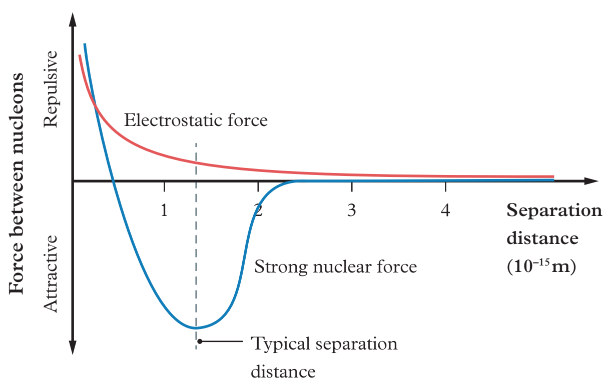

FIGURE 2 As the separation distance between protons increases, the attractive strong nuclear force reduces to almost zero and all that remains is the repulsive electrostatic force.

Real-world physics

The evolution of understanding on nuclear stability

The development of models of the atom often required a wide range of evidence from multiple scientists and across disciplines. Before the 1970s, physicists were uncertain as to how the atomic nucleus was bound together. It was known that the nucleus was composed of protons and neutrons, and that protons possessed positive electric charge while neutrons were electrically neutral.

By the understanding of physics at that time, positive charges would repel one another and the positively charged protons would cause the nucleus to fly apart. However, this was never observed. New physics was needed to explain this phenomenon.

The concept of a new strong nuclear force was introduced in 1935 by the Japanese physicist Hideki Yukawa, who suggested that the nucleons would exchange particles (called mesons) and this mechanism would create the attractive force. We now know about the strong nuclear force, which explains the stability of atoms. Since the 1970s physicists have continued to develop an understanding of the nucleus: they have discovered quarks, more neutrinos, the quark-gluon plasma, and how neutrinos oscillate. Much of this will be dealt with in your study of particle physics.

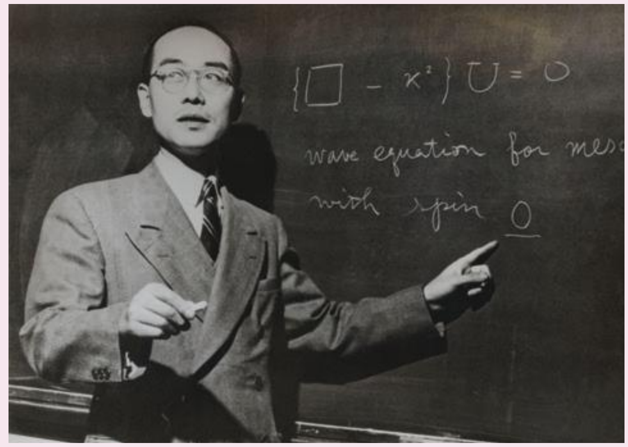

FIGURE 3 Hideki Yukawa (1907–1981), Japanese physicist, Nobel Prize winner in 1949

Apply your understanding

1 **Contrast** the original and modern understandings of nuclear stability. (2 marks)

2 **Explain** how other scientists could validate Yukawa's claims about the strong nuclear force. (2 marks)

Skill drill

Researching nuclear forces

Science inquiry skills: Understanding the scientific method (Lesson 1.3)

The strong nuclear force has several similarities to the electrostatic force, but also many important differences. These properties work together to produce a successful nuclear model of the atom.

Practise your skills

1 **Conduct** some research to **identify** and **construct** a question about the forces in a nucleus suitable for a research investigation into the nuclear model of an atom. (2 marks)

How do the numbers of protons and neutrons affect nuclear stability?

For smaller nuclei, the number of neutrons required for stability is about the same as the number of protons present – that is, they have an N/Z ratio of 1:1. For example, the most stable isotope of oxygen is $^{16}_{8}O$. It has eight protons and eight neutrons. Similarly, ordinary carbon is $^{12}_{6}C$ (6p, 6n).

However, as the number of protons increases, the strong (attractive) nuclear force becomes much weaker and it is the electrostatic (repulsive) force that dominates. So, the number of neutrons required for stability increases – the *N*/*Z* ratio becomes greater than 1:1 (around 1.5:1). Stable zinc is $^{64}_{30}Zn$, which has 30 protons and 34 neutrons, so the *N*/*Z* ratio is 1.13:1.

Table 1 lists the *N*/*Z* ratios of some common stable nuclides. The larger the atom, the greater the *N*/*Z* ratio needs to be for a stable nuclide. The *N*/*Z* ratio starts at 1.00 and increases to 1.59 for uranium.

Study tip

You need to be able to explain the stability of a nuclide in terms of the:
- strong nuclear force acting over short distances only
- electrostatic repulsion that must be overcome
- the relative number of protons and neutrons.

TABLE 1 Examples of nuclear force for some common stable nuclides

Stable nuclide	Protons (*Z*)	Neutrons (*N*)	*N*/*Z* ratio
$^{16}_{8}O$	8	8	1.00
$^{64}_{30}Zn$	30	34	1.13
$^{207}_{82}Pb$	82	125	1.52
$^{238}_{92}U$	92	146	1.59

The *N*/*Z* chart

If we plot the number of neutrons (y-axis) against the number of protons (x-axis) for all 2,500 known nuclides, we end up with a chart as shown in Figure 4. It is called an *N*/*Z* (or Segre) chart. This chart adorns the walls of every nuclear physics lab in the world. In fact, nuclear physicists probably carry laminated versions in their pockets. Ask them how radioactivity works and the first thing they go for is their chart – it is that useful!

The tiny black, red, green and yellow squares show stable nuclei, and the region where they occur is often called the "zone of stability". Outside this region, in the white area, no nuclides are found either in nature or in artificial reactions. In between these two regions are nuclides coloured from light blue to purple. These nuclides are unstable because of the competing electrostatic and strong nuclear forces. This causes them to more easily break apart.

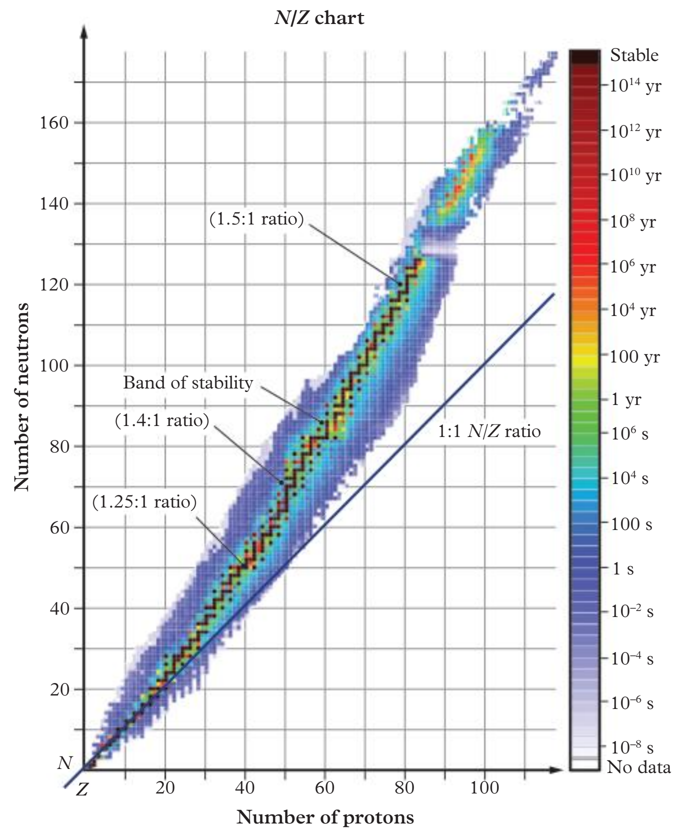

FIGURE 4 An *N*/*Z* chart showing the number of protons versus neutrons for common stable isotopes

The blue line at 45° in Figure 4 shows where the ratio of neutrons to protons is 1:1 (or $N = Z$). Progressively more neutrons are required as the proton number increases. The scale on the right shows how stable the nuclides are in terms of their half-life; this term describes their stability and you will learn more about it in Module 5. The black nuclides are very stable and last almost forever. The light blue nuclides last for a few seconds up to a year, whereas the purple nuclides exist for millionths of a second up to a few seconds. There are no completely stable nuclides above a proton number (Z) of 82 – that is, an atomic number of 82.

Check your learning 4.2

Check your learning 4.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the concept of the strong nuclear force in terms of the stability of an atom. (1 mark)

2 **Describe** what happens to a nuclide that is unstable. (1 mark)

3 **Explain** why protons in the nucleus repel each other while neutrons do not. (2 marks)

4 **Describe** the relationship between separation distance between nucleons and strong nuclear force. (2 marks)

5 **Explain** how the N/Z ratio in the nucleus affects nuclear stability. (2 marks)

6 From the graph in Figure 2, **identify** the nucleon separation distance at which the strong nuclear force is equal and opposite to the electrostatic force. (1 mark)

Analytical processes

7 **Deduce** the name of the element, the number of protons and the number of neutrons in each of the following:

- **a** Pu-244 (3 marks)
- **b** Lr-260 (3 marks)
- **c** Po-209 (3 marks)
- **d** $^{141}_{59}Pr$ (3 marks)

Analytical processes

8 **Determine** whether the following combinations are stable, using the N/Z graph in Figure 4.

- **a** $Z = 80$, $N = 85$ (1 mark)
- **b** $Z = 70$, $N = 95$ (1 mark)
- **c** $Z = 44$, $N = 90$ (1 mark)
- **d** $Z = 95$, $N = 141$ (1 mark)

9 **Determine** whether $^{90}_{30}Zn$ is stable and **justify** your answer. (2 marks)

Knowledge utilisation

10 **Evaluate** the following statement: "Nuclides will be stable if the number of neutrons exceeds the number of protons." (2 marks)

11 **Discuss** whether there is more than one nuclide that has a mass number of 90 and is stable. (2 marks)

12 **Evaluate** the following statement: "If a nuclide has an N/Z ratio of 1:1, it will not be stable." (3 marks)

MODULE 4

Lesson 4.3
Review: Nuclear model and stability

Summary

4.1
- The nuclear model of the atom states that an atom consists of a small nucleus (containing protons and neutrons) surrounded by electrons.
- Nuclides are represented using $^{A}_{Z}X$ nomenclature.
- Atomic mass is determined by mass number (number of protons and neutrons).
- Isotopes of the same element have the same number of protons but a different number of neutrons.

4.2
- Protons in the nucleus repel each other due to electrostatic repulsion.
- In stable nuclides, the strong nuclear force between neutrons and protons helps to hold protons together.
- The ratio of neutrons to protons in stable nuclides increases as the size of the atom increases.

Review questions 4.3A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 The nuclear model of an atom is best described as

A a small nucleus surrounded by electrons.
B a small package of protons, neutrons, and electrons.
C protons tightly bound to neutrons by the strong force.
D electrons orbiting a small core of protons and neutrons.

2 In the $^{A}_{Z}X$ nomenclature for nuclides, the symbols A, Z and X represent, in order

A mass number, symbol for the element, atomic number.
B symbol for the element, mass number, atomic number.
C mass number, atomic number, symbol for the element.
D atomic number, symbol for the element, mass number.

3 Isotopes are nuclei with

A same A and Z.
B same A, different Z.
C same Z, different A.
D Z greater than A.

4 Carbon-14 is depicted by the nomenclature for nuclides as

A $^{6}_{14}C$. **B** $^{14}_{6}C$. **C** $^{14}_{8}C$. **D** $^{8}_{6}C$.

5 Consider the nuclide $^{239}_{92}U$. If one extra nucleon (either proton or neutron) could be added, what would be the possible formulas for it?

A $^{240}_{92}U$ and $^{240}_{93}Np$ **B** $^{240}_{92}U$ and $^{240}_{93}U$
C $^{240}_{92}U$ and $^{239}_{93}Np$ **D** $^{239}_{93}Np$ and $^{240}_{93}Np$

6 Tritium is a hydrogen isotope with two neutrons. It is depicted by the nomenclature for nuclides as

A $^{3}_{1}H$. **B** $^{3}_{1}T$. **C** $^{2}_{1}H$. **D** $^{2}_{1}T$.

7 Protons in the nucleus repel each other because

A they have positive electric charge, so the electrostatic force is repulsive.
B they have negative electric charge, so the electrostatic force is repulsive.
C the strong force is repulsive at proton–proton distances.
D their attraction to neutrons is so weak.

8 Which of the following particles is acted on by both strong nuclear and electromagnetic forces?

A Proton **B** Neutron
C Electron **D** Atom

9 The strong nuclear force can be described as being
- **A** attractive at short ranges, attractive at long ranges.
- **B** attractive at short ranges, repulsive at long ranges.
- **C** repulsive at short ranges, attractive at long ranges.
- **D** repulsive at short ranges, repulsive at long ranges.

10 The strong nuclear force can be described as
- **A** being responsible for holding atoms together.
- **B** keeping the electrons attracted to the nucleus.
- **C** decreasing with the inverse square of the distance.
- **D** being stronger than the repulsive electrostatic forces.

11 The strong nuclear force operates between
- **A** nucleons.
- **B** protons.
- **C** protons and neutrons.
- **D** protons and electrons.

12 A nucleus becomes increasingly unstable when there is a surplus of
- **A** protons over electrons.
- **B** electrons over protons.
- **C** protons over neutrons.
- **D** neutrons over electrons.

13 The stability of a nucleus depends on
- **A** the relative number of protons and neutrons only.
- **B** the total number of protons and neutrons only.
- **C** the relative number and total number of protons and neutrons.
- **D** neither the relative number nor the total number of protons and neutrons.

Review questions 4.3B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

14 Define the terms “atomic number”, “element” and “isotope”, using hydrogen as an example. (3 marks)

15 Describe the terms “nuclide”, “nucleon”, “neutron” and “nucleus”, using carbon-12 as an example. (4 marks)

16 Calculate the number of protons and neutrons in each of the following nuclides.
- **a** Bi-216 (2 marks)
- **b** Zn-65 (2 marks)
- **c** Ba-136 (2 marks)

17 Calculate the number of protons and neutrons in each of the following.
- **a** ${}^{207}_{82}Pb$ (2 marks)
- **b** ${}^{35}_{17}Cl$ (2 marks)
- **c** ${}^{15}_{7}N$ (2 marks)
- **d** At–215 (2 marks)
- **e** ${}^{32}_{15}P$ (2 marks)

18 Identify the element represented by X in each of the following.
- **a** ${}^{233}_{92}X$ (1 mark)
- **b** ${}^{2}_{1}X$ (1 mark)
- **c** ${}^{226}_{88}X$ (1 mark)
- **d** ${}^{32}_{15}X$ (1 mark)

Analytical processes

19 Deduce the missing values from the table of nuclides to show the composition of each nuclide. (2 marks each row)

Symbol	Symbol	Protons	Neutrons	Nucleons	*A*	*Z*
$^{28}_{64}\text{Ni}$	Ni-64					
	P-30					
		29	35			
			35			30
	Kr-?			83		
					136	56
$^{228}_{89}?$						

20 For calcium isotopes with mass numbers of 40, 42, 43 and 45, determine:

a their symbols (4 marks)

b the number of neutrons in each (4 marks)

c the number of nucleons in each. (4 marks)

21 Compare strong nuclear force and the electrostatic force. (3 marks)

22 Infer why there are more neutrons than protons at high mass numbers. (3 marks)

23 Using the *N*/*Z* chart, **determine** whether the following nuclides are stable.

a $^{235}_{95}\text{Am}$ (1 mark)

b $^{250}_{100}\text{Fm}$ (1 mark)

c $^{92}_{50}\text{Sn}$ (1 mark)

d $^{180}_{80}\text{Hg}$ (1 mark)

Knowledge utilisation

24 Determine whether the nuclide $^{160}_{83}\text{Bi}$ would be stable (without referring to the *N*/*Z* chart). **Justify** your response. (2 marks)

Data drill

The abundance and stability of carbon isotopes

Carbon has many isotopes ranging from C-8 through to C-22 but there are only three that exist naturally. The percentage of these found in nature is C-12 (98.9%), C-13 (1.1%) and C-14 (<0.0001%). The rest are produced artificially in nuclear reactions.

Apply understanding

1 Determine the symbols for the three naturally occurring isotopes using $^{A}_{Z}\text{X}$ nomenclature. (3 marks)

2 Calculate the *N*/*Z* ratio for the three naturally occurring isotopes. (2 marks)

Analyse evidence

3 Classify each of C-8, C-12, C-13, C-22 as belonging to one of the four categories shown in Table 1. (4 marks)

TABLE 1 Categories for the naturally occurring isotopes of carbon

	Abundant	Not abundant
Natural		
Artificial		

Interpret evidence

4 Deduce which of the naturally occurring isotopes is the most stable. **Justify** your response. (3 marks)

5 Evaluate the following claim: “The more neutrons a carbon isotope has, the less abundant it is.” (3 marks)

Module 4 checklist: Nuclear model and stability

Quizlet: Revise key terms online to test your understanding

MODULE 5

Radioactive decay and half-life

Introduction

Radioactivity and nuclear energy have become some of the most important issues facing society. They can bring significant benefits, such as in medicine, research and industry. However, they also present a number of large risks, most of which relate to the damage they can do to living things. To work with radioactive materials safely, it is important to understand the processes in which they decay.

Prior knowledge

Prior knowledge quiz

Check your understanding of radioactivity and isotopes before you start.

Subject matter

Science understanding

→ Explain natural radioactive decay in terms of stability.
→ Describe alpha, beta positive, beta negative and gamma radiation, including the properties of penetrating ability, charge, mass and ionisation ability.
→ Explain how an excess of mass, protons or neutrons in a nucleus can result in alpha, beta positive and beta negative decay.
→ Solve problems involving balancing nuclear equations.
→ Describe spontaneous alpha, beta positive and beta negative decay using decay equations.
→ Explain how a radionuclide will, through a series of spontaneous decays, become a stable nuclide.
→ Describe the concept of half-life.
→ Solve radioactive decay problems using $N = N_0\left(\frac{1}{2}\right)^n$ and other arithmetic or graphical methods.

Science as a human endeavour

- → Appreciate the significant contributions of scientists such as Marie Curie, Irene Juliot-Curie, Lise Meitner and Otto Hahn who furthered our understanding of radiation and nuclear stability.
- → Explore advances in medical treatment and imaging that have come from a deepening understanding of the properties of nuclear radiation.
- → Consider how an understanding of radioactive decay can enable scientists to make reliable predictions in radiometric dating of materials.

Science inquiry skills

- → Investigate nuclear safety, considering the suitability of using the sources of information in terms of their credibility.
- → Examine exponential decay graphs and use these graphs to estimate half-lives.
- → Investigate shielding effects and/or the relationship between intensity and distance from a radioactive source.

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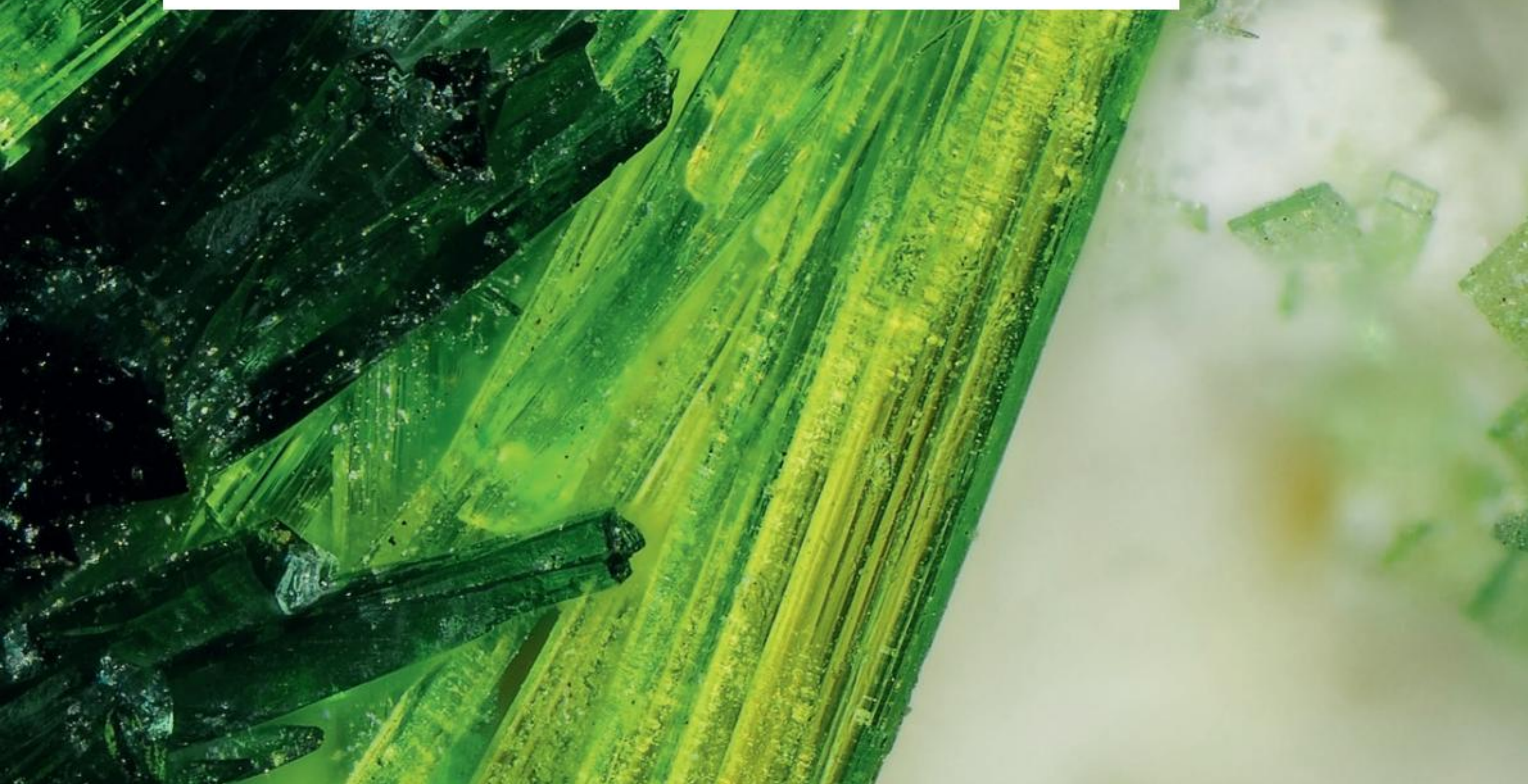
Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 5.3 Shielding effects from a radioactive source

Lesson 5.4 Intensity and distance from a radioactive source



Lesson 5.1
The discovery of nuclear radioactivity

Key ideas

- → Marie Curie and Henri Becquerel were pioneers in the research on radioactivity.
- → Radioactive decay is a spontaneous reaction in which an unstable nuclide disintegrates and emits radiation.
- → There are many different subatomic particles, each with its own distinguishing physical characteristics.

Learning intentions and success criteria

radioactive
substances which have nuclei with an excess of energy and spontaneously emit radiation to reduce excess energy

radionuclide
an unstable isotope of an element that decays or disintegrates spontaneously, thereby emitting radiation

natural radioactive decay
the process by which the nucleus of an unstable atom loses energy by emitting radiation

nuclear reaction
a reaction that alters the energy, composition or structure of an atomic nucleus

radioactivity
the loss of energy from an unstable atomic nucleus by radiation

What is radioactivity?

In the previous module, you learnt about nuclear stability and stable nuclides. These nuclides are not **radioactive**, meaning that they will not decay. The opposite is true: if a nuclide is not stable, it is considered radioactive (a **radionuclide**) and will undergo changes in its nucleus. This process is called **natural radioactive decay**. It is a **nuclear reaction**. During this spontaneous process, the radionuclide will disintegrate and emit radiation. We call this **radioactivity**.

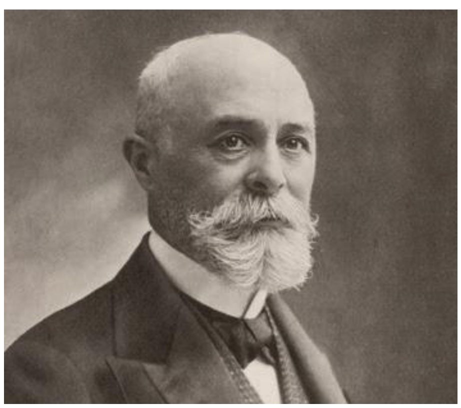


FIGURE 1 Henri Becquerel

FIGURE 2 Marie Curie

Who discovered radioactivity?

Radioactivity is all around us. The phosphorus P-32 in your bones is undergoing decay right now. Bananas contain K-40, an emitter of radioactivity. Cat litter has uranium and thorium, which also emit radioactivity. So does your granite benchtop. If radioactivity is all around us, why did it take so long to recognise its presence?

In 1896, French physicist Henri Becquerel (1852–1908) accidentally discovered that a uranium-rich mineral called pitchblende emitted radiation that could pass through paper and blacken a photographic plate. He published seven papers on the subject, then shifted his focus to the effect of magnetic fields on radiation. Two years later, a doctoral student, Marie Curie, began her study of Becquerel's rays. These led to the discovery of radionuclides and radioactivity.

Marie Curie and her husband Pierre Curie, a well-known French physicist, soon discovered two new radioactive elements. They named them polonium (after her native land, Poland) and radium (because it radiates). Shortly after completing her PhD, Marie, along with Pierre and Henri Becquerel, shared the 1903 Nobel Prize in Physics. Pierre Curie was killed in a traffic accident in 1906, but Marie Curie continued her study of radioactivity for nearly 30 more years. She was awarded the Nobel Prize in Chemistry in 1911 for her discovery of two new elements. Marie Curie died of blood cancer in 1934, most likely caused by exposure to radiation. Her books and papers are still radioactive, and you must put on gloves to handle them.

The work of Marie Curie was carried on by her daughter, Irene Joliot-Curie, and her husband Frederic Joliot, as well as many other brilliant scientists, including Lise Meitner and Otto Hahn (who Einstein called "the German Marie Curie").

What are the elementary particles?

In 1932, James Chadwick discovered the neutron and, very soon afterwards, American physicist Carl Anderson discovered another **elementary particle** – the "positive electron" or "positron". The existence of the positron had been predicted by Paul Dirac several years earlier and later detected in an experiment. This was a major change in physics as a science. Table 1 lists some important nuclear particles and forms of radiation. They are described fully in the next lesson.

elementary particle
a particle whose substructure is unknown

TABLE 1 Symbols of nuclear particles/radiation

Particle/radiation	Symbol
Alpha particle (α)	${}^{4}_{2}\mathrm{He}$
Proton	${}^{1}_{1}\mathrm{H}$ or ${}^{1}_{1}\mathrm{p}$
Neutron	${}^{1}_{0}\mathrm{n}$
Electron (β^- particle)	${}^{0}_{-1}\mathrm{e}$
Positron (β^+ particle)	${}^{0}_{+1}\mathrm{e}$
Gamma ray	γ

Check your learning 5.1

Check your learning 5.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** natural radioactive decay in terms of stability. (2 marks)

2 **Recall** the name of the particle that, before 1932, was thought to be the only particle in the nucleus. (1 mark)

3 **Recall** the name of the particle that was proposed by Paul Dirac several years before its discovery. **Explain** what makes his discovery unusual. (3 marks)

4 Use a periodic table to find out the symbols for the two elements isolated by Marie Curie. For each, **identify** the number of protons and electrons in the neutral atom. (2 marks)

5 **Explain** why you need to wear gloves when handling Marie Curie's laboratory notebooks. (2 marks)

Knowledge utilisation

6 **Investigate** the discovery of the six particles (alpha particle, proton, neutron, electron, positron and gamma ray).
   a **Identify** their dates of discovery and who discovered them. (6 marks)
   b **Sequence** them in order of discovery. (1 mark)

Lesson 5.2
Properties of nuclear radiation

Key ideas

→ Ionising radiation can remove electrons from atoms.
→ Alpha radiation has the highest ionisation ability and the lowest penetrating ability. Gamma radiation has the lowest ionisation ability and the highest penetrating ability.
→ The further away from a radioactive source, the less intense the radioactivity.
→ Very dense materials absorb more radiation and can be used for shielding.

Learning intentions and success criteria

heavy positive ion
the positively charged ion that remains after radiation has caused the removal of an electron

ionising radiation
radiation that can remove an electron from an atom and create a heavy positive ion and free electron

nuclear radiation
radiation emitted by the subatomic particles in an atomic nucleus, such as alpha, beta or gamma rays

alpha radiation
composite particle consisting of two protons and two neutrons (symbol: α or $^{4}_{2}$He) emitted from the nucleus of some radionuclides

beta positive radiation
stream of energetic positrons (symbol: β^+ or $^{0}_{+1}$e) emitted from the nucleus of some radionuclides, always accompanied by the emission of electron neutrinos

positron
a particle of matter with the same mass as an electron but a positive charge

What is nuclear radiation?

Radiation is emitted during the decay of unstable nuclei. This can be in the form of particles or rays. Any radiation that can remove an electron from an atom to create a **heavy positive ion** and free electron is termed **ionising radiation**. Ionising radiation includes electromagnetic radiation (gamma rays, X-rays and ultraviolet radiation), and energetic particles such as alpha and beta particles. Gamma rays are said to be **nuclear radiation** because they are created within the nucleus. X-rays are not nuclear radiation as they come from the electron cloud around the nucleus. In QCE Physics, we will focus on four types of nuclear radiation: alpha radiation, beta positive radiation, beta negative radiation and gamma radiation (or rays).

FIGURE 1 The presence of radioactive material is indicated using a trefoil symbol.

Visible light, another form of radiation, cannot cause ionisation of an atom as it lacks the energy – it simply gets absorbed and increases the atom's thermal energy. The energy of nuclear radiation is about a million times greater than that of visible light, and it can ionise matter and break molecular bonds.

Alpha radiation

Alpha radiation (α) or alpha particles are just helium nuclei, $^{4}_{2}$He, which are made up of two protons and two neutrons strongly bound together, giving them a mass of four units. Having two protons means alpha particles have a +2 charge. As they collide with matter, alpha particles slow down, transferring their kinetic energy to the other molecules, shaking many of them apart, and leaving a trail of positive and negative ions in their wake.

Beta positive radiation

Beta positive radiation (β^+) or beta positive particles are high-energy, high-speed **positrons** (positive electrons, $^{0}_{+1}$e) emitted from the nucleus. The formation of beta positive radiation also produces electron neutrinos. You will learn about these and their formation in the next lesson.

Beta negative radiation

Beta negative radiation (β^-) or beta negative particles are electrons, ${}^{0}_{-1}e$, emitted from the nucleus. They move at high speed, ranging from 0.3 to 0.99 times the speed of light ($3 \times 10^8\,m\,s^{-1}$) and thus have high kinetic energy. The formation of beta negative radiation also produces electron antineutrinos, which you will also learn about in the next lesson.

Gamma radiation

Gamma radiation differs from alpha and beta radiation in that it is not made up of charged particles. It has zero electric charge and zero mass. Instead, gamma rays (γ) are electromagnetic radiation of extremely short wavelength (about $10^{-13}\,m$), and thus a very high frequency (about $10^{21}\,Hz$).

beta negative radiation
a stream of energetic electrons (symbol: β^- or ${}^{0}_{-1}e$) emitted from the nucleus of some radionuclides, always accompanied by the emission of electron antineutrinos

gamma radiation
extremely high-frequency electromagnetic radiation (symbol: γ) emitted from the nucleus of some radionuclides

What are the properties of nuclear radiation?

We consider nuclear radiation in terms of three different properties:

- ionisation ability
- penetrating ability
- deflection in electric and magnetic fields.

Study tip

Radioactive particles are written using the ${}^{A}_{Z}X$ nomenclature where X = symbol for the element, A = mass number and Z = atomic number or nuclear charge. $Z = -1$ for beta negative radiation, as an electron has a negative charge, and $Z = +1$ for beta positive radiation.

Ionisation ability

All three types of nuclear radiation ionise materials. However, their ability to turn the atoms into ions by knocking electrons out of them differs, and thus each has a different **ionisation ability**. The higher the ionisation ability, the greater the ability to remove electrons from atoms.

Ionisation ability depends on:

- size (mass) of the particle – the bigger the particle, the greater the ionisation
- charge – the greater the charge, the greater the ionisation.

ionisation ability
a measure of the ability of radiation to remove electrons from a particle as it passes through it

Penetrating ability

Ionisation ability therefore determines how well the radiation penetrates (passes through) a material (i.e. its **penetrating ability**). The greater the ionisation ability, the lower the penetrating ability. This is because energy is used up during ionisation and so the radiation is not able to travel as far. Larger particles and particles that have a greater charge will have lower penetrating ability.

Figure 2 illustrates the differences in penetrating ability of the three different types of radiation. The higher the density of the substance that the radiation is passing through, the lower the penetration.

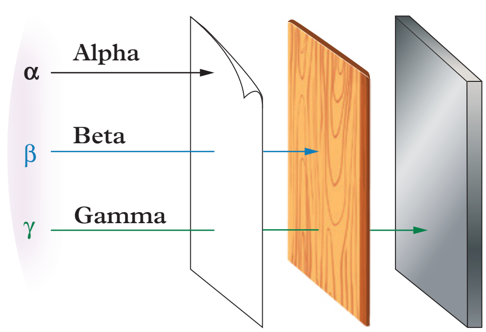


FIGURE 2 The relative penetrating power of the three types of nuclear radiation (alpha, beta, gamma) in substances of different thickness and density.

penetrating ability
the ability of each type of radiation to pass through matter

Study tip

A gamma ray is not a particle and is simply written as γ instead of using the ${}^{A}_{Z}X$ nomenclature.

Deflection in electric and magnetic fields

As nuclear particles pass through electric and magnetic fields, they are deflected. The direction and extent of their deflection depends on their mass and charge. We can therefore consider deflection in electric and magnetic fields as properties of nuclear radiation. This is shown in Figure 3.

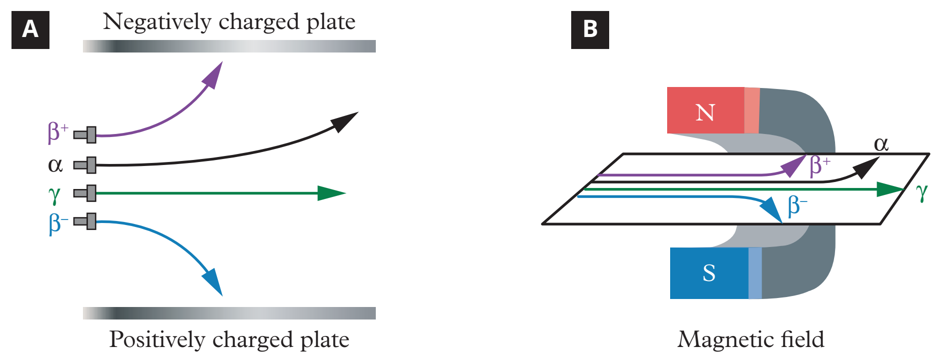


FIGURE 3 Nuclear radiation is deflected in (A) an electric field and (B) a magnetic field.

What are the properties of alpha radiation?

Alpha particles have a relatively large mass (4 amu), which makes them relatively easy to stop outside the human body. However, the electrical charge and energy of an alpha particle can cause damage to tissues over a short distance. Alpha radiation is unable to penetrate the outer layer of skin cells, but if it is eaten in food or breathed in, it can cause serious cell damage.

In an electric field, the positive alpha particles are deflected towards the opposite, negatively charged plate. When travelling at right angles to a magnetic field, they are deflected by the field. Note that not all alpha particles travel at the same speed. There is always some random variation, so there is a distribution of speeds and thus kinetic energies. The faster particles will ionise more and be slightly less deflected in electric and magnetic fields. This is true of all radiation.

What are the properties of beta radiation?

Beta positive radiation

Due to their smaller mass, beta positive particles can travel further in air than alpha particles (up to a few metres). They can be stopped by a thick piece of plastic or a stack of paper. Beta positive particles can penetrate skin a few centimetres, posing something of an external health risk. However, the main threat to human health is still primarily from internal emission from ingested material.

Like alpha particles, beta positive particles are positively charged and are therefore deflected towards the negatively charged plate in an electric field. Similarly, they are deflected when passing through a magnetic field and in the same direction as alpha particles, as they both have positive charges. Because they are lighter, beta particles are deflected more significantly than the heavier alpha particles; that is, their path is a sharper curve. Like alpha particles, they have a distribution of energies.

Study tip

You may come across beta negative and beta positive particles being referred to as “beta minus” and “beta plus” particles respectively.

Beta negative radiation

Beta negative radiation has the same penetrating properties as beta positive radiation. However, the particles are deflected in the opposite direction to beta positive particles in electric and magnetic fields because of their opposite charge.

What are the properties of gamma radiation?

Gamma rays have no charge, but they have very high energy and thus tremendous penetrating power. They interact with an electron or a nucleus in the absorbing material via a direct head-on collision. Gamma rays can be stopped by a thick or dense-enough layer of material. These materials, such as lead, make good absorbers mainly because they have many electrons available for collisions.

Of the three forms of radioactive decay, gamma rays are the most penetrating. However, under most circumstances, they cause the least amount of tissue damage over the same distance, but pose the greatest danger as they can transfer their energy to molecules throughout our body.

Gamma radiation is not deflected in electric or magnetic fields because it has no charge.

Study tip

A simple list of shielding materials for alpha, beta and gamma radiation is paper, aluminium foil and 5 cm lead respectively.

How do the forms of nuclear radiation compare?

The properties of alpha, beta positive, beta negative and gamma radiation are shown in Table 1.

TABLE 1 Summary of properties

Radiation	Symbol	Charge	Mass	Penetrating ability	Ionisation ability	Deflection in electric/magnetic fields
Alpha	α or ${}^{4}_{2}He$	2+	High (4.00 amu)	Low	High	Yes
Beta positive (positron)	β^{+} or ${}^{0}_{+1}e$	1+	Low (0.000549 amu)	Medium	Medium	Yes
Beta negative (electron)	β^{-} or ${}^{0}_{-1}e$	1−	Low (0.000549 amu)	Medium	Medium	Yes (opposite to α and β^{+})
Gamma	γ	0	Nil	High	Low	No

How do you stay safe around radioactive materials?

Ionising radiation is invisible. The only way you know that it is present – other than by symptoms of the damage it may be causing – is by using a radiation detector. In 1896, Becquerel used a photographic plate to detect radiation. In more modern times, we use a device called the Geiger counter.

The number of counts per second is a measure of the **intensity** (I) of the radiation from the source at that point. This is the average power per unit area ($W\,m^{-2}$) carried by the radiation. For a single source, it can be quantified as the number of counts per second (cps).

There are two main factors that affect the intensity of radiation: distance and shielding.

intensity
the average power per unit area ($W\,m^{-2}$) carried by radiation; the number of counts per second registered on a Geiger counter

Intensity and distance

Radiation spreads out in all directions from a source like light from a light bulb. It is like a sphere of increasing surface area. As the surface area of a sphere is proportional to the square of the radius, it should be no surprise that if intensity I is inversely proportional to surface area, it is also inversely proportional to radius squared. Hence, we have a $I \propto \frac{1}{r^2}$ relationship (Figure 4).

Study tip

Inverse-square relationships are introduced in Lesson 1.7 of the Physics toolkit. This is one of the most universal relationships in physics, so it may be worth revising it now.

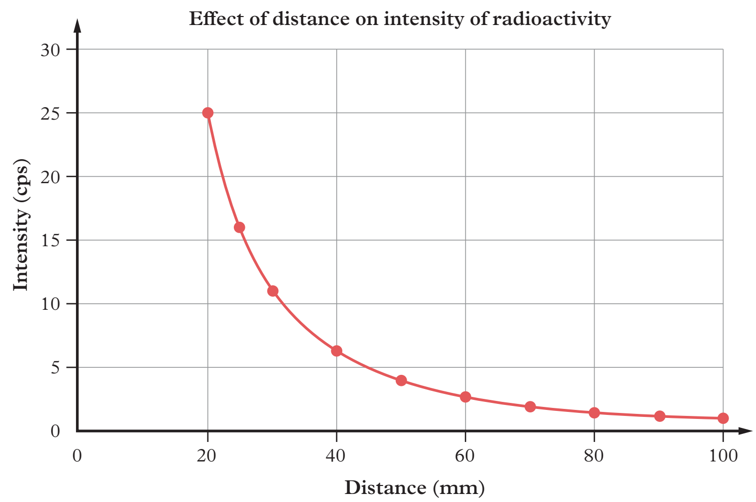


FIGURE 4 The intensity of radioactivity has an inverse-square relationship with distance from the source.

For a given source, this relationship gives us $\frac{I_1}{I_2} = \frac{(r_2)^2}{(r_1)^2}$, which enables us to calculate the change in intensity (from I_1 to I_2) when the distance changes (from r_1 to r_2).

Worked example 5.2A

Calculating the intensity of radioactivity at different distances

A Sr-90 source of beta negative particles has an intensity of 800 cps at a distance of 20.0 cm from the source. **Calculate** the intensity (3 s.f.) at

a 60.0 cm from the source (2 marks)

b 15.0 cm from the source. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the formula to determine intensity. The questions are worth 2 marks each, so we must gather the correct information and correctly apply the formula to complete the calculations.
Step 2: Identify the appropriate equation and gather any data you require.	$\frac{I_1}{I_2} = \frac{(r_2)^2}{(r_1)^2}$ $I_1 = 800$ cps, $r_1 = 20.0$ cm **a** $I_2 = ?$, $r_2 = 60.0$ cm **b** $I_2 = ?$, $r_2 = 15.0$ cm
Step 3: Rearrange the equation so that you can calculate the unknown value(s).	$I_2 = \frac{I_1 \times (r_1)^2}{(r_2)^2}$

Think	Do
Step 4: Substitute values into the equation to find the unknown.	**a** $I_2 = \frac{800 \times (20.0)^2}{(60.0)^2}$ (1 mark) $= 88.9$ **b** $I_2 = \frac{800 \times (20.0)^2}{(15.0)^2}$ (1 mark) $= 1{,}420$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures.	**a** 88.9 cps (1 mark) **b** 1,420 cps (1 mark)

Your turn

An americium-241 source of alpha particles has an intensity of 155 cps at a distance of 10.0 cm from the source. **Calculate** (3 s.f)

a the intensity at 17.0 cm (2 marks)

b the distance at which the intensity will be 250 cps. (2 marks)

Intensity and shielding effects

How much radiation penetrates matter depends on the type of matter and its density. A high atomic mass substance such as lead is very dense and can stop most radiation, providing it is thick enough. This means that lead is a good "shield". If you have had any X-rays, you will know that, sometimes, they get you to wear a lead apron to protect your body from stray radiation. The thicker the lead, the greater the shielding ability.

It seems logical that intensity would vary inversely with thickness. However, this is not quite the case. The relationship is one of exponential decay (Figure 6). The graph shows the results of an experiment using a Sr-90 beta negative source 10 cm away from a detector, with strips of aluminium foil placed between them to act as a shield. The intensity is 55 cps with no shielding, and as layers are added, the intensity drops exponentially. At six layers, the intensity has dropped to half its starting value – that is, from 55 cps to 22.5 cps. This thickness is called the half-value layer (HVL). This value is used to design protective equipment for workers in a radioactive environment.

FIGURE 5 X-ray clinics use lead aprons to shield patients from ionising radiation.

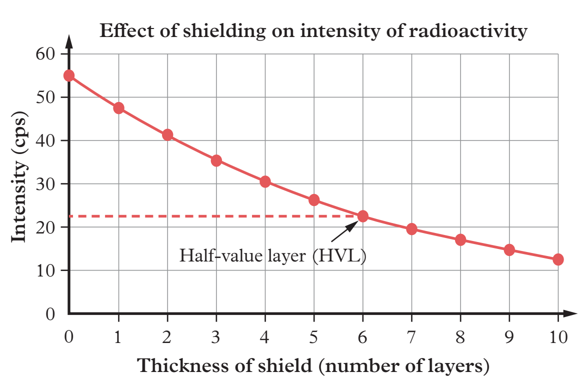


FIGURE 6 The intensity of radiation from a radioactive Sr-90 source has an exponential decay relationship with the thickness of aluminium shielding.

Study tip

The intensity vs thickness of shield graph looks like an inverse-square relationship, but it is not! See how the *y*-intercept is at 55 cps? With inverse and inverse-square relationships, the line never reaches the *y*-axis. In fact, as *x* approaches 0, *y* approaches infinity. The *y*-axis is called an asymptote.

Check your learning 5.2

Check your learning 5.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the term "ionising radiation". (1 mark)
2 **Explain** the relationship between ionisation ability and penetrating ability, using alpha particles as an example. (3 marks)
3 **Explain** why an alpha particle is considered dangerous even though it cannot penetrate human skin. (2 marks)

Analytical processes

4 **Compare** the ionisation ability and penetrating ability of the following pairs of nuclear particles.
  a A beta positive particle and an alpha particle (3 marks)
  b A gamma particle and a beta negative particle (3 marks)
  c A beta positive particle and a beta negative particle (3 marks)
5 A strontium-90 source has an intensity of 80 cps at a distance of 30.0 cm. **Calculate** the intensity (3 s.f.) if the distance to the source is tripled. (2 marks)

Knowledge utilisation

6 Nuclear particles can be deflected by a magnetic field, as shown in Figure 3B. Three factors affect this: (i) opposite charges will deflect in opposite directions; (ii) the greater the charge, the greater the deflection; (iii) the greater the mass, the smaller the deflection. **Propose** how a proton and an alpha particle differ in their deflections in a magnetic field. (3 marks)
7 **Assess** why alpha particles are not all the same and have different penetrating abilities even though they are all made of two protons and two neutrons. (2 marks)
8 **Predict** whether the half-value layer (HVL) in Figure 6 would increase, decrease or stay the same if lead foil of the same thickness was used. (3 marks)
9 **Evaluate** the following claim: "Gamma radiation has a high penetrating ability, making it more dangerous than alpha radiation, which cannot travel as far." (4 marks)

Practical

Lesson 5.3
Shielding effects from a radioactive source

Learning intentions and success criteria

Video demonstration

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Practical

Lesson 5.4
Intensity and distance from a radioactive source

Learning intentions and success criteria

Video demonstration

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Lesson 5.5
Balancing nuclear equations

Key ideas

→ Radioactive decay can be represented by balanced nuclear equations.

How do we represent radioactive decay?

Learning intentions and success criteria

The world is made up of stable nuclei – atoms don't all just disintegrate in front of us. But there are some atoms that are radioactive and decay or disintegrate into other types of atoms. Some nuclei, such as palladium-221, may last for only 6 microseconds, whereas lead-206 will last for billions of years and is said to be infinitely stable. Between these two extremes are nuclei that may exist for seconds, hours, days or years before decaying. For example, another isotope of lead, Pb-214, will typically last for 27 minutes before decaying.

When the original unstable "parent" nucleus decays, it produces a "daughter" nucleus and at least one other particle. The reaction can be written as a worded chemical equation:

parent nucleus → daughter nucleus + particle(s)

For example:

uranium-238 → thorium-234 + alpha particle

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

These are called nuclear equations.

Study tip

On the products side of a reaction, it does not matter if you write the particle first or the daughter nucleus first.

How do we balance nuclear equations?

We must check that the nuclear equations are "balanced", as we do with chemical reactions. When an equation is balanced, the sum of the mass numbers and nuclear charges on each side are equal. There are three rules to follow in order to balance a nuclear reaction:

FIGURE 1 Radioactive atoms continue to release dangerous radiation for a long time. Waste containing these atoms might need storage for thousands of years.

1 **The sum of the mass numbers on the left of the equation must equal the sum of the mass numbers on the right side.** In the example, 234 + 4 = 238, so this rule is obeyed.
2 **The total charge on the left side of the equation must equal the total charge on the right side.** This is to obey the **law of conservation of electric charge**. "Charge" refers to the nuclear charge of the radioactive atom and its emitted particles. A proton ($^{1}_{1}H$) has a charge of +1, and so does a beta positive particle ($^{0}_{+1}e$). An electron ($^{0}_{-1}e$) has a charge of –1. In the example, the left side shows 92 protons, so the charge is +92 or simply 92. The sum of the nuclear charges on the right is 90 + 2 = 92, so the rule is obeyed.
3 **Coefficients must be used to show when multiple particles are emitted.** For example, if two alpha particles are emitted, they should be written as $2^{4}_{2}He$.

law of conservation of electric charge the total electric charge of an isolated system remains constant regardless of changes within the system

Worked example 5.5A

Balancing nuclear equations

Determine X (in the form $^{A}_{Z}X$) for the following nuclear equation and write your answer as a balanced nuclear equation. (2 marks)

$$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + X$$

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to ascertain after consideration. We need to find X. The question is worth 2 marks, so we must work out what X is and express it in the correct format.
Step 2: Recall rule 1, which states that the sum of the mass numbers (top numbers) on each side of the equation must be equal. Determine the mass number for X (the daughter nucleus) by subtracting the mass number for the alpha particle from the mass number of the parent nucleus.	226 – 4 = 222 Therefore, A = 222.
Step 3: Recall rule 2, which states that the sum of the nuclear charges (bottom numbers) on $^{A}_{Z}X$ on each side of the equation must be equal. Determine the atomic number for X (the daughter nucleus) by subtracting the atomic number for the alpha particle from the atomic number of the parent nucleus.	88 – 2 = 86 Therefore, Z = 86.
Step 4: Use the atomic number to identify the element and write the parent nucleus in $^{A}_{Z}X$ form.	Z = 86 is radon, so X = Rn. $^{222}_{86}Rn$ (1 mark)
Step 5: Finalise your answer.	$^{226}_{88}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{86}Rn$ (1 mark)

Your turn

Determine the symbol for the nuclide undergoing decay in the form $^{A}_{Z}X$ for the following nuclear equation. (2 marks)

$$X \rightarrow {}^{235}_{Z}U + {}^{4}_{2}He$$

Check your learning 5.5

Check your learning 5.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Recall** the three rules for balancing an equation. (3 marks)

2 **Identify** the charge on the nucleus of radionuclide $^{14}_{6}C$. (1 mark)

3 **Describe** what the symbol $3\,^{0}_{+1}e$ represents. (2 marks)

Analytical processes

4 **Deduce** the number of neutrons in $2\,^{4}_{2}He$. (2 marks)

5 For the following symbols, **determine** the number of protons and neutrons present.

- **a** $^{234}_{92}U$ (2 marks)
- **b** Th-230 (2 marks)

6 **Deduce** the symbol (in the form $^{A}_{Z}X$) of an atom with 24 protons and 30 neutrons. (1 mark)

7 **Determine** the product (in the form $^{A}_{Z}X$) of each of the following equations.

- **a** $^{214}_{83}Bi \rightarrow {}^{0}_{-1}e$ + ? (1 mark)
- **b** $^{234}_{93}Np \rightarrow {}^{0}_{+1}e$ + ? (1 mark)
- **c** $^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn$ + ? (1 mark)
- **d** $^{45}_{20}Ca \rightarrow {}^{0}_{-1}e$ + ? (1 mark)
- **e** $^{58}_{29}Cu \rightarrow {}^{0}_{+1}e$ + ? (1 mark)
- **f** $^{234}_{94}Pu \rightarrow {}^{4}_{2}He$ + ? (1 mark)

Knowledge utilisation

8 **Justify** why this equation appears balanced but contains errors: $^{5}_{7}N \rightarrow {}^{5}_{6}C + {}^{0}_{+1}e$. (2 marks)

Lesson 5.6
Types of radioactive decay

Key ideas

→ Radionuclides can undergo alpha, beta positive, beta negative or gamma decay.

→ The type of decay can be predicted by looking at the type of nuclide instability – that is, whether there is an excess of mass, neutrons or protons in a nucleus.

→ The decay series shows the successive chain of decay that a nuclide goes through.

What are the types of radioactive decay?

There are three main ways in which nuclei undergo natural radioactive decay: alpha decay, beta negative (electron) decay and beta positive (positron) decay. The name of each indicates what sort of particle is produced. The type of decay that occurs depends on the type of nuclide instability – specifically, whether there is an excess of:

- protons and neutrons – too much mass (alpha decay)
- only neutrons (beta negative decay); or
- only protons (beta positive decay).

Learning intentions and success criteria

Study tip

The terms "nucleus" and "nuclide" are often used interchangeably.

How does alpha decay occur?

Alpha decay occurs when there is too much mass. For example, atoms heavier than uranium-238 do not occur naturally because they have too many neutrons and protons to be stable. They have too much mass for the nuclear "glue" to work.

Because the strong nuclear force is a short-range force, it acts only between neighbouring nucleons. However, the repulsive electrostatic force can act across the whole nucleus. For very large nuclei, the large number of protons means the total repulsive force is great compared with the attractive strong nuclear force between nucleons, which cannot hold the nucleus together. The only way to achieve stability is to shed some protons and neutrons. This occurs in packets of two protons and two neutrons as fast-moving, energetic alpha particles or helium nuclei (${}^{4}_{2}He$, Figure 1). The daughter nucleus has two fewer protons and two fewer neutrons than the parent.

alpha decay
a type of radioactive decay caused by an excess of mass in a nuclide, releasing a ${}^{4}_{2}He$ nucleus (two protons, two neutrons)

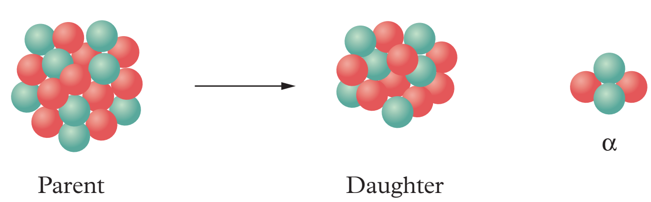


FIGURE 1 In alpha decay, mass is shed in the form of alpha particles.

Study tip

The reactant and product nuclides in radioactive decay are called "parent" and "daughter" nuclides for historical reasons. It was borrowed from biology in 1938 when referring to cell fission. There is no such thing as a "son nuclide".

This can be represented with the equation:

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He + \gamma $$

where X is the parent nucleus and Y is the daughter nucleus. In the daughter nucleus, the mass number is $A - 4$ (since a total of four nucleons are removed) and the atomic number is $Z - 2$ (since a total of two protons are removed).

The daughter nuclides produced by alpha decay often have their neutrons and protons in an "excited" (high energy) state. The excess energy associated with this excited state is released in the form of a photon in the gamma ray (γ) portion of the electromagnetic spectrum. Most of the time, the gamma ray is emitted within 10^{-12} seconds of alpha particle emission. An example of natural alpha decay is:

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He} + \gamma$$

This is considered a **transmutation**, as the element's identity has changed. In the example, uranium has become thorium.

transmutation
the change of one chemical element into another by a nuclear reaction

What are neutrinos?

In the 1920s, accurate measurements of the masses of reactants and products in the formation of beta radiation showed that the masses were not equal. Some mass appeared to be lost. Physicists were troubled by the prospect of the law of conservation of mass being violated. In 1930, Wolfgang Pauli (1900–1958) proposed an alternative solution: the missing mass was being carried off by a particle of zero charge and negligible mass that made it difficult to detect. The Italian physicist Enrico Fermi (1901–1954) suggested the name **neutrino**, meaning "little neutral one".

As they have no charge, their atomic number in $^{A}_{Z}\text{X}$ nomenclature is zero ($Z = 0$). Although the evidence is still not 100% clear, their mass is also considered to be zero or close to zero. For balancing equations, it is considered zero, so $A = 0$. Neutrinos, therefore, have the symbol $^{0}_{0}\nu_e$, but are generally written simply as ν_e.

There are currently six types of neutrinos, but those relevant to beta decay are the electron neutrino and its **antiparticle**, the electron **antineutrino** ($^{0}_{0}\bar{\nu}_e$ or just $\bar{\nu}_e$).

Study tip

Neutrinos interact so weakly that they are almost never observed directly, but they play a fundamental role in particle physics and should be included in your equations.

neutrino
an elementary subatomic particle very similar to an electron, but without electrical charge and with a very small mass (symbol: $^{0}_{0}\nu_e$ or ν_e)

antiparticle
a particle with the same mass but opposite charge to its corresponding particle; for example, a positron is an antiparticle of the electron, and vice versa

antineutrino
an elementary subatomic particle without electrical charge and with negligible mass; electron antineutrinos are associated with beta negative decay

beta negative decay
a type of radioactive decay caused by an excess of neutrons in a nuclide, releasing an energetic electron ($^{0}_{-1}\text{e}$) and associated electron antineutrino ($\bar{\nu}_e$)

How does beta negative decay occur?

Beta negative decay occurs when there are too many neutrons in the nucleus for the number of protons. The parent nucleus will emit an electron and an electron antineutrino. The daughter nucleus will have one more proton and one fewer neutron than its parent, but why?

One of the neutrons becomes a proton and, in the process (to conserve charge), an electron is released. In fact, neutrons decay in this manner. Outside the nucleus, neutrons ($^{1}_{0}\text{n}$) are only stable for about 10.2 minutes before they decay into a proton ($^{1}_{1}\text{p}$), an electron ($^{0}_{-1}\text{e}$) and an electron antineutrino ($\bar{\nu}_e$):

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$$

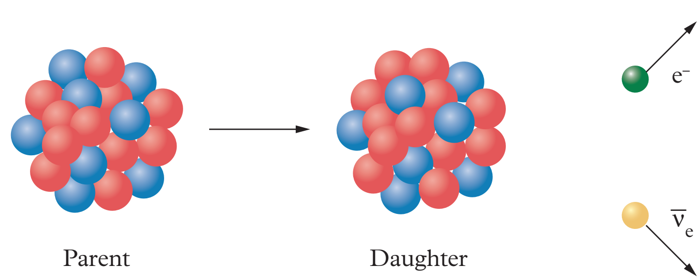


FIGURE 2 In beta negative decay, electrons and antineutrinos are shed.

A beta negative particle is an electron that has come from the nucleus. The symbol $^{0}_{-1}\text{e}$ stands for an electron that has a charge of –1 (i.e. $Z = -1$) and a negligible mass (the mass number $A = 0$). When a parent nucleus emits a beta particle, the daughter nuclide produced has the same mass number as the parent:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu}_e + \gamma(\text{energy})$$

When there is excess energy in the nucleus remaining after beta particle emission, a gamma ray is released. However, this does not always occur. Two examples of beta negative decay are:

$$^{239}_{92}U \rightarrow {}^{239}_{93}Np + {}^{0}_{-1}e + \bar{\nu}_e + \gamma(\text{energy})$$

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \bar{\nu}_e$$

The number of nucleons has not changed, but the daughter nuclide has one more proton than the parent. Beta negative decay involves transmutation.

How does beta positive decay occur?

Beta positive decay (β^+) occurs when there are too many protons in the nucleus for the number of neutrons. It is also known as positron decay. A positron is a positive electron, represented as ${}^{0}_{+1}e$, β^+ or e^+. It has the same mass as an electron ($A = 0$), but it has the opposite charge. Therefore, its atomic number is said to be $Z = +1$, the same as its charge.

In beta positive decay, the number of nucleons (A) does not change. But, when the number of protons decreases, a proton changes into a neutron and a positron is ejected along with an electron neutrino:

$$^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + \nu_e$$

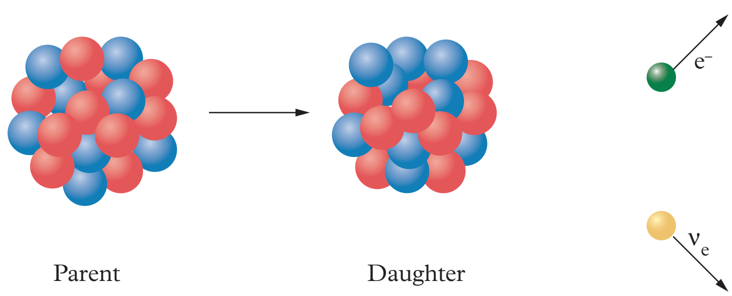


FIGURE 3 In beta positive decay, positrons and neutrinos are shed.

However, an isolated proton does not change into a neutron and a positron. This would seem impossible as the mass of a neutron is heavier than that of a proton; this would therefore require energy. Remember, we are talking about spontaneous decay – that is, no energy is required. Instead, positron emission occurs when the nucleus of an atom rearranges. The mass of the parent nuclide is heavier than that of the daughter nuclide and the positron, so energy would be released.

When the positron collides with its antiparticle, an electron, they annihilate each other and give out a burst of gamma rays. The gamma rays travel in opposite directions:

$${}^{0}_{+1}e + {}^{0}_{-1}e \rightarrow 2\gamma$$

Two examples of beta positive emission are:

$$^{23}_{12}Mg \rightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + \nu_e$$

$$^{40}_{19}K \rightarrow {}^{40}_{18}Ar + {}^{0}_{+1}e + \nu_e$$

As you can see, beta positive emissions are the products of transmutations.

beta positive decay
a type of radioactive decay caused by an excess of protons in a nuclide, releasing a positron (${}^{0}_{+1}e$) and associated electron neutrino (ν_e)

Study tip

If you are finding it hard to remember which type of nuclide instability is associated with which particle, try remembering the following:
"Too many **N**eutrons give beta **N**egative."
"Too many **P**rotons give beta **P**ositive."

Study tip

You don't need to include gamma ray emission in a nuclear equation unless the question instructs you to. Not all beta decay reactions release gamma rays.

Study tip

You can determine whether alpha, beta positive or beta negative decay has occurred by comparing the mass and atomic numbers of the parent and daughter nuclides.

Worked example 5.6A

Balancing nuclear equations

Determine X and Y (in the form ${}^{A}_{Z}X$) for the following nuclear equation and write your answer as a balanced nuclear equation. (3 marks)

$${}^{23}_{12}Mg \rightarrow {}^{23}_{11}Na + X + Y$$

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to ascertain after consideration. We need to find X and Y. The question is worth 3 marks, so we must work out what X and Y are and express them in the correct format.
Step 2: Recall rule 1, which states that the sum of the mass numbers (top numbers) on each side of the equation must be equal. Determine the mass number for X by subtracting the mass number for the daughter nuclide from the mass number of the parent nuclide.	23 – 23 = 0
Step 3: Recall which particle has a mass number of zero (0).	Only electrons (${}^{0}_{-1}e$), positrons (${}^{0}_{+1}e$) or neutrinos (${}^{0}_{0}\nu_e$) have a mass number of 0 (A = 0). There is not enough information to decide which of these three it is.
Step 4: Recall rule 2, which states that the nuclear charges (bottom numbers) on each side of the equation must be equal. Determine the charge for X by subtracting the atomic number for the daughter nuclide from the atomic number of the parent nuclide.	12 – 11 = +1
Step 5: Use the atomic number to identify the element and write the parent nucleus in ${}^{A}_{Z}X$ form. Since Z = +1, X must be either a proton (${}^{1}_{1}H$) or positron (${}^{0}_{+1}e$).	X must be a positron (${}^{0}_{+1}e$), since A = 0. (1 mark)
Step 6: Substitute X into the equation.	${}^{23}_{12}Mg \rightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + Y$
Step 7: Recognise the type of decay that has occurred and identify Y.	Since a positron is emitted, the process is beta positive decay. Thus, Y must be a neutrino (ν_e). (1 mark)
Step 8: Finalise your answer.	${}^{23}_{12}Mg \rightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + \nu_e$ (1 mark)

Your turn

Determine X and Y (in the form ${}^{A}_{Z}X$) for the following nuclear equation and write your answer as a balanced nuclear equation. (4 marks)

$${}^{3}_{1}H \rightarrow {}^{3}_{2}He + X + Y$$

Real-world physics

Breakthrough experiments on beta positive decay

Dr Joan Freeman was an Australian physicist born in Perth, WA, in 1918. She was educated at the Sydney Church of England Girls' Grammar School and the University of Sydney. It was the news, in 1932, that physicists had succeeded in "splitting the atom" that inspired her to consider a career in scientific research. She received a scholarship to work at the Cavendish Laboratory in Cambridge. Here, she obtained her PhD through research into short-range alpha particles and then began her research into beta decay at the British Atomic Energy Research Establishment.

Freeman was part of a team at Birmingham University carrying out experiments on beta decay that lead to uncovering a new elementary particle, the W boson. This was confirmed 13 years later in the USA and remains a part of current "Standard Model", which you will learn about in Unit 4.

Freeman experienced fearsome discrimination in her early years but never let it get her down. In 1976, she became the first woman and the second Australian to be awarded the British Institute of Physics' prestigious Rutherford Medal.

Apply your understanding

1 **Construct** a balanced nuclear equation to show the beta decay of O-14 to form N-14. (2 marks)
2 The W boson is considered an elementary particle. **Describe** what this term means. (1 mark)

FIGURE 4 Dr Joan Freeman at Harwell Laboratory with a spectrometer she designed.

How does gamma decay occur?

Unlike the alpha and beta decay, which occur as a result of an excess of subatomic particles, **gamma decay** occurs when an atomic nucleus drops from a high-energy "excited" state to a lower energy "ground" state, releasing gamma radiation.

gamma decay a type of radioactive decay in which an unstable atomic nucleus dissipates energy by emitting gamma radiation

Just as electrons transition from one "excited" energy level (shell) to a lower "ground" level and emit electromagnetic radiation, the nucleus drops from an excited energy level to a lower one and emits gamma radiation. Gamma photons (particles of radiation) have a million times more energy than photons of visible light and even thousands of times more than X-rays.

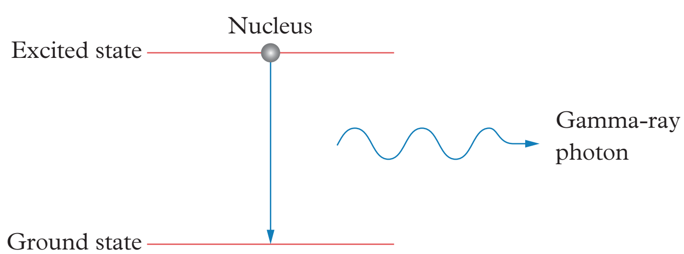


FIGURE 5 Gamma decay occurs when the nucleus shifts from a high energy state to a lower one.

In pure gamma decay, there is no change to the number of protons or neutrons, and therefore no transmutation. Only energy in the form of electromagnetic radiation of a particular wavelength and frequency is released from within the nucleus.

The following equation shows Co-60 undergoing beta decay to form an "excited" Ni-60 nucleus (as indicated by the asterisk), which then decays to the ground state by two successive gamma ray emissions:

$$^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni}^* + {}^{0}_{-1}\text{e}$$
$$^{60}_{28}\text{Ni}^* \rightarrow {}^{60}_{28}\text{Ni} + 2\gamma$$

Study tip

The band of stability is sometimes called the "zone", "region" or "valley" of stability.

Study tip

Remember the 3N and 3P rules:
Negative side, excess of **N**eutrons, beta **N**egative decay.
Positive side, too many **P**rotons, beta **P**ositive decay (Figure 6).
Your teacher may call the left-hand side "above the band of stability" and the right-hand side "below the band of stability".

How can you use the *N*/*Z* chart to predict type of decay?

We can use the *N*/*Z* chart to predict the type of decay radionuclides will undergo. Those on the left or negative side of the band of stability have too many neutrons to be stable. For example, when the number of protons is 40, stable nuclides shown in black have about 50 neutrons. The nuclides further up the 40-proton line are shown in blue and purple and are unstable.

To become stable, these nuclides need to lose some neutrons. Nuclides cannot lose neutrons but they can convert a neutron into a proton and thus undergo nuclear decay. In the process, they give off a beta negative particle. Therefore, nuclides on the negative side of the graph have too many neutrons and undergo beta negative decay.

Nuclides on the right-hand side have an excess of protons. To get rid of some protons, the nuclide can convert them to neutrons by beta positive decay.

There are no stable nuclides with an atomic number *Z* (protons) greater than 82 (lead). We say that any nuclide with $Z > 82$ has "an excess of mass" and will undergo alpha decay.

What do decay series show?

Sometimes a radioactive isotope decays into a daughter isotope that is also radioactive. This daughter isotope then decays into another isotope, which decays further, and so on. This successive chain of decays is called a **decay series**. These chains are best shown as a graph.

decay series
a sequence of nuclides formed by successive radioactive decays until a stable decay product, the end product, is formed

Figure 7 shows the uranium–lead decay series. U-238 undergoes alpha decay to Th-234, which in turn undergoes beta decay, and so on until the stable isotope Pb-206 is reached.

In alpha decay, ${}^{4}_{2}He$ is lost, so the mass number decreases by 4 and the atomic number decreases by 2. This appears as a diagonal downward arrow in the decay series. Beta negative decay (in which $n \rightarrow p$) has no effect on mass number, so it appears as an arrow pointing to the right. Beta positive decay appears as an arrow pointing to the left.

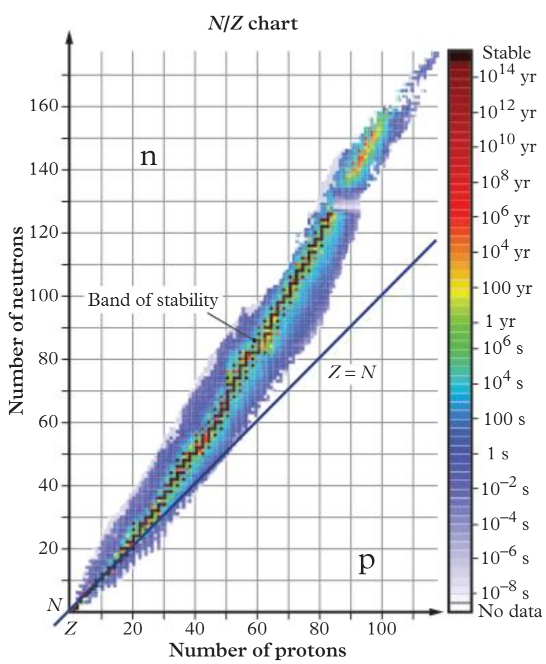


FIGURE 6 In this *N*/*Z* chart, the "n" stands for negative side, excess of neutrons and beta negative decay. The "p" stands for positive side, excess of protons and beta positive decay.

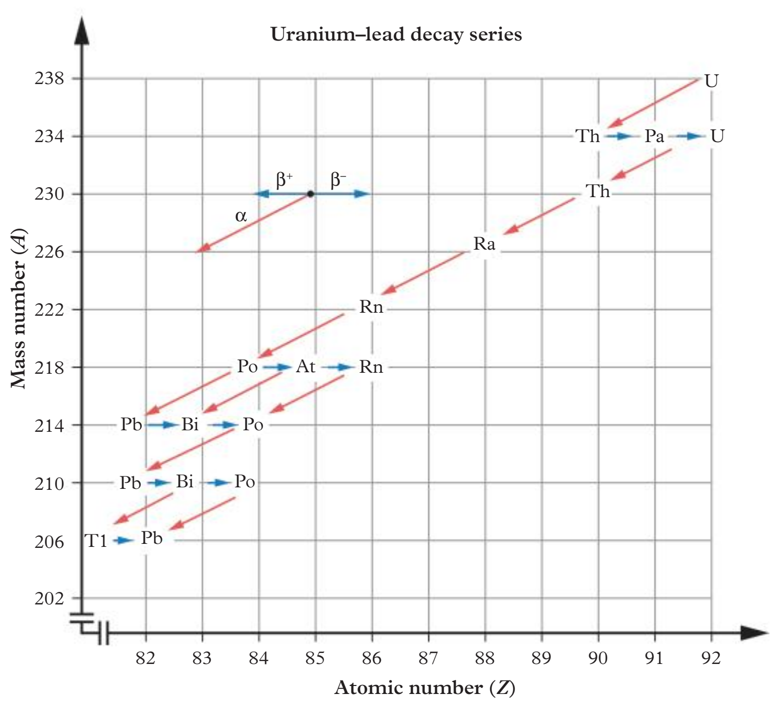


FIGURE 7 The uranium–lead decay series shows nuclide decay to Pb-206 via a number of different routes.

In the uranium–lead decay series, note that there are several paths the sequence can take. For example, Po-218 can undergo alpha decay to Pb-214 or beta negative decay to At-218. The series ends at the stable lead isotope Pb-206. Other radioactive series also exist.

Check your learning 5.6

Check your learning 5.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the differences between alpha, beta positive, beta negative and gamma decay. (4 marks)

2 **Explain** how a radionuclide will, through a series of spontaneous decays, become a stable nuclide. (2 marks)

3 **Describe** what is meant by a decay series. (1 mark)

Analytical processes

4 **Determine** equations for the beta negative decay of

- **a** C-14 (3 marks)
- **b** Na-24 (3 marks)
- **c** P-32. (3 marks)

5 **Determine** equations for the beta positive decay of

- **a** ^{22}Na (3 marks)
- **b** ^{18}F. (3 marks)

6 **Interpret** the meaning of the following equations

$^{241}_{95}Am \rightarrow ^{237}_{93}Np^* + ^{4}_{2}He$

$^{237}_{93}Np^* \rightarrow ^{237}_{93}Np + \gamma$ (2 marks)

7 **Determine** the composition of two new heavy nuclides that have been prepared recently, given these incomplete equations.

- **a** $^{249}_{98}Cf + ^{12}_{6}C \rightarrow 4\,^{1}_{0}n + ?$ (1 mark)
- **b** $^{242}_{94}Pu + ^{22}_{10}Ne \rightarrow 4\,^{1}_{0}n + ?$ (1 mark)

Knowledge utilisation

8 **Deduce** the type of decay in the following reactions using the N/Z chart in Figure 6. **Justify** your choice by referring to an excess of mass, protons or neutrons.

- **a** $^{180}_{80}Hg$ (2 marks)
- **b** $^{102}_{50}Sn$ (2 marks)
- **c** $^{250}_{100}Fm$ (2 marks)
- **d** $^{223}_{95}Am$ (2 marks)

9 **Deduce** the type of decay, if any, in the following reactions. **Justify** your choice by referring to an excess of mass, protons or neutrons.

- **a** $^{100}_{40}Zr$ (1 mark)
- **b** $^{80}_{30}Zn$ (1 mark)
- **c** $^{229}_{90}Th$ (1 mark)
- **d** $^{95}_{45}Rh$ (1 mark)

10 **Deduce** the type of decay, if any, in the following reactions. **Justify** your choice by referring to an excess of mass, protons or neutrons.

- **a** $^{115}_{50}Sn$ (2 marks)
- **b** $^{25}_{10}Ne$ (2 marks)
- **c** $^{159}_{65}Tb$ (2 marks)
- **d** $^{219}_{85}At$ (2 marks)

11 **Construct** equations showing the two steps in the beta negative decay of Ir-192, which produces an intermediate excited nuclide that further decays by gamma emission. (6 marks)

Lesson 5.7
Half-life

Key ideas

→ Half-life is the time it takes for half of the quantity of a radionuclide to decay.

→ Radiometric dating is used to determine the age of materials based on their radioactivity.

Learning intentions and success criteria

What is half-life?

Radioactive decay is a random event. It is quite impossible to predict when a particular nucleus will decay, but it is possible to predict the number of nuclei that will decay in a given time from a particular source.

For example, N-13 undergoes beta positive decay to form C-12:

$$^{13}_{7}\text{N} \rightarrow {}^{12}_{6}\text{C} + {}^{0}_{+1}\text{e} + \nu_e$$

Suppose we started with a sample containing 10,000 N-13 nuclei (N = 10,000, where N is the number of atoms). After 10 minutes, there would be about 5,000 N-13 nuclei left (N = 5,000, half the starting number) and the rest would have decayed into C-12. After another 10 minutes, there would be about 2,500 nuclei of N-13 left (N = 2,500, half of 5,000). A further 10 minutes would take the number down to 1,250 nuclei of N-13 (N = 1,250, half of 2,500). The period of 10 minutes in which half the N-13 nuclei decay is called the **half-life** ($t_{\frac{1}{2}}$). This is shown in Table 1 and Figure 1. Each radioactive nucleus has a different half-life.

half-life
the time taken for half of the atoms in a sample of the material to undergo radioactive decay (symbol: $t_{\frac{1}{2}}$)

TABLE 1 Decay of a sample of N-13, where N_0 is the initial number of nuclei

Time elapsed, t (minutes)	Number of N-13 nuclei remaining, N
0	10,000 (= N_0)
10	5,000
20	2,500
30	1,250
40	625

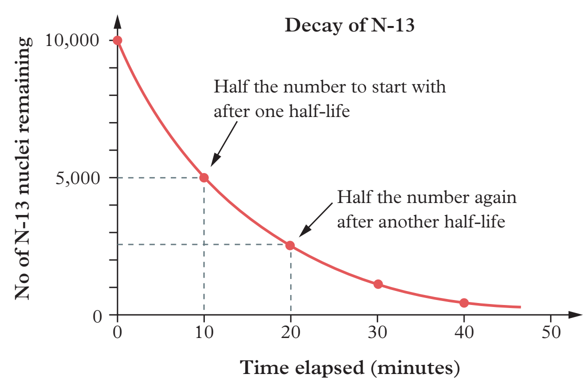
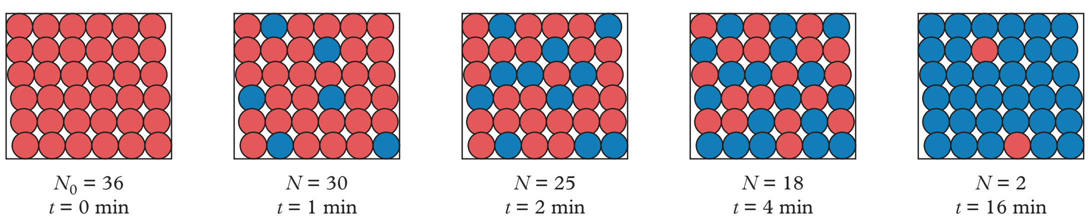


FIGURE 1 Plot of decay data from Table 1 ($t_{\frac{1}{2}}$ = 10 min)

Figure 2 shows another in which thallium-206 (red) decays into lead-206 (blue). Initially, there are 36 thallium-206 nuclei. After 4 minutes, only half of the original 36 atoms are left. We say that thallium-206 has a half-life of 4 minutes.

FIGURE 2 Thallium-206 (red) slowly decays to lead-206 (blue) ($t_{\frac{1}{2}}$ = 4 min).



Examples of common half-lives

Half-lives can be very short, such as those measured in millionths of a second, or very long, such as for lead, which would last billions of years. Some common half-lives are shown in Table 2.

TABLE 2 Half-lives can be very short or very long.

Nuclide	Decay	Half-life
^{206}Pb	stable	infinite
^{238}U	α	4.47 billion years
^{234}Th	β^-, γ	24.1 days
^{222}Rn	α	3.82 days
^{218}Po	α	3.05 minutes
^{214}Po	α	1.64×10^{-4} s
^{1}H proton	γ	10^{31} years
^{1}n neutron	β^+	10.2 minutes

How is half-life calculated?

We can develop a formula that relates the number of radioactive nuclei remaining (N) with the number at the start (N_0) and the time elapsed (t) (Table 3).

TABLE 3 Determining the number of radioactive nuclei remaining

n = number of half-lives	Number of radioactive nuclei remaining (N)	Formula
Start $n = 0$	N_0	$N_0 \times \left(\frac{1}{2}\right)^0$
After 1 half-life	$N_0 \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^1$
After 2 half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^2$
After 3 half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}$	$N_0 \times \left(\frac{1}{2}\right)^3$
After n half-lives	$N_0 \times \frac{1}{2} \times \frac{1}{2} \ldots n$ times	$N_0 \times \left(\frac{1}{2}\right)^n$ or $N_0\left(\frac{1}{2}\right)^n$

In general, we can say that:

$$N = N_0\left(\frac{1}{2}\right)^n$$

where n = number of half-lives. This is calculated by:

$$n = \frac{\text{time elapsed}}{\text{half-life}} \text{ or } n = \frac{t}{t_{\frac{1}{2}}}$$

Study tip

When performing calculations involving half-life, the times must be in the same unit (seconds, minutes, years, etc.).

Worked example 5.7A

Calculating the amount of nuclide remaining after a given time

Iodine-131 has a half-life of 8 days and undergoes beta negative decay according to the equation:

$$^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e + \overline{v}_e$$

If a milk sample contains 3.0×10^{18} I-131 nuclei at a particular time, **determine** the number of I-131 nuclei (2 s.f.) present after

a 5 half-lives (40 days) (1 mark)

b 60 days (2 marks)

c 2 years. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to establish after a calculation. We need to apply the half-life formulas to find the number of nuclei remaining. Each part is worth either 1 or 2 marks, so we must correctly apply the formulas and complete the calculation(s) for each.
Step 2: Identify the appropriate equations and gather any data that you require.	$N = N_0\left(\frac{1}{2}\right)^n$ $n = \frac{t}{t_{\frac{1}{2}}}$ $t_{\frac{1}{2}} = 8$ days, $N_0 = 3.0 \times 10^{18}$ **a** $n = 5, N = ?$ **b** $t = 60$ days, $n = ?, N = ?$ **c** $t = 2$ years, $n = ?, N = ?$
Step 3: Substitute the known values into the equations. Find the unknowns. Make sure that the units for time are the same.	**a** $N = (3.0 \times 10^{18})\left(\frac{1}{2}\right)^5$ $= 9.4 \times 10^{16}$ **b** $n = \frac{60}{8}$ $= 7.5$ (1 mark) $N = N_0\left(\frac{1}{2}\right)^n$ $= (3.0 \times 10^{18})\left(\frac{1}{2}\right)^{7.5}$ $= 1.7 \times 10^{16}$ **c** $n = \frac{2 \times 365}{8}$ $= 91.25$ (1 mark) $N = (3.0 \times 10^{18})\left(\frac{1}{2}\right)^{91.25}$ $= 10 \times 10^{-9}$ This is less than 1 nucleus so it is clearly impossible. It is likely that the last I-131 nucleus decayed a long time before this.
Step 4: Finalise your answers and make sure you have included the correct units, used the scientific notation correctly, and expressed your answers to the correct number of significant figures.	**a** 9.4×10^{16} nuclei (2 s.f.) (1 mark) **b** 1.7×10^{16} nuclei (2 s.f.) (1 mark) **c** Zero nuclei (1 mark)

Your turn

The radionuclide Pu-236 has a half-life of 2.898 years. If a sample contains 300.0 mg when first measured, **determine** the amount present after

a 3.83 years (2 marks)

b 14.22 years. (2 marks)

Worked example 5.7B

Calculating time elapsed for a nuclide to decay

Iodine-131 has a half-life of 8 days. If a sample contains 3.0×10^{18} I-131 nuclei at a particular time, **determine** the time that would have elapsed for there to be 1 million (1.0×10^6) I-131 nuclei left. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to establish after a calculation. We need to apply the half-life formulas to find time. The question is worth 4 marks, so we must correctly apply the formulas and complete the calculations.
Step 2: Identify the appropriate equations and gather any data that you require.	$N = N_0\left(\frac{1}{2}\right)^n$ $n = \frac{t}{t_{\frac{1}{2}}}$ $t_{\frac{1}{2}} = 8$ days, $N_0 = 3.0 \times 10^{18}$, $N = 1.0 \times 10^6$ $n = ?$, $t = ?$
Step 3: Substitute the known values into the equation to find n. Rearrange to find the unknown. You will need to take the log of both sides. There are two other methods you could use. Method 2 involves rearranging the original formula first, and requires your calculator to be able to find $\log_y x$. You can use trial and error as a last resort. Just substitute any value for n and compare your answer to the required value. If it is too high or too low, try another n value. This method is not recommended, but is allowed.	**Method 1:** $1.0 \times 10^6 = 3 \times 10^{18}\left(\frac{1}{2}\right)^n$ $\frac{1.0 \times 10^6}{3.0 \times 10^{18}} = \left(\frac{1}{2}\right)^n$ $3.333 \times 10^{-13} = \left(\frac{1}{2}\right)^n$ (1 mark) $\log_{10}(3.333 \times 10^{-13}) = \log_{10}\left(\frac{1}{2}\right)^n$ $= n \times \log_{10}\left(\frac{1}{2}\right)$ (1 mark) $-12.48 = n \times -0.301$ $n = \frac{-12.48}{-0.301}$ $= 41.45$ (1 mark) **Method 2:** Rearrange the original formula using $y = a^x \Leftrightarrow \log_a y = x$. $N = N_0\left(\frac{1}{2}\right)^n \Leftrightarrow n = \log_{\frac{1}{2}}\left(\frac{N}{N_0}\right)$ $n = \log_{\frac{1}{2}}\left(\frac{1.0 \times 10^6}{3.0 \times 10^{18}}\right)$ $= 41.45$
Step 4: Substitute the known values into the equation to find t. Rearrange to find the unknown.	$41.45 = \frac{t}{8}$ $t = 41.45 \times 8$ $= 332$
Step 5: Finalise your answer and make sure you have included the correct units, used the scientific notation correctly, and expressed your answer to the correct number of significant figures.	330 days (2 s.f.) (1 mark)

Your turn

Na-22 is a radioactive nuclide with a half-life of 2.06 years. A sample is measured to have 250 mg of the nuclide present at the start of a trial. **Determine** how much time will have elapsed when there is only 20 mg remaining. (4 marks)

What is radiometric dating?

A key use of radioactivity is for determining the age of ancient samples of rocks, and plant and animal tissue. This is called radiometric dating ("metric" means "to measure"). There are many methods for doing this.

FIGURE 3 The amount of uranium trapped in a rock can be used to estimate the age of the rock.

Dating rocks using uranium decay

The universe is about 13.7 billion years old. Our Earth has been around for over 4 billion (4×10^9) of those years. Grains of the mineral zircon from gneiss rocks have been measured as being 3.962 billion years old, with a margin of error of 3 million years; that is, 3.962 ± 0.003 billion years old. This estimate is based on the belief that small amounts of radioactive uranium-238 were trapped in the zircon at the time of crystallisation. Since then, the uranium has gradually decayed, eventually changing into stable lead. The age calculation is done by measuring the amounts of lead and uranium trapped in the rock. By knowing the half-life of U-238, the age t can be calculated.

Dating plants and animals using radiocarbon dating

Study tip

In the half-life equation, *N* is the quantity of the radionuclide. It can be the number of nuclei (or atoms), the mass of the radionuclide or the ratio of nuclides.

The vast majority of the carbon atoms are present as the isotope C-12, but a very small fraction (about 1.35×10^{-12}:1) are the radioactive isotope C-14. This level is commonly described as 1.35 ppt, meaning "parts per trillion" (10^{-12}). This ratio (R_0) has remained constant for thousands of years because, even though C-14 decays (with a half-life of 5,730 years), more is being made by the cosmic radiation from space bombarding nitrogen in the atmosphere:

$$^{14}_{7}\text{N} + ^{1}_{0}\text{n} \rightarrow ^{14}_{6}\text{C} + ^{1}_{1}\text{H}$$

All living things exchange carbon from (or to) carbon dioxide with the environment. When plants and animals die, they stop exchanging C-14 with the atmosphere, so the C-14 decays without being replaced. As a result, the C-14:C-12 ratio (R_t) drops. After 5,730 years, it would be half the normal (living) ratio. If the ratio can be determined, then the time that has elapsed since death can be established.

This means that the age of any object made from previously living material, such as wood, can be estimated using radiocarbon dating. You can use any half-life formula to determine the time that has elapsed. In place of the values for initial and final activity, number of particles or mass, you can just use the initial and final ratios.

FIGURE 4 Radiocarbon dating can be used to determine the age of Huon pine trees in Tasmania.

Real-world physics

Exploring human occupation based on new evidence from the Madjedbebe rock shelter

The earliest human occupation of the land currently known as Australia has been debated, with initial estimates of 20,000 to 40,000 years ago. But over the past decade, this figure has been pushed further and further back with the evolution of radiometric dating techniques.

One method is the dating of minerals using single-grain optically stimulated luminescence (OSL). As minerals age and become exposed to cosmic radiation, they trap more electrons. When exposed to sunlight, these electrons are released and luminescence is detected. The greater the signal, the older the grain, and the older the mineral. OSL dating is combined with determinations of the radioactivity of the rock sample and the material surrounding it to provide more evidence for scientists to make reliable predictions in radiometric dating of materials.

Scientists applied this method to individual grains of quartz from Madjedbebe, a rock shelter located on Mirrarr land, near Kakadu National Park in the Northern Territory. They found that human settlement of Madjedbebe occurred around 65,000 years ago, indicating that the land currently known as Australia was occupied long before European colonisation.

FIGURE 5 Rock art on the stone at the Madjedbebe rock shelter site

Single-grain OSL allows the dating of non-living artefacts and can measure back from 100 to 350,000 years ago. Compare this with radiocarbon dating, which is only useful for specimens that were previously living and has a limit of about 50,000 years.

Apply your understanding

1 **Contrast** the maximum age of samples that can be dated by radiocarbon methods and OSL. (2 marks)

2 **Explain** why radiocarbon methods are unsuitable for dating sand grains. (2 marks)

Worked example 5.7C

Calculating the age of wood with carbon dating

The Huon pine is Australia's oldest living tree. Fossil records from a tree found in a boggy area in South West Tasmania found the carbon-14 present was 65.0% of the carbon-14 in the atmosphere today. C-14 has a half-life of 5,730 years. **Determine** the age of the tree (3 s.f.). (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to establish after a calculation. We need to apply the half-life formulas to find age. The question is worth 4 marks, so we must correctly apply the formulas and complete the calculations.
Step 2: Identify the appropriate equations and gather any data that you require.	$N = N_0\left(\frac{1}{2}\right)^n$ $\frac{N}{N_0} = 65.0\%$ or 0.650 $n = \frac{t}{t_{\frac{1}{2}}}$, $t_{\frac{1}{2}} = 5{,}730$ years $n = ?$, $t = ?$

Think	Do
Step 3: Substitute the known values into the equation to find n. Rearrange to find the unknown. You will need to take the logs of both sides.	$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$ $0.650 = \left(\frac{1}{2}\right)^n$ (1 mark) $\log_{10}(0.650) = n\log_{10}\left(\frac{1}{2}\right)$ (1 mark) $-0.1866 = n \times (-0.3010)$ $n = 0.62$ (1 mark)
Step 4: Substitute the known values into the equation to find t. Rearrange to find the unknown.	$n = \frac{t}{t_{\frac{1}{2}}}$ $0.62 = \frac{t}{5{,}730}$ $t = 3{,}550$
Step 5: Finalise your answer and make sure you have included the correct units, used the scientific notation correctly, and expressed your answer to the correct number of significant figures.	3,550 years (3 s.f.) (1 mark)

Your turn

A sample of a wooden axe handle found on an archaeological site has 0.375 times as many carbon-14 atoms as an equal mass of living wood. **Determine** the age of the axe handle in years (3 s.f.). (4 marks)

Check your learning 5.7

Check your learning 5.7: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** what is meant by "number of half-lives, n". (2 marks)

Analytical processes

2 A piece of wood from a giant redwood tree has a C-14 ratio only one-quarter of that found in living tissue. **Determine** the age of the wood. (3 marks)

3 For hundreds of years, the Shroud of Turin had been claimed to be the burial garment of Jesus. Recently, a sample was analysed and found to have a C-14 count of 92% of that found in living tissue.
   a **Determine** the age of the shroud. (3 marks)
   b **Determine** the amount of C-14 as a percentage of the C-14 in living tissue if the garment really was from 2,000 years ago. (3 marks)

4 The amount of N-13 measured in a sample was 23.0 μg. The half-life of N-13 is 10.0 minutes. **Determine** the mass of N-13 remaining after
   a 3 minutes (3 marks)
   b 25 minutes. (3 marks)

5 **Determine** how many grams of Rn-222 would be left in a sample after 2 weeks if there was 1.15 g at the start. The half-life of Rn-222 is 3.82 days. (3 marks)

6 **Determine** how much U-235 would be present on Earth for every 100 units of U-238 that was present when Earth was formed 4.54 billion years ago. The half-life of U-238 is 4.47×10^9 years (4.47 billion years). (3 marks)

7 Thorium-233 has a half-life of 21.83 minutes. If a sample contains 3.0×10^{15} atoms of Th-233 at a particular time, **determine** the time that would have elapsed for there to be 2.0×10^{13} atoms left. (4 marks)

Knowledge utilisation

8 A lab technician has a sample of radioactive phosphorus but is unsure which isotope is present. They believe it to be P-30. The technician measured the amount and found there was 3.70 mg present. After exactly 7.0 days it was measured again and there was 2.63 mg present.
   a **Calculate** the number of half-lives, n, that would have elapsed. (3 marks)
   b **Justify** whether the sample could have been P-30. The half-life of P-30 is 2.496 minutes and that of P-32 is 14.268 days. (2 marks)

MODULE 5

Lesson 5.8
Review: Radioactive decay and half-life

Summary

5.1
- Marie Curie and Henri Becquerel were pioneers in the research on radioactivity.
- Radioactive decay is a spontaneous reaction in which an unstable nuclide disintegrates and emits radiation.
- There are many different subatomic particles, each with its own distinguishing physical characteristics.

5.2
- Ionising radiation can remove electrons from atoms.
- Alpha radiation has the highest ionisation ability and the lowest penetrating ability. Gamma radiation has the lowest ionisation ability and the highest penetrating ability.
- The further away from a radioactive source, the less intense the radioactivity.
- Very dense materials absorb more radiation and can be used for shielding.

5.3
- Practical: Shielding effects from a radioactive source

5.4
- Practical: Intensity and distance from a radioactive source

5.5
- Radioactive decay can be represented by balanced nuclear equations.

5.6
- Radionuclides can undergo alpha, beta positive, beta negative or gamma decay.
- The type of decay can be predicted by looking at the type of nuclide instability – that is, whether there is an excess of mass, neutrons or protons in a nucleus.
- The decay series shows the successive chain of decay that a nuclide goes through.

5.7
- Half-life is the time it takes for half of the quantity of a radionuclide to decay.
- Radiometric dating is used to determine the age of materials based on their radioactivity.

Key formulas

Half-life	$N = N_0\left(\frac{1}{2}\right)^n$
Number of half-lives	$n = \frac{t}{t_{\frac{1}{2}}}$

Review questions 5.8A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 A positron is an atomic particle that has

A the mass of an electron and the charge of a proton.

B the mass of an electron and the charge of a neutron.

C the mass of a neutron and the charge of a proton.

D the mass of a proton and the charge of an electron.

2 Uncharged particles produced during natural radioactive decay are likely to have

A low penetrating power, low ionisation power.

B low penetrating power, high ionisation power.

C high penetrating power, low ionisation power.

D high penetrating power, high ionisation power.

3 Which one of these nuclear reactions is possible?

A ${}^{218}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\mathrm{He}$

B ${}^{14}_{7}\mathrm{N} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{0}_{-1}\mathrm{e} + \nu_e$

C ${}^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{-1}\mathrm{e} + \mathrm{n}$

D ${}^{23}_{11}\mathrm{Na} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He}$

4 What are the numbers of protons Z and neutrons N in the missing product (shown by the question mark) of the following reaction?

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow ? + {}^{140}_{55}\mathrm{Cs} + 4\,{}^{1}_{0}\mathrm{n} $$

A $Z = 55$ and $N = 37$

B $Z = 37$ and $N = 55$

C $Z = 92$ and $N = 37$

D $Z = 37$ and $N = 92$

5 Which one of the following particles is always associated with beta negative decay?

A Gamma particle

B Electron neutrino

C Antielectron neutrino

D Electron antineutrino

6 Natural radioactive decay by the emission of beta negative particles is generally the result of

A an excess of protons over neutrons.

B an excess of neutrons over protons.

C an excess of mass.

D a deficit of mass.

7 Mg-23 undergoes natural radioactive decay to form Na-23. Which one of the following shows the other products of the decay?

A ${}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$

B ${}^{0}_{+1}\mathrm{e} + \bar{\nu}_e$

C ${}^{0}_{-1}\mathrm{e} + \nu_e$

D ${}^{0}_{+1}\mathrm{e} + \nu_e$

8 Protactinium-236 undergoes the following natural radioactive decay:

$$ {}^{236}_{91}\mathrm{Pa} \rightarrow \alpha $$

The daughter nuclide is

A ${}^{232}_{89}\mathrm{Ac}$

B ${}^{240}_{89}\mathrm{Ac}$

C ${}^{232}_{93}\mathrm{Np}$

D ${}^{232}_{93}\mathrm{Np}$

9 Which one of the following shows a balanced equation for natural beta negative decay?

A ${}^{239}_{92}\mathrm{U} \rightarrow {}^{240}_{92}\mathrm{U} + {}^{-1}_{0}\mathrm{e} + \bar{\nu}_e + \gamma$

B ${}^{239}_{92}\mathrm{U} \rightarrow {}^{240}_{92}\mathrm{U} + {}^{0}_{-1}\mathrm{e} + \nu_e + \gamma$

C ${}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{91}\mathrm{Pa} + {}^{0}_{-1}\mathrm{e} + \nu_e + \gamma$

D ${}^{239}_{92}\mathrm{U} \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e + \gamma$

10 Identify the parent nuclide for this decay reaction:

$$ {}^{A}_{X}\mathrm{Z} \rightarrow {}^{21}_{10}\mathrm{Ne} + {}^{0}_{+1}\mathrm{e} + \nu_e + \gamma $$

A ${}^{21}_{9}\mathrm{F}$

B ${}^{21}_{10}\mathrm{Ne}$

C ${}^{21}_{11}\mathrm{Na}$

D ${}^{21}_{11}\mathrm{B}$

11 Which pair could be the parent and daughter nuclides for a beta positive decay reaction?

A ${}^{11}_{5}\mathrm{B} \rightarrow {}^{11}_{6}\mathrm{C}$

B ${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B}$

C ${}^{11}_{11}\mathrm{Na} \rightarrow {}^{11}_{10}\mathrm{Ne}$

D ${}^{21}_{10}\mathrm{Ne} \rightarrow {}^{22}_{9}\mathrm{F}$

12 What reaction is represented by the following equation?

$$ {}^{239}_{94}\mathrm{Pu} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{4}_{2}\mathrm{He} $$

A Alpha decay of Pu-239

B Beta negative decay of Pu-239

C Alpha decay of Pu-94

D Beta positive decay of Pu-239

13 Neptunium-223 has a half-life of 2×10^{-6} s. How much time would it take for a sample of Np-223 to decay to half its original value?

A 1×10^{-6} s

B 2×10^{-3} s

C 2×10^{-6} s

D 2×10^{-3} s

14 The radioactive nuclide roentgenium-282 has a half-life of 100 s exactly. If a specimen contains 10 mg at the start of a test, how many seconds will elapse before the amount has dropped to 2.5 mg?

A 25

B 100

C 200

D 400

15 Berkelium-252 is a radionuclide with a half-life of 110 s. If there is 5 mg present in a specimen at the start of an experiment, how many mg will be present after 8.0 minutes have elapsed?

A 0.049

B 0.24

C 0.95

D 4.8

16 The amount of the radionuclide lead-214 in a specimen is measured to be 15 mg. After 100 s have passed, the amount present is 1.15 mg. The half-life of Pb-214 is

A 3.7 s.

B 7.7 s.

C 27 s.

D 370 s.

Review questions 5.8B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

17 **Define** the terms “alpha radiation”, “antiparticle”, “beta negative radiation”, “beta positive radiation”, and “gamma radiation”. (5 marks)

18 **Explain** whether C-14 dating can be used to measure the age of stone walls and tablets of ancient civilisations. (3 marks)

Analytical processes

19 Use the data in the table to work out the relationship between distance and activity (**sketch** a graph, linearise it and **determine** the equation of a line of best fit). (4 marks)

Distance, *d* (mm)	4	6	8	14	20	30	40
Intensity, *I* (cps)	11,266	5,046	2,956	638	230	152	136

20 **Determine** the missing symbols in the following equations.

a $^{?}_{?}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$ (1 mark)

b $^{?}_{?}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\text{He}$ (1 mark)

21 **Determine** the balanced equation for the beta negative decay of I-131. (3 marks)

22 **Determine** the balanced equation for a beta positive decay in which the daughter nuclide is neon-21. (3 marks)

23 The alpha decay of a plutonium nuclide produces U-235. **Determine** the balanced equation for this decay. (3 marks)

24 Radium-226 undergoes three successive alpha decays to give a daughter nuclide of lead-214. **Determine** the balanced equations to show this sequence. (3 marks)

25 **Deduce** what elements are formed by the radioactive decay shown in brackets for each of the following.

a $^{24}_{11}\text{Na}$ (β^-) (1 mark)

c $^{210}_{84}\text{Po}$ (α) (1 mark)

b $^{22}_{11}\text{Na}$ (β^+) (1 mark)

d $^{32}_{15}\text{P}$ (β^-) (1 mark)

26 A certain nuclide $^{b}_{a}\text{X}$ ejects an alpha particle, then emits a beta particle. **Determine** the balanced equation, for each decay step, showing mass numbers and atomic numbers using Y and Z as daughter nuclide symbols. (4 marks)

27 **Deduce** the missing nuclides in the following nuclear equations.

a $^{11}_{5}\text{B} + {}^{4}_{2}\text{He} \rightarrow {}^{14}_{7}\text{N} + ?$ (1 mark)

b $^{23}_{11}\text{Na} + {}^{1}_{0}\text{n} \rightarrow ?$ (1 mark)

c $^{27}_{13}\text{Al} + {}^{2}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + ?$ (1 mark)

d $? + {}^{4}_{2}\text{He} \rightarrow {}^{42}_{20}\text{Ca} + {}^{1}_{1}\text{H}$ (1 mark)

e $? + {}^{1}_{0}\text{n} \rightarrow {}^{27}_{12}\text{Mg} + {}^{1}_{1}\text{H}$ (1 mark)

f $? + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$ (1 mark)

28 **Deduce** the symbols for heavy nuclides formed in the following equations.

a $^{249}_{98}Cf + ^{12}_{6}C \rightarrow 4\,^{1}_{0}n + ?$ (1 mark)

b $^{242}_{94}Pu + ^{22}_{10}Ne \rightarrow 4\,^{1}_{0}n + ?$ (2 marks)

29 Using the descriptions, **determine** the balanced equation for decay of the following nuclides.

a $^{38}_{20}Ca$ (too many protons) (2 marks)

b $^{35}_{15}P$ (too many neutrons) (2 marks)

c $^{12}_{6}C$ (in the band of stability) (1 mark)

30 **Deduce** the stable nuclide formed when Sr-96 undergoes four successive $^{0}_{-1}e$ emissions and show a balanced equation for the reaction. (2 marks)

31 Iridium-192 is used in the treatment of early breast cancer. It has a half-life of 74 days. **Determine** the time, in days, required for 3.6 mg of an iridium-192 to decay to

a 0.90 mg (3 marks)

b 0.25 mg. (3 marks)

32 Carbon-14 was used to date a medieval linen sample. **Determine** the age of the sample if it had a C-14:C-12 ratio that was only 89.7% of the expected living tissue ratio. (3 marks)

33 The table shows the number of atoms in a sample of a beta-emitting phosphorus nuclide over time.

Time elapsed (h)	Number of atoms
0.0	36,506
0.5	31,501
0.75	29,268
1.0	27,106
2.0	20,244
5.0	8,256
10.0	1,913
13.0	800
18.0	181

a **Identify** the half-life of the sample. (2 marks)

b **Determine** the number of atoms present after 36 days. (3 marks)

34 Some rocks in your neighbourhood show that their percentage of uranium-236 is 67% of the original amount. **Determine** the age of the rocks given that $t_{\frac{1}{2}}$ for U-236 is 2.39×10^{7} years. (3 marks)

35 The half-life of a cobalt-60 source used for food irradiation is 5.26 years.

a If the original sample has 3.5×10^{24} atoms of Co-60, **determine** how many atoms will be left after 2 years. (3 marks)

b If it is not safe for disposal until the amount of radioactive isotope is less than one-thousandth of its original amount, **determine** how many years this is. (3 marks)

36 Marie Curie conducted many experiments on the radium isotope Ra-226, which has a half-life of 1,600 years. In Curie's lab 120 years ago there was a 1.250 mg sample of radium. **Determine** how much Ra-226 would be present in that sample today. (3 marks)

37 Actinium-228 is a beta emitter used as an agent for radiation therapy to target cancer cells in the body. A sample used in a hospital has 315 mg in 1 mL. After 18 hours, the amount had dropped to 41.4 mg in the 1 mL. **Determine** the half-life of actinium-228. (3 marks)

Knowledge utilisation

38 The U-238 present on Earth was created in a supernova 10 billion years ago. Imagine you were observing it in a lab and suddenly one of the atoms decayed and gave off an alpha particle. **Propose** why it would suddenly do this after so long, and **deduce** what might have triggered it. (4 marks)

39 **Design** an experiment involving radiation to measure how much liquid is in a can without opening it. Hint: alpha radiation would not be suitable for this experiment. **Consider** why not. (3 marks)

40 The table shows data collected at 8.00 a.m. on each school day. To measure the intensity of the sample, the time was measured for 2,000 counts on a Geiger counter.

Day	Time for 2,000 counts
Mon	1 min 16 s
Tues	1 min 39 s
Wed	2 min 10 s
Thu	2 min 51 s
Fri	3 min 40 s

Deduce on which day since Monday one half-life would have passed and **explain** your reasoning. (3 marks)

Data drill

Radiation intensity over varying distances

A student set up the apparatus shown in Figure 1 to conduct an experiment to address the following research question: What is the relationship between the intensity of radiation from a strontium-90 beta negative source when separated by distances (r) of 20 mm ≤ r ≤ 40 mm?

The data for the experiment is presented in Table 1. The data was processed and linearised as shown in Figure 2.

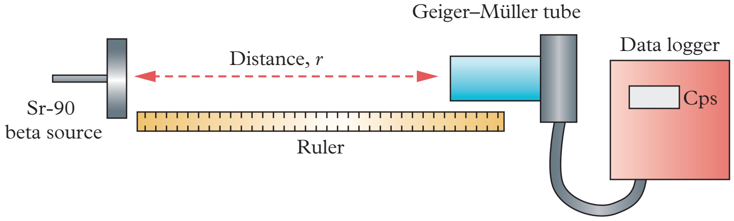


FIGURE 1 Apparatus for the radiation intensity experiment

TABLE 1 Results from the radiation intensity experiment

Distance, r (mm)	Intensity, I (cps), excluding background radiation				
	Test 1	Test 2	Test 3	Mean, $\bar{x}$	Uncertainty, δx
20.0	32.0	29.0	26.0	29.0	3.0
22.5	23.1	25.1	21.1	23.1	2.0
25.0	14.9	20.8	17.8	**Question 1**	**Question 2**
30.0	12.9	15.1	17.2	15.1	2.2
40.0	9.3	10.3	8.3	9.3	1.0

Apply understanding

1 **Calculate** the average intensity at a distance of 25.0 mm (1 d.p.). (1 mark)

2 **Calculate** the absolute uncertainty in the average intensity at a distance of 25.0 mm (1 d.p.). (1 mark)

Analyse data

3 **Identify** the absolute uncertainty in the gradient and y-intercept of the linear trendline. (2 marks)

Interpret evidence

4 **Draw** a quantitative conclusion about the relationship between the radiation intensity and distance. Include the absolute or percentage uncertainty and show your reasoning. (4 marks)

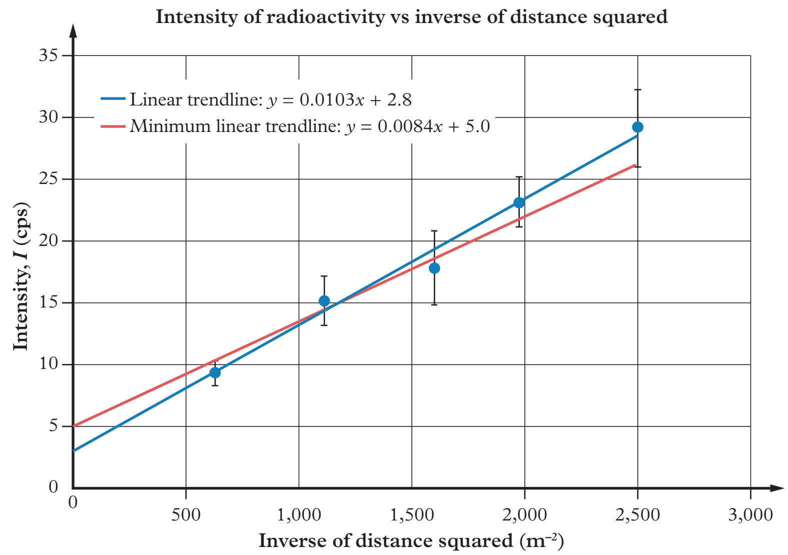


FIGURE 2 Processed data for the radiation intensity experiment

Module 5 checklist: Radioactive decay and half-life

Quizlet: Revise key terms online to test your understanding

MODULE 6

Nuclear energy and mass defect

Introduction

Nuclear reactions occur when the protons and neutrons in the nucleus of an atom rearrange. In this process, the energy that holds the protons and neutrons together – the binding energy – is released. We looked at natural, spontaneous nuclear reactions (radioactive decay) in Module 5. Now we will study artificial nuclear reactions and identify two particular types that are occurring before our very eyes.

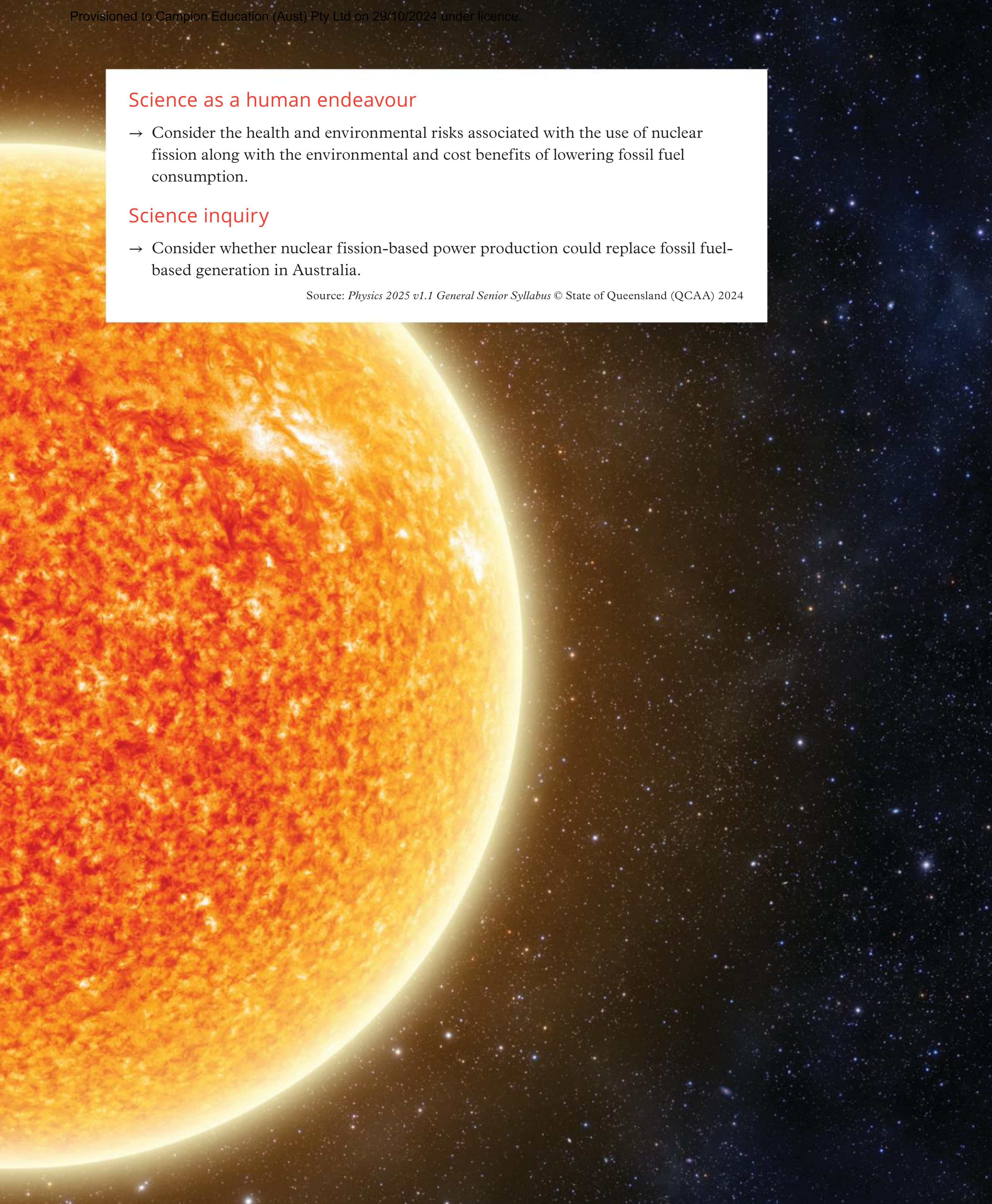
Prior knowledge

Prior knowledge quiz Check your understanding of nuclear energy before you start.

Subject matter

Science understanding

→ Describe energy in terms of electron volts (eV) and joules (J).
→ Describe the concept of artificial transmutation.
→ Describe nuclear fission and nuclear fusion with the aid of nuclear equations.
→ Distinguish between artificial transmutations and natural radioactive decay.
→ Explain a neutron-induced nuclear fission reaction, including references to extra neutrons produced from many of these reactions.
→ Explain a fission chain reaction.
→ Describe the concepts of mass defect, binding energy and binding energy per nucleon.
→ Describe the mass–energy equivalence relationship.
→ Solve problems involving the mass–energy equivalence relationship using $\Delta E = \Delta mc^2$.
→ Explain that more energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.



Science as a human endeavour

→ Consider the health and environmental risks associated with the use of nuclear fission along with the environmental and cost benefits of lowering fossil fuel consumption.

Science inquiry

→ Consider whether nuclear fission-based power production could replace fossil fuel-based generation in Australia.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Lesson 6.1
Artificial transmutation

Key ideas

→ Artificial transmutations, such as proton, alpha, deuteron and neutron bombardment, are used to form new elements.

Learning intentions and success criteria

What are artificial transmutations?

Nuclear bombs don't explode by themselves – thankfully. The nuclear reactions inside them must be started by someone artificially. That is, they are not natural and do not happen spontaneously. We can therefore classify nuclear reactions into two types: natural (spontaneous) radioactive decay or artificial nuclear reactions.

The radioactive decay processes discussed in Module 5 are examples of spontaneous or "natural" nuclear reactions. They occur naturally by themselves, with no external influence or particles required. Other nuclear reactions can be induced artificially. The process of doing this is called **artificial transmutation**.

artificial transmutation the process in which an isotope is intentionally made to change into an isotope of another element by being bombarded with particles that cause a nuclear process

deuteron the nucleus of a deuterium atom consisting of a proton and a neutron; (symbol: ${}^{2}_{1}\mathrm{H}$)

There are many ways to do this, but it typically involves bombarding a nucleus with a projectile, such as a proton ${}^{1}_{1}\mathrm{p}$ or ${}^{1}_{1}\mathrm{H}$, an alpha particle ${}^{4}_{2}\mathrm{He}$, a **deuteron** ${}^{2}_{1}\mathrm{H}$, a neutron ${}^{1}_{0}\mathrm{n}$, or other small nuclei such as ${}^{12}_{6}\mathrm{C}$, ${}^{15}_{7}\mathrm{N}$ or ${}^{16}_{8}\mathrm{O}$.

Proton bombardment

Firing a proton at a stable nucleus can cause the nucleus to split in two. For example, a lithium atom is very stable so it doesn't decay naturally, but when a proton is fired at lithium, it transmutes (changes) into two helium nuclei (alpha particles) with a flash of gamma energy (γ):

$$ {}^{1}_{1}\mathrm{p} + {}^{7}_{3}\mathrm{Li} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} + \gamma $$

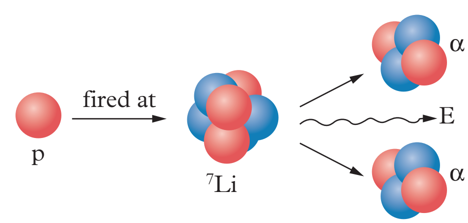


FIGURE 1 Proton bombardment of a Li-7 nucleus

Alpha bombardment

In 1919, after the proton had been discovered, physicist Ernest Rutherford designed a series of experiments to probe further into the production of the proton. He bombarded nitrogen gas with "bullets" of alpha particles ${}^{4}_{2}\mathrm{He}$:

$$ {}^{4}_{2}\mathrm{He} + {}^{14}_{7}\mathrm{N} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} $$

The equation shows that the artificial transmutation of nitrogen into oxygen had occurred. Rutherford also found that when faster, higher-energy alpha particles were used, neutrons were sometimes formed. For example, when beryllium nuclei are bombarded with high-energy alpha particles, carbon nuclei and fast-moving neutrons are produced (Figure 2):

$$ {}^{4}_{2}\mathrm{He} + {}^{9}_{4}\mathrm{Be} \rightarrow {}^{12}_{6}\mathrm{C} + {}^{1}_{0}\mathrm{n} $$

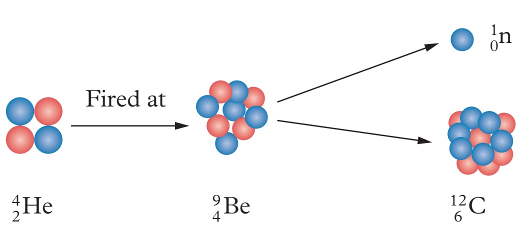


FIGURE 2 Bombardment of a beryllium nucleus by high-energy alpha particle "bullets"

Deuteron bombardment

Although it is almost impossible to turn lead into gold, deuterons ($^{2}_{1}H$) can be used to make gold from mercury or platinum:

$$^{2}_{1}H + ^{199}_{80}Hg \rightarrow ^{197}_{79}Au + ^{4}_{2}He$$

$$^{2}_{1}H + ^{196}_{78}Pt \rightarrow ^{197}_{79}Au + ^{1}_{0}n$$

For both of these reactions, the deuterons must be given a high enough speed by a suitable accelerator so that they can enter the nuclei of the target atoms. It is expensive to use such an accelerator, so it is cheaper to mine gold from the ground.

Neutron bombardment

Another common way of producing artificial transmutation is by using neutrons as the bombarding particles. Because they carry no charge, neutrons can enter the nuclei of the target atoms more easily than charged particles can. The target is said to have "captured" the neutron. Some examples of transmutations caused by neutron bombardment and capture are:

$$^{10}_{5}B + ^{1}_{0}n \rightarrow ^{7}_{3}Li + ^{4}_{2}He$$

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U$$

$$^{59}_{27}Co + ^{1}_{0}n \rightarrow ^{60}_{27}Co$$

The Co-60 produced in the last reaction decays spontaneously by β^- and γ emission to stable Ni-60. An electron antineutrino $\overline{\nu}_e$ is also produced, as it is with all β^- decay:

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + ^{0}_{-1}e + \overline{\nu}_e + \gamma$$

Cobalt-60 is used as the gamma source for school radioactive specimens. By completely encasing the radioactive sample in plastic, the beta negative particles are absorbed while the gamma rays can penetrate through it.

Check your learning 6.1

Check your learning 6.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Identify** the names of these bombarding particles: $^{4}_{2}He$, $^{1}_{1}H$, $^{1}_{1}p$, $^{2}_{1}H$, $^{1}_{0}n$. (5 marks)

2 **Describe** artificial transmutation, using Rutherford's alpha bombardment of nitrogen as an example. (2 marks)

Analytical processes

3 **Deduce** the product of this proton bombardment reaction: $^{31}_{15}P + ^{1}_{1}H \rightarrow ^{1}_{0}n + ?$ (1 mark)

4 **Derive** balanced equations of the following reactions and **identify** the type of bombardment for each.

a $^{6}_{3}Li + ^{2}_{1}H \rightarrow ^{1}_{1}H + ?$ (2 marks)

b $^{27}_{13}Al + ? \rightarrow ^{27}_{12}Mg + ^{1}_{1}H$ (2 marks)

5 **Derive** a balanced equation for a reaction in which the deuteron bombardment of As-75 produces a proton and one other nuclide. (1 mark)

Lesson 6.2
Mass defect and binding energy

Key ideas

→ Mass defect accounts for the “missing” energy when a new nucleus is made.

→ The greater the binding energy per nucleon, the greater the nuclear stability.

Learning intentions and success criteria

What is mass defect?

When accurate measurements of the masses of nucleons and nuclei are made, a significant discrepancy emerges. The mass of a nucleus is always less than the combined individual masses of its component nucleons.

For example, the mass of a deuterium nucleus is 2.013553 amu but the sum of the masses of the individual proton (1.007276 amu) and neutron (1.008665 amu) is 2.015941 amu. The difference in mass (0.002388 amu) is called the **mass defect** (Δm). “Defect” means something is missing, so you need to think of the relationship the other way around. If you made a nucleus from component particles, it would be lighter than the particles making it up. It would appear that some mass has “disappeared”, so it is called a defect.

mass defect
the difference between the mass of a nucleus and the sum of the masses of the constituent particles of which it is made

Carbon-12 as an example

Let’s look at another example, this time using the mass of the whole atom including electrons, as that is the way masses are normally listed in tables.

A carbon-12 atom $^{12}_{6}C$ has an exact mass (including its 6 electrons) of 12.000000 amu. We also know the masses of its component particles: a proton has a mass of 1.007276 amu, a neutron equals 1.008665 amu, and an electron is 0.000549 amu. We can add up the masses of the 6 protons, 6 neutrons and 6 electrons in a C-12 atom as follows:

6 protons: $6 \times 1.007276\,\text{amu} = 6.043656\,\text{amu}$

6 neutrons: $6 \times 1.008665\,\text{amu} = 6.051990\,\text{amu}$

6 electrons: $6 \times 0.000549\,\text{amu} = 0.003294\,\text{amu}$

Total mass: $= 12.098940\,\text{amu}$

This is greater than the mass of the atom (12.000000 amu). To put it another way: the exact mass of a $^{12}_{6}C$ nuclide (including its 6 electrons) is less than the sum of its component particles. Where has the missing 0.098940 amu gone? Has it disappeared into thin air?

The difference in mass was defined by scientist F. W. Aston as the “mass defect”. When dealing with mass defect, we express the nuclide masses to six decimal places, as the mass defects are very small. If you round off the nuclide masses to fewer decimal places, the answer could be wrong.

Which is used: the mass of the atom or mass of the nucleus?

When calculating mass defect, which do we use: the mass of a nuclide including its electrons, or the mass of the nucleus by itself? It is very difficult for scientists to measure the mass of the nucleus of an atom (the “nuclear” mass). It is much easier to measure the mass of the whole atom (the “nuclide” mass), including electrons, and this is the way scientists report the masses. These masses appear in Appendix 1.

When calculating mass defects of atoms, you will need to include the mass of the electrons in the mass of constituent particles so that the number of electrons is the same on both sides of the equation and cancels out. In the previous example, the mass of the C-12 atom is 12.000000 but this includes the 6 electrons in the cloud with a mass of 0.003294 amu. The mass of the nucleus alone would then be 12.000000 amu − 0.003294 amu = 11.996706 amu. This is how you may see it in QCAA exams, or it could be given in kg. If it was in kg, it would be 1.991453×10^{-27} kg.

What is binding energy?

The mass defect represents the mass that has been converted to **binding energy**. This is the energy that binds or holds the nuclear particles together. Therefore, binding energy is the mechanical work that must be done against the forces holding a nucleus together to disassemble it into constituent particles.

binding energy
the energy needed to overcome the forces holding a nucleus together to disassemble it into constituent particles

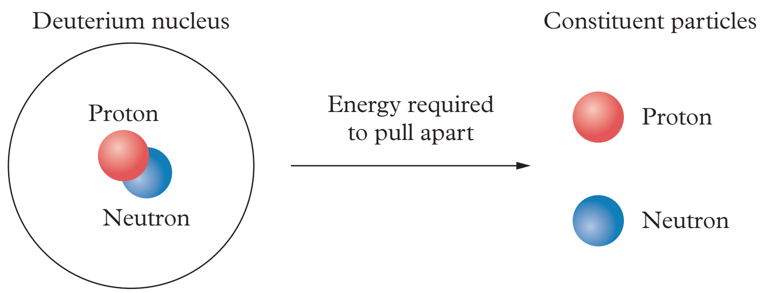


FIGURE 1 Pulling apart a nucleus requires overcoming the binding energy, which then appears as mass in the products.

Mass defect is calculated using the following formula:

$$\Delta m = m_{cp} - m_{nuclide}$$

where m_{cp} is the mass of the constituent particles and $m_{nuclide}$ is the mass of the newly formed nuclide (nucleus plus electrons). When you pull a carbon nucleus apart, it requires energy. The energy that goes into the particles gets converted to a mass of 0.09894 amu.

$$\begin{aligned}\Delta m &= m_{cp} - m_{nuclide}\\ &= 12.09840\,\text{amu} - 12.000000\,\text{amu}\\ &= 0.098940\,\text{amu}\end{aligned}$$

We can put this another way:

Nuclide (low mass) + binding energy (mass defect) = constituent particles (higher mass)
12.000000 amu + 0.098940 amu = 12.098940 amu

Study tip

In a question, you may be given a table of nuclide masses such as in Appendix 1. These masses include the electrons. Alternatively, you may be provided with the nucleus masses in the question itself without electrons included. Check to see whether the masses include electrons or are for the nucleus alone. It makes a big difference.

How do you express binding energy in joules?

Einstein showed that mass and energy are equivalent, and one can be expressed as the other. His equation showing the relationship between mass and energy is usually written as $\Delta E = \Delta mc^2$.

We can use it to calculate the amount of energy involved. In physics, it is called the **mass–energy equivalence relationship**:

$$\Delta E = \Delta mc^2$$

where ΔE is energy in joules and Δm is mass defect in kilograms. The delta symbol, Δ, makes it clear that we are talking about the change in energy associated with the change in mass. The constant of proportionality is c^2 where c is the speed of light in a vacuum ($3 \times 10^8\,\text{m s}^{-1}$).

mass–energy equivalence relationship
states that all objects having mass, or massive objects, have a corresponding intrinsic energy, even when they are stationary; related by $\Delta E = \Delta mc^2$

Study tip

The speed of light in a vacuum, c, is $3 \times 10^8\ \text{m s}^{-1}$, and you can assume it has 3 significant figures even though in the QCAA Formula and data book it is shown with just 1 s.f.

To complete the conversion, we first convert the mass defect in atomic mass units (amu) to mass defect in kilograms (kg): 1 amu = 1.66×10^{-27} kg.

Using the mass–energy equivalence relationship, this means that:

$$\begin{aligned}\Delta E &= \Delta mc^2\\ &= 1.66 \times 10^{-27}\ \text{kg} \times (3 \times 10^8)^2\\ &= 1.49 \times 10^{-10}\ \text{J (per amu)}\end{aligned}$$

We can also apply this to ^{12}C: $\Delta m = 0.098940$ amu

$$\begin{aligned}&= 0.098940\ \text{amu} \times 1.66 \times 10^{-27}\ \text{kg per amu}\\ &= 1.642 \times 10^{-28}\ \text{kg}\end{aligned}$$

You do not need to worry about significant figures at this stage, but four is adequate. Now, we can calculate the binding energy in joules, J, by a simple conversion using the mass–energy equivalence relationship:

$$\begin{aligned}\Delta E &= \Delta mc^2\\ &= 1.642 \times 10^{-28}\ \text{kg} \times (3 \times 10^8)^2\\ &= 1.48 \times 10^{-11}\ \text{J}\end{aligned}$$

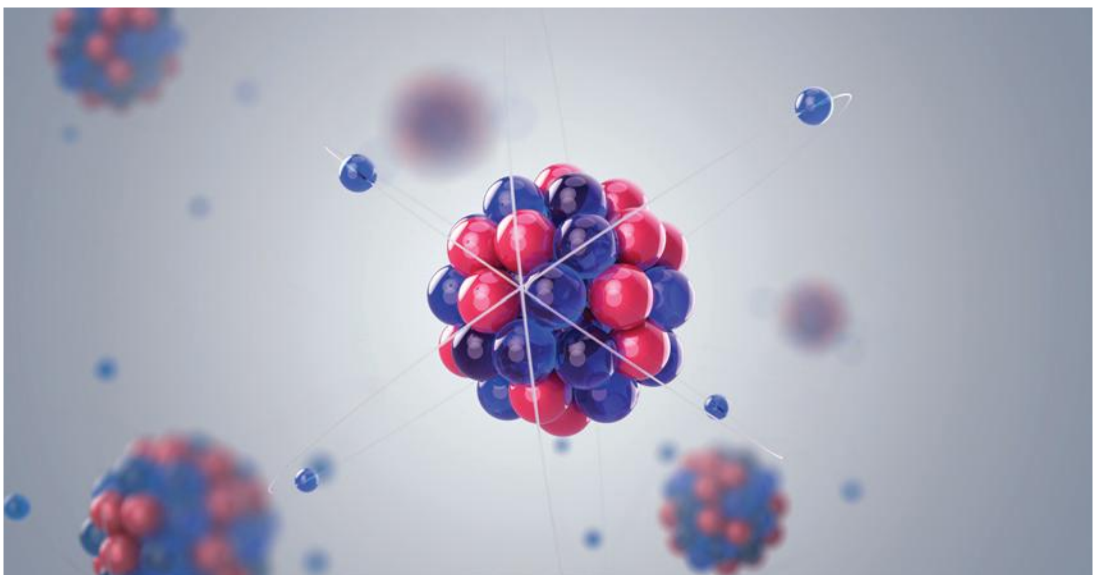


FIGURE 2 Binding energy is the energy required to separate this nucleus into separate neutrons (blue) and protons (red).

Binding energy in joules per nucleon

binding energy per nucleon
the binding energy divided by the number of nucleons in the nucleus of an atom

Physicists also like to express the energy as **binding energy per nucleon**. This means we need to convert binding energy in joules to binding energy in joules per nucleon. In the case of carbon, there are 12 nucleons (6p + 6n), so the binding energy of 1.48×10^{-11} J is divided by 12:

$$\begin{aligned}\text{binding energy per nucleon} &= \frac{\text{binding energy}}{\text{number of nucleons}}\\ &= \frac{1.48 \times 10^{-11}\ \text{J}}{12}\\ &= 1.23 \times 10^{-12}\ \text{J per nucleon}\end{aligned}$$

Binding energy in electron volts

Another common unit for energy used by physicists is **electron volts (eV)**. The electron volt is a unit of energy equal to the work done on an electron in accelerating it through a region of space where there is a potential difference of one volt. One eV is equal to 1.60×10^{-19} J. We could express binding energy in electron volts (eV) or megaelectron volts (MeV, that is, a million eV). MeV is an energy term used by physicists as a more convenient unit at an atomic scale than joules.

electron volt (eV) a unit of energy defined as the work done on an electron to move it through an electrical potential difference of 1 V; equal to 1.60×10^{-19} J

We can convert 1 amu into eV. We saw before that $1\,\text{amu} = 1.49 \times 10^{-10}$ J and we know that $1\,\text{eV} = 1.6 \times 10^{-19}$ J, so:

$$1\,\text{amu} = \frac{1.49 \times 10^{-10}\,\text{J}}{1.6 \times 10^{-19}\,\text{J}\,\text{eV}^{-1}}$$
$$= 9.315 \times 10^{8}\,\text{eV or } 931.5\,\text{MeV}$$

For ^{12}C, the mass defect of 0.098940 amu can be converted to MeV:

$$0.098940\,\text{amu} \times \frac{931.5\,\text{MeV}}{\text{amu}} = 92.16\,\text{MeV}$$

Recall that physicists also like to express binding energy per nucleon. In this case, it would be as MeV per nucleon. For ^{12}C, there are 12 nucleons (6p + 6n), so the binding energy of 92.16 MeV is for 12 nucleons, which means there is $92.16 \div 12 = 7.68$ MeV per nucleon.

Study tip

$1\,\text{amu} = 1.66 \times 10^{-27}\,\text{kg}$
$= 1.49 \times 10^{-10}\,\text{J}$
$= 931.5\,\text{MeV}$

Study tip

You don't need to learn the conversions between amu and kg or J. They are in the QCAA Formula and data book, but it is handy to know that 1 amu = 931.5 MeV.

TABLE 1 Summary for $^{12}_{6}$C

Quantity	Symbol	Value
Mass of component particles including 6 electrons (amu)	m_{cp}	12.098940
Mass of nucleus and electrons (amu)	$m_{nuclide}$	12.000000
Mass defect (amu)	Δm	0.098940
Mass defect (kg)	Δm	1.643×10^{-28}
Binding energy (J)	BE	1.48×10^{-11}
Binding energy per nucleon (J)	BE per nucleon	1.23×10^{-12}
Binding energy (MeV)	BE	92.16
Binding energy per nucleon (MeV)	BE per nucleon	7.68

Worked example 6.2A

Calculating mass defect and binding energy

The nuclide $^{4}_{2}$He has a mass including electrons of 4.002603 amu. **Calculate**

a mass defect in amu (6 d.p.) (2 marks)
b mass defect in kg (3 s.f.) (1 mark)
c binding energy in J (3 s.f.) (1 mark)
d binding energy per nucleon in J (3 s.f.) (1 mark)
e binding energy in MeV (3 s.f.) (1 mark)
f binding energy per nucleon in MeV (3 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply various formulas and find the values for the nuclide. The mark allocation is varied, so we must gather the correct information, correctly apply the formulas and complete the calculations as required.

Think	Do
Step 2: Select the correct formulas and gather any data required. Locate relevant nuclide masses in Appendix 1 or in the question itself.	$\Delta m = m_{cp} - m_{nuclide}$ $\Delta E = \Delta mc^2$ m(proton) = 1.007276 amu m(neutron) = 1.008665 amu m(electron) = 0.000549 amu m(nuclide) = 4.002603 amu
Step 3: For part **a**, look at the $^{A}_{Z}X$ nomenclature for the given nuclide and calculate the mass of its components.	**a** 2p = 2 × 1.007276 = 2.014552 amu 2n = 2 × 1.008665 = 2.017330 amu 2e = 2 × 0.00049 = 0.001098 amu m_{cp} = 2.014552 + 2.017330 + 0.001098 = 4.032980 amu (1 mark) $m_{nuclide}$ = 4.002603 amu
Step 4: Substitute the known values into the formula and find the unknown. Check the number of decimal places (6).	$\Delta m = m_{cp} - m_{nuclide}$ = 4.032980 − 4.002603 = 0.030377 amu (1 mark)
Step 5: For part **b**, complete the conversion. Remember 1 amu = 1.66×10^{-27} kg.	**b** Δm in kg = 0.030377amu × $\frac{1.66 \times 10^{-27}\,\text{kg}}{\text{amu}}$ = 5.043×10^{-29} kg (1 mark)
Step 6: For part **c**, substitute the known values into the formula and find the unknown.	**c** $\Delta E = \Delta mc^2$ = 5.043×10^{-29} kg × $(3 \times 10^8)^2$ = 4.538×10^{-12} J (1 mark)
Step 7: For part **d**, complete the conversion by dividing by the number of p and n in the nucleus (that is, the mass number, A).	**d** ΔE in J per nucleon = $\frac{\Delta E}{A}$ = $\frac{4.540 \times 10^{-12}\,\text{J}}{4}$ = 1.135×10^{-12} J per nucleon (1 mark)
Step 8: For part **e**, complete the conversion. Remember 1 amu = 931.5 MeV.	**e** ΔE in MeV = 0.030377 amu × $\frac{931.5\,\text{MeV}}{\text{amu}}$ = 28.3 MeV (1 mark)
Step 9: For part **f**, complete the conversion by dividing by the number of p and n in the nucleus (that is, the mass number, A).	**f** ΔE in MeV = $\frac{28.3\,\text{MeV}}{4}$ = 7.07 MeV per nucleon (1 mark)

Your turn

The nuclide $^{14}_{7}N$ has a mass of 14.003074 amu including electrons. **Calculate** (3 s.f.)

a mass defect in amu (6 d.p.) (2 marks)
b mass defect in kg (1 mark)
c binding energy in J (1 mark)
d binding energy per nucleon in J (1 mark)
e binding energy in MeV (1 mark)
f binding energy per nucleon in MeV. (1 mark)

How is binding energy related to nuclear stability?

The more nucleons that are present in an atom's nucleus, the greater the forces holding the nucleus together and hence the greater the binding energy necessary to pull it apart. For example, ^{12}C has a binding energy of 92.16 MeV, while that of ^{235}U is 1,783.9 MeV.

Expressing the required energy as the binding energy "per nucleon" gives a measure of how stable the nucleus is. The greater the binding energy per nucleon, the greater the stability and the harder it is to rip the nucleus apart into its component particles.

Let's compare the stability of the nuclides ^{12}C and ^{235}U.

^{12}C has a binding energy of $\frac{92.16\,\text{MeV}}{12} = 7.68\,\text{MeV}$ per nucleon.

^{235}U has a binding energy of 1,783.9 MeV but it has 235 nucleons: $\frac{1{,}783.9}{235} = 7.59\,\text{MeV}$ per nucleon. Therefore, the carbon nucleus is more stable.

If we plot a graph of the binding energy per nucleon against the mass number (Figure 3), we can see the most stable nuclides are those with the highest binding energy per nucleon. They have mass numbers around 55 to 58 amu (e.g. $^{56}_{26}Fe$ at a value of 8.7 MeV per nucleon, or $^{62}_{28}Ni$ at 8.8 MeV per nucleon). Iron-56 is the most stable isotope, with the highest binding energy per nucleon of any known nuclide (8.7906 MeV per nucleon).

Heavy nuclides with mass numbers to the right of this region of very stable nuclides (yellow band) are most likely to undergo nuclear fission and break into smaller nuclides to become more stable. Light nuclei to the left of this region are more likely to undergo nuclear fusion and join together to form heavier nuclides. Fission and fusion reactions are covered in the next section.

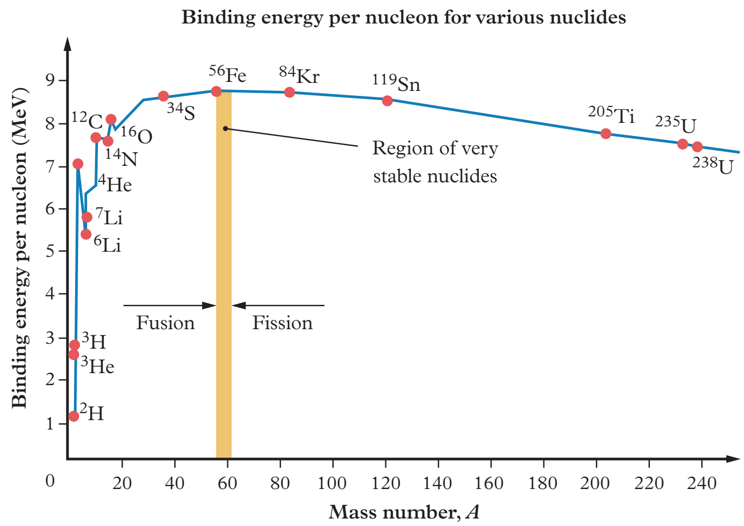


FIGURE 3 Variation in binding energy per nucleon

Check your learning 6.2

Check your learning 6.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the term "mass defect", using H-2 as an example. (2 marks)

2 **Explain** the meaning of "binding energy", in the context of carbon-12. (2 marks)

3 **Explain** how a nucleus can have less mass than its components when, in comparison, a brick house has the same mass as the components (bricks and mortar) that make it up. (2 marks)

4 **Calculate** the binding energy of the nucleus for the following nuclides and express your answers in MeV, MeV per nucleon, J, and J per nucleon (3 s.f.). Consult Appendix 1 for nuclide masses (which includes electrons).

- **a** Tritium $^{3}_{1}H$ (4 marks)
- **b** He-3 (4 marks)
- **c** N-14 (4 marks)
- **d** O-16 (4 marks)

5 Binding energy per nucleon is expressed in joules and also in MeV.

- **a** Na-24 has a mass of 23.984924 amu, not including electrons. **Calculate** the binding energy per nucleon of its nucleus in joules (3 s.f.). (4 marks)
- **b** The isotope Am-241 has a nucleus with a mass of $4.001979014 \times 10^{-25}$ kg excluding electrons. **Calculate** the binding energy of the nucleus in MeV (4 s.f.). (4 marks)

6 Using the graph in Figure 3

- **a** **determine** the binding energy released per O-16 nucleon in MeV (1 d.p.) (1 mark)
- **b** **calculate** the mass defect in kg (3 s.f.). (3 marks)

Analytical processes

7 **Calculate** the binding energy per nucleon for $^{56}_{26}Fe$ and **compare** it with the approximate value of 8.70 MeV per nucleon obtained from the graph in Figure 3. (5 marks)

8 Using the graph in Figure 3, **draw a conclusion** about the relative stability of U-235 and He-4. (3 marks)

Lesson 6.3
Nuclear fission

Key ideas

→ Neutron-induced nuclear fission reactions form new nuclides through bombarding atoms with neutrons.

→ Nuclei with a larger mass number than Fe-56 are more likely to undergo nuclear fission.

→ Fission chain reactions occur when neutrons produced from fission cause another fission reaction to occur, producing more neutrons that cause further fission reactions.

What is nuclear fission?

Learning intentions and success criteria

nuclear fission
a nuclear reaction in which a large unstable nucleus splits, forming two or more smaller, more stable nuclides and releasing neutrons and energy

Artificial nuclear reactions can be classified by the type of bombardment used, but they can also be classified as either nuclear fission or nuclear fusion. In this section, we will first look at nuclear fission.

In **nuclear fission**, the lighter colliding particle makes the heavy parent more unstable. It causes the parent to fragment or fission (Latin "fissus" meaning "cleaved" or "split") into smaller nuclei and other particles. These smaller particles have higher binding energy per nucleon than the heavy parent nucleus. Energy (in the form of gamma rays) is released in this fission process.

Fission is more likely for atoms on the right of Fe-56 in the stability graph in Figure 3 in Lesson 6.2.

Many of these reactions produce extra neutrons. For example:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \gamma \text{ } (3.2 \times 10^{-11}\,J, \text{ or } 202.79\,MeV)$$

What is neutron-induced nuclear fission?

The German scientists Otto Hahn and Fritz Strassmann made an amazing discovery in 1938. When U-235 was bombarded with neutrons, smaller nuclei were sometimes produced (for example, $^{136}_{56}Ba$ and $^{84}_{36}Kr$), which were approximately half the size of the original. They were baffled by this, but Lise Meitner and Otto Frisch (Jewish physicists who escaped Nazi Germany in 1938 and were working in Scandinavia) quickly realised what happened.

The U-235 nucleus absorbed the neutron to form a U-236 nucleus. Then, like a drop of water, it split into two pieces, one much bigger than the other (Figure 1). They called it "nuclear fission" because it reminded them of biological fission (cell division). More specifically, we can call this **neutron-induced nuclear fission**. A tremendous amount of energy is released because the mass of U-235 is considerably greater than that of the fission fragments.

neutron-induced nuclear fission
nuclear fission reaction induced by the bombardment of a nuclide with neutrons, often producing extra neutrons; also known as artificial transmutation

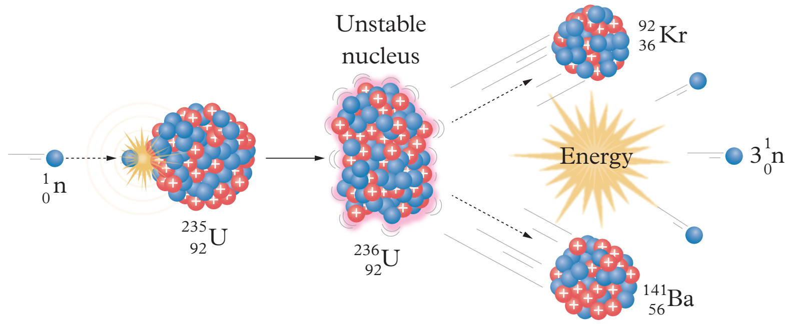


FIGURE 1 Neutron-induced nuclear fission of U-235

During nuclear fission, more neutrons must be released than are consumed to produce a **chain reaction**. The released neutrons continue to react with other uranium nuclei, and so on. Figure 2 shows a four-generation chain reaction.

chain reaction
a series of nuclear fissions, each initiated by a neutron produced in a preceding fission

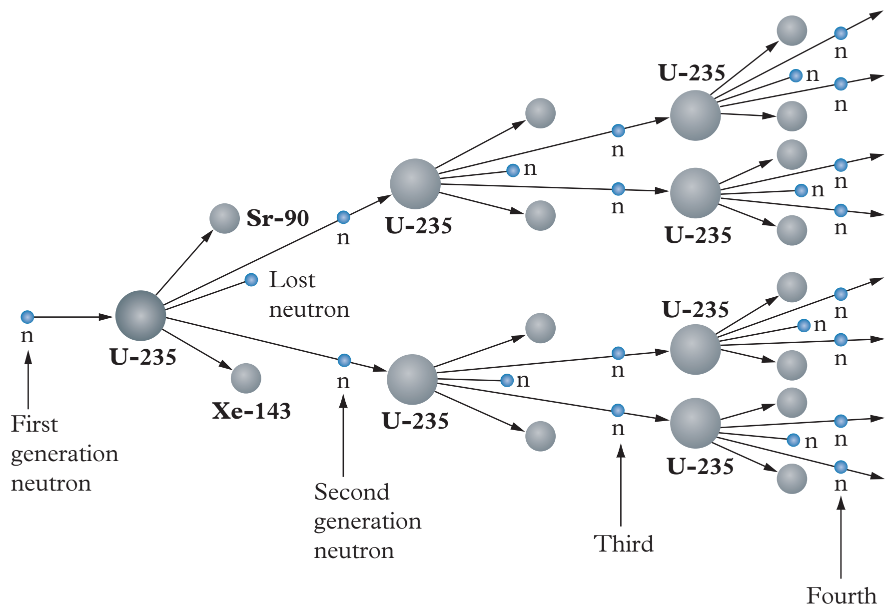


FIGURE 2 A chain reaction can occur when a neutron strikes a U-235 nucleus. However, the neutron must be travelling at the right speed – not too fast and not too slow – and there must be a lot of U-235 present.

The liquid drop model for fission

The nucleus of an atom is a complicated body that is not fully understood. However, some of its features can be described by an idealised model. When we say "model", we don't mean a physical object. "Model" in this context means a representation that describes, simplifies or provides an explanation of the workings of something (in this case, a nucleus). A model is rarely the work of any one person – it usually arises from collaboration across many disciplines.

According to the liquid drop model, the atomic nucleus behaves like the molecules in a drop of liquid. In the ground state, the nucleus is spherical. Surface tension makes the surface of the drop as small as possible by making the drop spherical. The nuclear strong force between nucleons (protons or neutrons) also draws the nucleons together. However, this spherical shape crowds the protons together, and the electrostatic repulsion force (or Coulomb force) between protons pushes them apart. It is a balance between pushing and pulling forces – a spherical and non-spherical shape. This is where you can think of it as a wobbling drop of water.

If sufficient kinetic energy is added, such as in the arrival of a neutron, this spherical nucleus is distorted into a dumbbell shape and splits into two fragments. Since these fragments are a more stable configuration, the splitting of such heavy nuclei is accompanied by energy release.

For heavy nuclei, where the electrostatic repulsion is strong, fissioning is a way to release the strain. It also makes lighter nuclei that are less resistant to deformation so they don't fission as easily.

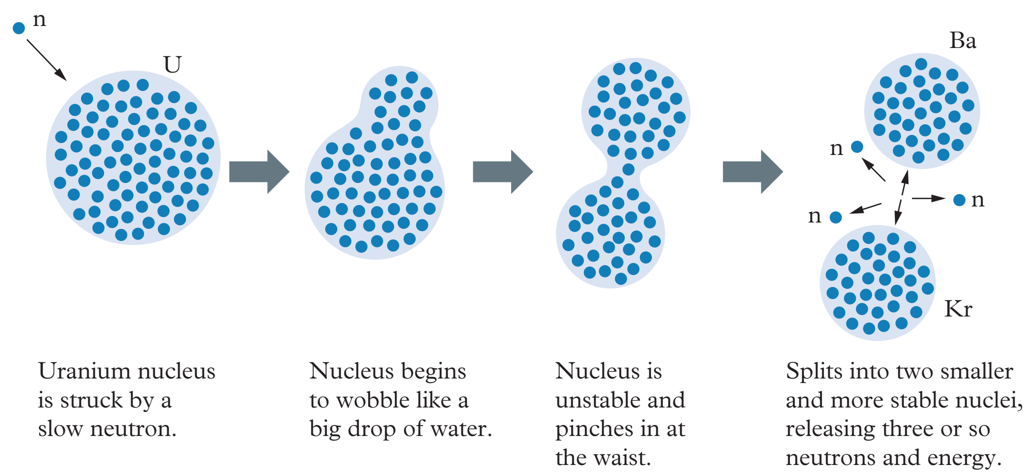


FIGURE 3 The water drop model showing the disintegration of uranium-235 by a slow neutron. In this depiction, all nucleons are shown in the same colour.

In each generation, the number of fissioning nuclei increases even though some neutrons do not go on to strike another U-235 atom. These excess neutrons are said to be "lost". In a nuclear reactor, a chain reaction is kept under control by absorbing excess neutrons with "control rods" of substances such as cadmium.

How do we calculate energy change in nuclear fission?

We can use the mass defect formula to calculate the change in energy in a nuclear fission reaction. We use Einstein's mass–energy equivalence relationship:

$$\Delta E = \Delta mc^2$$

where ΔE = energy released or absorbed (in J), Δm = change in mass or mass defect (in kg) in a reaction, and c = speed of light ($3 \times 10^8\,\mathrm{m\,s^{-1}}$).

To find the energy change for a nuclear reaction, you must know the mass of each constituent particle in the equation for the reaction. The energy can be expressed as per fission event (atom of reactant), per kilogram of reactant, or percentage of mass converted. When you eventually come to comparing energy released by different nuclear reactions, you need to make sure the units are the same.

Worked example 6.3A

Calculating energy produced from nuclear fission

If 1.0 g (1.0×10^{-3} kg) of a substance is converted completely into energy, **calculate** the energy produced (in joules, 2 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the mass–energy equivalence relationship formula and find the change in energy. The question is worth 1 mark, so we must gather the correct information, correctly apply the formula and complete the calculations.
Step 2: Select the correct formula and gather any data required.	$\Delta E = \Delta mc^2$ $m = 1.0 \times 10^{-3}$ kg, $c = 3 \times 10^8$ m s^{-1}
Step 3: Substitute the known values into the formula and find the unknown.	$\Delta E = 1.0 \times 10^{-3}$ kg $\times (3 \times 10^8)^2$ $= 9.0 \times 10^{13}$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures (2).	9.0×10^{13} J (2 s.f.) (1 mark)

Your turn

One atom of C-12 has a mass of 12.00 amu or 1.992×10^{-26} kg. **Calculate** the energy produced (in joules, 2 d.p.), assuming that the entire mass could be converted to energy. Note: this is unlikely in reality. (1 mark)

Energy per fission event

For a "fission event", we base our calculations on the reactants expressed as atoms. One "fission event" occurs when one parent atom of each reactant undergoes fission. A similar approach is taken for fusion reactions, which you will learn about in the next section.

To calculate the energy change for a nuclear reaction in joules **per fission event** or **per atom of reactant**:

Step 1. Identify the masses of all the nuclides involved.

Step 2. Calculate the sum of the masses of all the products (m_p) and the sum of the masses of all the reactants (m_r).

Step 3. Calculate the change in mass (Δm) in amu by subtracting the combined mass of the reactants from the combined mass of the products ($m_p - m_r$).

Step 4. Convert the change in mass (the mass defect, Δm) from amu into kg (1 amu = 1.66×10^{-27} kg).

Step 5. Convert the change in mass (Δm, in kg) into its equivalent change in energy (in joule, J) using Einstein's equation ($\Delta E = \Delta mc^2$), where Δm is the mass defect in kg, and c is the speed of light (3×10^8 m s^{-1}). This gives the energy in J per atom of reactant. We can also call it joules per fission (J per fission).

Energy per kilogram of reactant

To express the energy output per kilogram of reactant, you need to work out the mass of reactants in kilograms and scale up the energy to 1 kg. This is calculated using the following steps.

Step 1. Calculate the mass of one atom of reactant in kg:
= mass number in amu × 1.66 × 10^{-27} kg per amu

Step 2. Calculate the number of atoms of reactant present in 1 kg of reactant:
$= \frac{1.0\,\text{kg}}{\text{mass of one atom in kg}}$

Step 3. Calculate the total energy produced for 1 kg of reactant:
E_{total} = energy from one atom × number of atoms. Answer is in J kg^{-1}.

Percentage of mass converted

Only one step is required to express mass conversion to energy as a percentage of mass converted.

Express the mass defect in amu as a percentage of the mass of reactants in amu:

$$\%\text{ mass converted} = \frac{\Delta m}{m_r} \times 100$$

If the question asks for the mass converted as a percentage of U-235, then you would use the mass of U-235 (235.043930 amu) instead of the total mass of reactants (m_r), which includes the bombarding neutron (236.052595 amu). When expressed to 2 s.f., it generally makes no difference.

Worked example 6.3B

Calculating energy per fission event and per kg

Uranium-235 can undergo fission according to this reaction:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{94}_{38}\text{Sr} + {}^{139}_{54}\text{Xe} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

Calculate the energy, in joules, released (3 s.f.)

a per fission event for U-235 (5 marks)

b per nucleon of U-235 (2 marks)

c per kilogram of U-235 reacted. (3 marks)

Note: the masses of the various nuclides can be found in Appendix 1.

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the mass–energy equivalence relationship formula and find the change in energy, then express the answers correctly. The questions are worth a variety of marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. Locate relevant nuclide masses in Appendix 1 to identify the masses of all the nuclides involved.	$\Delta m = m_p - m_r$ $\Delta E = \Delta mc^2$ % mass converted $= \frac{\Delta m}{m_r} \times 100$ Mass of reactants, m_r: m(U-235) = 235.043930 amu m(neutron) = 1.008665 amu Mass of products, m_p: m(Sr-94) = 93.915356 amu m(Xe-139) = 138.918792 amu m(3 neutrons) = (3 × 1.008665) amu

Think	Do
Step 3: Calculate the sum of the masses of all the products and the sum of the masses of all the reactants.	Total m_r = 236.052595 amu (1 mark) Total m_p = 235.860143 amu (1 mark)
Step 4: Substitute the known values into the formula and find the unknown. Calculate the change in mass by subtracting the combined mass of the reactants from the combined mass of the products.	$\Delta m = 235.860143 - 236.052595$ $= -0.192452$ amu (1 mark)
Step 5: For part **a**, complete the conversion. Remember 1 amu = 1.66×10^{-27} kg.	**a** Δm in kg $= 0.192452\,\text{amu} \times \frac{1.66 \times 10^{-27}\,\text{kg}}{\text{amu}}$ $= 3.196 \times 10^{-28}$ kg (1 mark)
Step 6: Substitute the known values into the formula and find the unknown. Make sure you have included units and the correct number of significant figures (3).	$\Delta E = \Delta mc^2$ $= 3.196 \times 10^{-28} \times (3 \times 10^8)^2$ J $= 2.88 \times 10^{-11}$ J (for one atom of U-235) (1 mark)
Step 7: for part **b**, determine how many nucleons are in the reactant. This equals the mass number.	**b** U-235 has 235 nucleons. (1 mark)
Step 8: Calculate the energy per nucleon. Check that the correct number of significant figures is used (3).	J per nucleon $= \frac{2.88 \times 10^{-11}}{235}$ $= 1.23 \times 10^{-13}$ (1 mark)
Step 9: For part **c**, calculate the mass of one atom of reactant in kg. Remember 1 amu = 1.66×10^{-27} kg.	**c** m(U-235) = 235.043 amu × 1.66×10^{-27} kg per amu $= 3.90 \times 10^{-25}$ kg (1 mark)
Step 10: Calculate how many atoms of reactant are present in 1 kg of reactant.	Number of atoms present $= \frac{1\,\text{kg}}{3.90 \times 10^{-25}\,\text{kg}}$ $= 2.56 \times 10^{24}$ atoms (1 mark)
Step 11: Calculate the total energy produced for 1 kg of reactant. Check that the correct units are used, and the answer expressed to the correct number of significant figures (3).	Energy released by 1 kg of reactant $= 2.88 \times 10^{-11} \times 2.56 \times 10^{24}$ $= 7.38 \times 10^{13}\,\text{J kg}^{-1}$ (1 mark)

Your turn

Uranium-235 can undergo fission according to this reaction:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3\,^{1}_{0}\text{n}$$

Using the masses of nuclides in Appendix 1, **calculate** the energy, in joules, released (3 s.f.)

a per fission event for U-235 (5 marks)

b per nucleon of U-235 reacted (2 marks)

c per kilogram of U-235. (1 mark)

Real-world Physics

Fission reactors and nuclear waste problems

One issue that has created significant debate and social upheaval is nuclear power. People want cheap electricity but they don't want hugely expensive nuclear power stations; they want to reduce carbon pollution but they don't want to store nuclear waste; they want export income but they don't want to mine and sell uranium; and they want to be safe from foreign invaders but they don't want the atomic bomb.

There are significant health and environmental risks associated with the use of nuclear fission, but there are also the environmental and cost benefits of lowering fossil fuel consumption.

You could argue that nuclear power plants are better for the environment than the traditional fossil fuel-burning power plants because they don't pollute the air with greenhouse gases and therefore reduce the risk of global warming. Fossil-fuel plants are notorious for greenhouse gas emissions, but nuclear reactors raise many concerns too. Those concerns include:

- a reactor blowing up like a uranium bomb
- a reactor having a meltdown because of the heat generated by the fission process
- radioactive gases escaping into the atmosphere, similar to Chernobyl and Fukushima
- radioactive wastes having to be stored for millions of years
- taking more energy to build, run and decommission a nuclear power plant than what it will ever produce while operating
- a fission reactor being a net carbon polluter over its lifetime, even if it doesn't produce carbon pollution while running
- terrorists stealing uranium to make a bomb.

Apply your understanding

1 **Select** three of the claims listed and **develop** a research question for each. (3 marks)

Check your learning 6.3

Check your learning 6.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** why we still use models in nuclear physics. (2 marks)

2 **Explain** a neutron-induced nuclear fission reaction, using a nuclear equation. (3 marks)

3 **Define** the term "chain reaction" in the context of nuclear fission, using an example. (2 marks)

4 **Describe** the "liquid drop model" of a nucleus undergoing fission. (3 marks)

Analytical processes

5 **Determine** the missing products in the following neutron-induced fission reactions.

a $^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + ?^{1}_{0}\text{n}$ (1 mark)

b $^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{137}_{52}\text{Te} + ^{?}_{?}? + 2^{1}_{0}\text{n}$ (1 mark)

c $^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{152}_{60}\text{Nd} + ^{81}_{?}? + ?^{1}_{0}\text{n}$ (2 marks)

6 Plutonium-239 is a nuclide that undergoes neutron-induced fission. A typical reaction is

$$^{239}_{94}\text{Pu} + ^{1}_{0}\text{n} \rightarrow ^{133}_{55}\text{Cs} + ^{104}_{39}\text{Y} + 3^{1}_{0}\text{n}$$

The exact masses of the nuclides, including electrons, are given.

m(Pu-239) = 239.052164 amu

m(Cs-133) = 132.905452 amu

m(Y-104) = 103.904030 amu

m(neutron) = 1.008665 amu

Determine the energy released for the reaction in

a joules per atom of Pu-239 (3 s.f.) (5 marks)

b joules per nucleon of Pu-239 (3 s.f.). (2 marks)

7 **Determine** how many joules would be released if 1 amu of mass was completely converted to energy, given that 1 amu of mass $= 1.66 \times 10^{-27}$ kg (3 s.f.). (1 mark)

8 Consider the following fission reaction:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{90}_{38}\text{Sr} + ^{144}_{54}\text{Xe} + 2^{1}_{0}\text{n}$$

The masses of the nuclides, including electrons, are m(U-235) = 235.043390 amu; m(Sr-90) = 89.907144 amu; m(Xe-144) = 143.938945 amu.

Determine the energy released in

a joules per fission (3 s.f.) (6 marks)

b joules per nucleon of U-235 (3 s.f.). (6 marks)

Lesson 6.4
Nuclear fusion

Key ideas

→ Nuclear fusion reactions form new nuclides through the combination of two or more atomic nuclei.

→ Nuclei with a mass number smaller than that of Fe-56 are more likely to undergo nuclear fusion.

→ Nuclear fission and fusion reactions can both act as sources of power.

What is nuclear fusion?

Learning intentions and success criteria

When you look at the Sun, you are seeing the result of a nuclear fusion reaction at its core. But what makes it different from nuclear fission? Fusion is the opposite of fission. In fission, we split a large nucleus into smaller pieces, but in fusion we combine smaller nuclei to form a bigger one.

In **nuclear fusion**, the colliding particle unites with the parent and fuses (Latin "fusus" meaning "melted" or "united") into a single nucleus with a higher mass. Sometimes, other small particles (n, p) are given off. The new composite nucleus is more stable than the colliding particles as its binding energy per nucleon is greater.

nuclear fusion
a nuclear reaction in which two or more atomic nuclei combine to form one or more different, heavier nuclides and subatomic particles

We said earlier that the greater the binding energy per nucleon, the more stable the nucleus. The stability graph peaks at Fe-56 and "droops" either side. To the left, particles can improve their stability by fusing into a bigger nucleus. When they fuse, they release energy.

Nuclear fusion releases more energy per nucleon than nuclear fission because a greater percentage of the mass is transformed into energy. An example of nuclear fusion is:

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + \gamma \ (2.8 \times 10^{-18}\,\text{J, or } 17.6\,\text{MeV})$$

Physicists John Cockcroft and Ernest Walton carried out this reaction in the laboratory in England in 1932. It was the first artificial fusion reaction to produce energy. Nuclear fusion is difficult to achieve. For two small nuclei to fuse, their massive electrostatic repulsions must be overcome. Cockcroft and Walton achieved this, and their work marked the start of research into fusion as a source of energy.

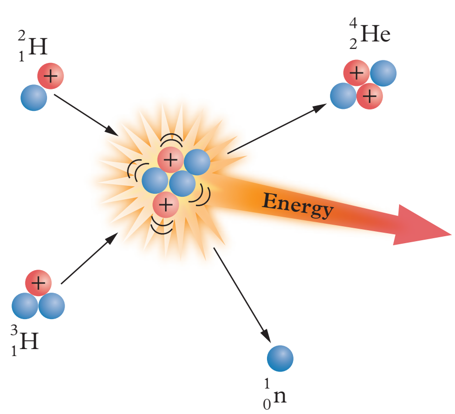


FIGURE 1 The fusion reaction between deuterium and tritium forms the larger helium nucleus.

Proton–proton chain reactions

Fusion is not something new. Nuclear fusion has been powering the Sun and other small stars for billions of years. In the Sun, hydrogen ${}^{1}_{1}H$ (a proton) is first fused to form the isotope deuterium ${}^{2}_{1}H$ and by-products of a beta positive particle (the positron, ${}^{0}_{+1}e$) and an electron neutrino (${}^{0}_{0}\nu$ or ν_e).

$${}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{+1}e + {}^{0}_{0}\nu_e + \gamma \ (0.42\,MeV)$$

This reaction is then followed by two other fusion reactions to form stable helium ${}^{4}_{2}He$:

$${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{1}H + \gamma \ (5.49\,MeV)$$

$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2{}^{1}_{1}H \ (12.86\,MeV)$$

proton–proton chain reaction
a series of nuclear fusion reactions in which four hydrogen nuclei (protons) are combined to form one helium nucleus

The two protons released then go on to repeat the cycle. This is called a **proton–proton chain reaction**.

How do we calculate energy change in nuclear fusion?

As in nuclear fission reactions, the difference in mass between the reactants and products represents the change in energy. This difference in mass arises because of the difference in nuclear binding energy between the atomic nuclei before and after the reaction.

Helium is very stable and has a high binding energy per nucleon compared with deuterium and tritium. We can see this using calculations. Let's consider the last reaction above:

$${}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + 2{}^{1}_{1}H$$

The data in Appendix 1 shows nuclide masses (including electrons) as:

- $m({}^{3}_{2}He) = 3.016029\,amu$
- $m({}^{4}_{2}He) = 4.002603\,amu$
- $m({}^{1}_{1}H) = 1.007825\,amu$
- $m_r = 2 \times 3.016029\,amu = 6.032058\,amu$
- $m_p = 2 \times 1.007825 + 4.002603 = 6.018253\,amu$
- $\Delta m = m_p - m_r = 6.018253 - 6.032058 = -0.013805\,amu$

The sign for Δm is negative, which means energy is released. This is showing that the reactants are heavier than the products, so the reactants have given up some mass as energy.

We could also say that the binding energy by the products is higher than that of the reactants. This means that the products are more stable. We can then calculate the energy in joules equivalent to 0.013805 amu, as we did for nuclear fission:

$$\Delta E = \Delta mc^2 = (0.013805 \times 1.66 \times 10^{-27})\,(3 \times 10^8)^2 = 2.06 \times 10^{-12}\,J \text{ per fusion event}$$

In MeV, $\Delta E = 0.013805\,amu \times 931.5\,MeV$ per amu $= 12.86\,MeV$ per fusion event.

We can then calculate the energy released in joules per nucleon by dividing the energy in joules by the number of nucleons: $\Delta E = \frac{2.06 \times 10^{-12}\,J}{6 \text{ nucleons}} = 3.43 \times 10^{-13}\,J$ per nucleon.

Worked example 6.4A

Calculating energy released in a fusion reaction

The fusion of two atoms is represented by the nuclear equation:

$${}^{2}_{1}H + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}H + \gamma$$

Calculate the energy released in

a MeV per fusion event (2 d.p.) (4 marks)

b joules per fusion event (3 s.f.) (2 marks)

c joules per nucleon of reactants (3 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the mass–energy equivalence relationship formula and find the change in energy, then express the answers correctly. The questions are worth a variety of marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. Locate relevant nuclide masses in Appendix 1 to identify the masses of all the nuclides involved.	$\Delta m = m_p - m_r$ $\Delta E = \Delta mc^2$ $m(^2_1H) = 2.014102$ amu $m(^3_2He) = 3.016029$ amu $m(^4_2He) = 4.002603$ amu $m(^1_1H) = 1.007825$ amu
Step 3: Calculate the sum of the masses of all the products and the sum of the masses of all the reactants.	$m_r = 2.014102 + 3.016029 = 5.030131$ amu (1 mark) $m_p = 4.002603 + 1.007825 = 5.010428$ amu (1 mark)
Step 4: Substitute the known values into the formula and find the unknown. Calculate the change in mass by subtracting the combined mass of the reactants from the combined mass of the products.	$\Delta m = 5.010428 - 5.030131$ $= -0.019703$ amu (1 mark)
Step 5: For part **a**, complete the conversion. Remember 1 amu = 931.5 MeV.	**a** Energy(MeV) $= 0.019703\text{ amu} \times \frac{931.5\text{ MeV}}{\text{amu}}$ $= 18.35$ MeV (2 d.p.) (1 mark)
Step 6: For part **b**, complete the conversion. Remember 1 amu = 1.66×10^{-27} kg.	**b** Δm in kg $= 0.019703\text{ amu} \times \frac{1.66 \times 10^{-27}\text{ kg}}{\text{amu}}$ $= 3.27 \times 10^{-29}$ kg (1 mark)
Step 7: Substitute the known values into the formula and find the unknown. Make sure you have included units and the correct number of significant figures.	$\Delta E = 3.37 \times 10^{-29} \times (3 \times 10^8)^2$ $= 2.94 \times 10^{-12}$ J (1 mark)
Step 8: For part **c**, determine the number of nucleons in the reactants. It is equal to the sum of the mass numbers.	**c** Number of nucleons = 2 + 3 = 5 (1 mark)
Step 9: Calculate the energy per nucleon by dividing the total energy per fusion event by the total number of nucleons. Make sure you have included units and the correct number of significant figures (3).	Energy per nucleon $= \frac{2.94 \times 10^{-12}\text{ J}}{5}$ $= 5.88 \times 10^{-13}$ J per nucleon (1 mark)

Your turn

The fusion of two atoms is represented by the nuclear equation:

$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$

Calculate the energy released in

a MeV per fusion event (1 d.p.) (4 marks)

b joules per fusion event (1 s.f.) (2 marks)

c joules per nucleon of reactant (2 s.f.). (2 marks)

How do you compare energy released in nuclear reactions?

Remember that when we compare the energy released by a reaction, we need to make sure the values we are comparing have the same units. It is common to express the energy released as:

- per nuclear fusion or fission event
- per nucleon reacted
- per kilogram of reactants.

Fission vs fusion

Let's consider Worked example 6.3B. When U-235 underwent a neutron-induced fission reaction, the energy output was calculated as 2.88×10^{-11} J per fission event or 1.23×10^{-13} J per nucleon. On the other hand, the energy produced by a fusion reaction such as $^{2}_{1}H + ^{3}_{2}He \rightarrow ^{4}_{2}He + ^{1}_{1}H + \gamma$ (Worked example 6.4A) was shown to be 2.94×10^{-12} J per fusion event, or 5.88×10^{-13} J per nucleon.

Although the energy production per event is greater for fission, when we compare the energy per nucleon and per kilogram, the fusion reaction produces much more energy than the fission reaction. In general, we can say that more energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.

Study tip

More energy is released per nucleon in nuclear fusion than in nuclear fission because a greater percentage of the mass is transformed into energy.

TABLE 1 Comparison of fission and fusion reactions

	Fission of U-235	Fusion of $^{2}_{1}H$	Energy production
J per event	2.88×10^{-11}	2.94×10^{-12}	fission = 10 × fusion
J per nucleon	1.23×10^{-13}	5.88×10^{-13}	fusion = 4 × fission
J per kg	7.38×10^{13}	8.79×10^{14}	fusion = 12 × fission

Real-world physics

Controlled and uncontrolled fusion

Since the 1950s, the use of controlled fusion for electricity production has been considered technically feasible. The International Thermonuclear Experimental Reactor (ITER) is an international nuclear fusion research and engineering megaproject being built in southern France. It will be the world's largest magnetic confinement plasma physics experiment.

Because of the massive electrostatic repulsion protons experience with other protons, the nuclei have to be slammed together at huge speeds. This means high kinetic energy and high temperatures are required. In fact, temperatures of over 150 million °C are required. The ITER's thermonuclear fusion reactor will use over 300 MW of electrical power and absorb 50 MW of thermal power, causing the plasma to create 500 MW of heat from fusion for periods of 400 to 600 seconds.

The expected cost of the ITER has gone from $5 billion to $20 billion since first proposed, and the scheduled date for full-power operation is now 2035. Australia is a partner in the project.

While nuclear fusion for peaceful purposes (such as electricity production) seems a long way off, nuclear fusion in the form of uncontrolled fusion has already been harnessed for destructive purposes, such as in the form of the hydrogen bomb. This type of bomb is technically more advanced than the bombs that use nuclear fission and is potentially more devastating.

After the United States dropped a fission bomb on Japan towards the end of the war in 1945, the Soviet Union decided to develop its own in the late 1940s. Not be outdone, the United States began to work on new technology known as the thermonuclear or hydrogen bomb (H-bomb). H-bombs differ from fission bombs in that most of their explosive power comes from nuclear fusion. The first successful fusion bomb detonation was in 1952 in the United States. It was said the explosion was "brighter than a thousand suns" (Figure 2). The explosive power of a fusion bomb is thousands of times greater than that of fission devices.

FIGURE 2 The first fusion bomb (known as "Mike") was detonated on 31 October 1952.

Apply your understanding

1 A fusion bomb consists of a strong metal case packed with chemical and nuclear fuel. When the chemical explosive is fired, the U-235 core is compressed to a smaller sphere. This causes it to undergo fission. The high energy and temperature initiate a fusion reaction between the deuterium and tritium inside it. Neutrons and gamma rays are released in the reaction. **Deduce** the balanced nuclear equation for the fusion reaction between deuterium and tritium. (1 mark)

2 **Compare** controlled and uncontrolled nuclear fusion. (3 marks)

Skill drill

Fission versus fusion

Science inquiry skills: Processing and analysing data (Lesson 1.7)

Your research investigation should be targeted to an audience who understands scientific literature and the context of your claim; however, they may not know the full scientific details relevant to your research questions. This is your opportunity to demonstrate your scientific understanding of the topic and the processes that occur within it.

The following claim has been made:

"Nuclear bombs release harmful ionising radiation."

Practise your skills

1 **Identify** the key concepts that must be explained. (1 mark)

2 **Explain** whether you would need to consider both fission and fusion bombs. (2 marks)

3 **Propose** a possible research question related to this claim. (1 mark)

4 **Evaluate** whether a suitable research question for this claim could be: "Are fusion bombs are better than fission bombs?" (4 marks)

Check your learning 6.4

Check your learning 6.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** nuclear fusion, using a nuclear equation. (2 marks)

2 The following reaction has an energy output of 2.95×10^{-12} J per fusion event.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n$$

Calculate the energy released in joules per kilogram of reactant ($J\,kg^{-1}$, 2 d.p.). (4 marks)

3 The following reaction has an energy output of 5.23×10^{-13} J per fusion event.

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n$$

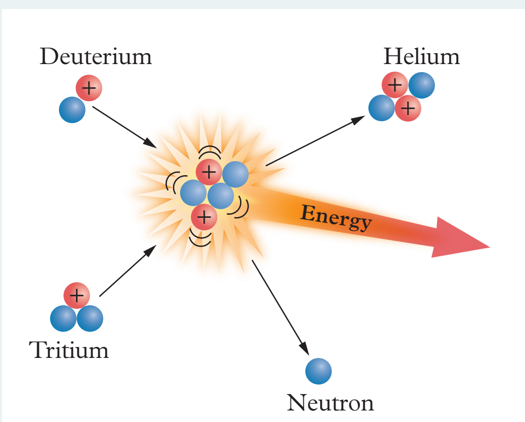
Calculate the energy released in

a joules per fission event (2 s.f.) (5 marks)

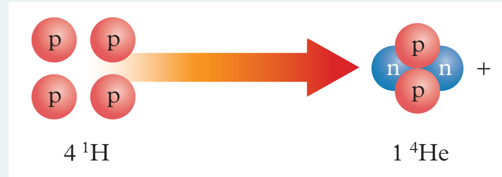
b joules per nucleon of reactants (2 s.f.). (2 marks)

Analytical processes

4 **Deduce** a balanced equation for these fusion reactions.

a 

(1 mark)

b 

(1 mark)

c $^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + ?$ (1 mark)

5 **Determine** which of these neutron-induced reactions produces the greater amount of energy per fission:

$n + {}^{3}He \rightarrow {}^{4}He + \gamma$ or $n + {}^{1}H \rightarrow {}^{2}H + \gamma$

(9 marks)

Knowledge utilisation

6 **Discuss** whether a fission or fusion reaction generates more energy per event. (3 marks)

7 An Australian \$1 coin has a mass of 9.0 g. Using the formula $\Delta E = \Delta mc^2$, the mass is equivalent to 8.1×10^{14} J. This is about the total energy consumption of a town of 40,000 people for 1 year (at 5,817 kWh per person per year). **Discuss** how this can be. (4 marks)

MODULE 6

Lesson 6.5
Review: Nuclear energy and mass defect

Summary

6.1
- Artificial transmutations, such as proton, alpha, deuteron and neutron bombardment, are used to form new elements.

6.2
- Mass defect accounts for the "missing" energy when a new nucleus is made.
- The greater the binding energy per nucleon, the greater the nuclear stability.

6.3
- Neutron-induced nuclear fission reactions form new nuclides through bombarding atoms with neutrons.
- Nuclei with a larger mass number than Fe-56 are more likely to undergo nuclear fission.
- Fission chain reactions occur when neutrons produced from fission cause another fission reaction to occur, producing more neutrons that cause further fission reactions.

6.4
- Nuclear fusion reactions form new nuclides through the combination of two or more atomic nuclei.
- Nuclei with a mass number smaller than that of Fe-56 are more likely to undergo nuclear fusion.
- Nuclear fission and fusion reactions can both act as sources of power.

Key formulas

Mass defect (binding energy)	$\Delta m = m_{cp} - m_{nuclide}$
Mass–energy equivalence relationship	$\Delta E = \Delta mc^2$
Change in mass	$\Delta m = m_p - m_r$
Percentage of mass converted	$\% \text{ mass converted} = \frac{\Delta m}{m_r} \times 100$

Review questions 6.5A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 The reaction $^{1}_{1}p + ^{7}_{3}Li \rightarrow ^{4}_{2}He + ^{4}_{2}He + \gamma$ is described as

A alpha decay.
B fusion.
C deuteron bombardment.
D lithium bombardment.

2 Which of the following isotopes has the highest nuclear binding energy per nucleon?

A ^{4}He
B ^{16}O
C ^{32}S
D ^{55}Mn

3 The nuclide $^{56}_{26}Fe$ has a binding energy of 492 MeV. The binding energy per nucleon is

A 6 MeV.
B 8.8 MeV.
C 16.4 MeV.
D 18.9 MeV.

4 Uranium-235 releases energy in a process called fission. Fission is

A the addition of a neutron to the nucleus.
B the release of gamma radiation.
C the combination of two smaller nuclei to form a larger one.
D the splitting of the nucleus into two smaller nuclei.

5 The following fusion reaction occurs in the Sun:

$$^{4}_{2}He + ^{3}_{2}He \rightarrow ^{7}_{4}Be$$

The masses of the nuclei including electrons are ^{3}He = 3.016029 u, ^{4}He = 4.002603 u, ^{7}Be = 7.016929 u. Using the table of nuclides in Appendix 1, the energy of the reaction is closest to

A 920 MeV absorbed.
B 1.6 MeV absorbed.
C 920 MeV released.
D 1.6 MeV released.

6 Which one of the following statements is correct?

A Mass number is the sum of all protons and electrons in an atom.
B Mass defect is the difference in mass between a nucleus and its component particles.
C Nuclei that release the highest binding energies are the most stable nuclei.
D Einstein's relationship about mass and energy says that mass and energy are equal.

7 When ^{235}U is bombarded with one neutron, fission occurs and the products are three neutrons, ^{94}Kr and which one of the following?

A ^{139}Ba **B** ^{141}Ba
C ^{139}Ce **D** ^{139}Xe

8 The mass of a $^{11}_{5}B$ nuclide including electrons is 11.009305 amu. The mass of the nucleus in amu without electrons is

A 11.003266. **B** 11.006560.
C 11.009305. **D** 11.015344.

9 For the nuclear reaction:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{55}Cs + ^{96}_{37}Rb + \text{neutrons}$$

the number of neutrons produced is

A 1. **B** 2.
C 3. **D** 4.

10 Identify the missing nuclide $^{A}_{Z}X$ in this reaction:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{137}_{52}Te + ^{A}_{Z}X + 2^{1}_{0}n$$

A $^{97}_{40}Zr$
B $^{98}_{40}Zr$
C $^{97}_{40}Bk$
D $^{97}_{38}Sr$

11 Identify the symbol for the neutrino in this equation:

$$^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{+1}e + \text{neutrino}$$

A $^{0}_{0}\nu_e$
B $^{0}_{+1}\nu_e$
C $^{0}_{0}\overline{\nu}_e$
D $^{0}_{+1}\overline{\nu}_e$

12 In the following equation, one of the symbols is shown as ${}^{A}_{Z}X$. Identify the type of reaction shown by this equation:

$${}^{2}_{1}H + {}^{A}_{Z}X \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

A Proton bombardment
B Alpha decay
C Hydrogen fusion
D Fission

13 Identify the missing symbols in the following equation:

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{146}_{?}La + {}^{?}_{?}? + 3{}^{1}_{0}n$$

A ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{146}_{57}La + {}^{89}_{35}Ac + 3{}^{1}_{0}n$
B ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{146}_{57}La + {}^{89}_{35}Br + 3{}^{1}_{0}n$
C ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{146}_{57}La + {}^{87}_{32}Ge + 3{}^{1}_{0}n$
D ${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 3{}^{1}_{0}n$

14 Consider the following equation.

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$$

State the type of reaction represented and whether the products (${}^{4}_{2}He + {}^{1}_{0}n$) are heavier or lighter than the reactants.

A Fission, lighter
B Fission, heavier
C Fusion, lighter
D Fusion, heavier

15 A possible uranium fission reaction is

A ${}^{235}_{92}U \rightarrow {}^{148}_{57}La + {}^{87}_{35}Br$
B ${}^{235}_{92}U \rightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 1$ neutron
C ${}^{235}_{92}U + 1$ neutron $\rightarrow {}^{146}_{57}La + {}^{87}_{35}Br + 3$ neutrons
D ${}^{235}_{92}U + 3$ neutrons $\rightarrow {}^{150}_{57}La + {}^{87}_{35}Br + 1$ neutron

16 The correct formula for the mass–energy equivalence relationship is

A $E_k = \frac{1}{2}mv^2$
B $\Delta E_p = mg\Delta h$
C $Q = mL_f$
D $\Delta E = \Delta mc^2$

17 Which of the following is the correct definition of the binding energy of a nucleus?

A The product of the binding energy per nucleon and the nucleon number
B The minimum work required to completely separate the nucleons from each other
C The energy that keeps the nucleus together
D The energy released during the emission of an alpha particle

Review questions 6.5B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

18 **Define** the terms "binding energy", "binding energy per nucleon", "electron volt", "mass defect", "mass number" and "unified atomic mass unit". (6 marks)

19 Using the table in Appendix 1, **identify** the exact mass of a Be-7 nuclide (including electrons). (1 mark)

20 The mass of a carbon-14 nuclide including electrons is 14.003242 amu. **Calculate** the mass of the nucleus in amu. (1 mark)

21 **Calculate** the mass defect in amu and binding energy (MeV per nucleon) for each nuclide.

a ${}^{35}_{15}S$ (2 marks)
b ${}^{235}_{92}U$ (2 marks)
c Cd-113 (3 marks)
d Li-7 (3 marks)

22 For each nuclide, **calculate** the binding energy in J, J per nucleon, MeV and MeV per nucleon.

a sodium ${}^{23}_{11}Na$ (5 marks)
b beryllium Be-7 (5 marks)
c potassium K-40 (5 marks)

23 **Define** the terms "artificial transmutation", "nuclear fission" and "nuclear fusion". (3 marks)

24 **Explain** what it means to have a fission chain reaction. (1 mark)

25 **Recall** Einstein's mass–energy equivalence relationship in symbol form and **explain** its meaning. (2 marks)

26 **Calculate** the energy released per nucleon (in MeV per J) in this neutron-induced fission reaction:

$$n + \text{U-235} \rightarrow \text{Kr-92} + \text{Ba-142} + 2n$$

The masses of the nuclides, including electrons, are:
m(U-235) = 235.043930 amu
m(Ba-142) = 141.916432 amu
m(Kr-92) = 91.926173 amu. (4 marks)

Analytical processes

27 **Distinguish** between artificial transmutations and natural radioactive decay. (2 marks)

28 **Determine** which nuclide has the highest binding energy per nucleon by using the graph of variation in binding energy per nucleon. (1 mark)

29 A physicist discovered a particle with a mass of 2.02733 amu. It is neutral, so they assumed it was two neutrons bound together.

- **a** **Calculate** the binding energy of the newly discovered particle. (3 marks)
- **b** **Describe** what is unreasonable about the assumption of the constituent particles. (2 marks)

30 The table lists the variation in total binding energy (MeV). **Using** the data in the table, test the following claim:
"The more nucleons present, the greater the forces holding the nucleus together and hence the greater the binding energy."

Z	A	MeV
30	66	578.136
30	67	585.189
31	69	601.996
32	72	628.686
33	75	652.564
34	76	662.073
34	77	669.492
36	80	695.434
38	86	748.928
40	90	783.893

- **a** **Justify** whether the data in the table supports this claim. (3 marks)
- **b** **Determine** the graphical shape of the relationship (linear, etc.). (1 mark)
- **c** **Determine** the mathematical relationship. (1 mark)
- **d** **Predict** if the trend line is likely to go through (0, 0). (1 mark)

31 **Determine** the products of this proton bombardment reaction: ${}^{9}_{4}\text{Be} + {}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + ?$ (1 mark)

32 Consider the following neutron-induced fission reaction:

$$n + {}^{238}_{92}\text{U} \rightarrow {}^{96}_{38}\text{Sr} + {}^{140}_{54}\text{Xe} + 3{}^{1}_{0}n$$

The masses of the nuclides including electrons are given: m(Sr-96) = 95.921707 amu and m(Xe-140) = 139.921646 amu.
Calculate the energy released in MeV and J. (4 marks)

33 Consider the following fission reaction:

$${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{141}_{55}\text{Cs} + {}^{93}_{37}\text{Rb} + 2{}^{1}_{0}n$$

Calculate the energy released in

- **a** MeV (4 marks)
- **b** joules. (2 marks)

Knowledge utilisation

34 Consider these two nuclear reactions:
I ${}^{239}_{94}\text{Pu} + {}^{1}_{0}n \rightarrow {}^{137}_{52}\text{Te} + {}^{100}_{42}\text{Mo} + 3{}^{1}_{0}n$
II $2{}^{2}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He}$

- **a** **Determine** which of the reactions produces more energy per kilogram of reactant. (13 marks)
- **b** **Evaluate** the conclusion about these reactions: "Fusion produces more energy per kilogram than a fission reaction." (3 marks)

35 **Solve** by balancing these fission reactions.

- **a** ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{133}_{?}\text{Sn} + {}^{101}_{?}? + ?{}^{1}_{0}n$ (2 marks)
- **b** ${}^{235}_{92}\text{U} + {}^{1}_{0}n \rightarrow {}^{138}_{?}\text{Xe} + {}^{?}_{?}? + 3{}^{1}_{0}n$ (2 marks)

36 In a particular fission event in which a nucleus of U-235 is struck by a slow neutron, no neutrons are created. If one of the fission fragments is Ge-83, **deduce** the other fragment. (1 mark)

37 Nuclear fission of U-235 releases about 3.5×10^{-11} J of energy per fission event.

- **a** **Calculate** this energy as J per kg of U-235 reacted. (4 marks)
- **b** **Determine** how many times greater this is than the combustion of methane, which releases 50 MJ kg^{-1}. (2 marks)

38 The "Little Boy" fission bomb dropped on Hiroshima, Japan, to end WWII contained 64 kg of enriched uranium. When the bomb exploded, only 0.88 kg of the U-235 underwent fission. Each U-235 atom split into two radionuclides. One of the long-term effects from a nuclear explosion is the radioactive fallout.

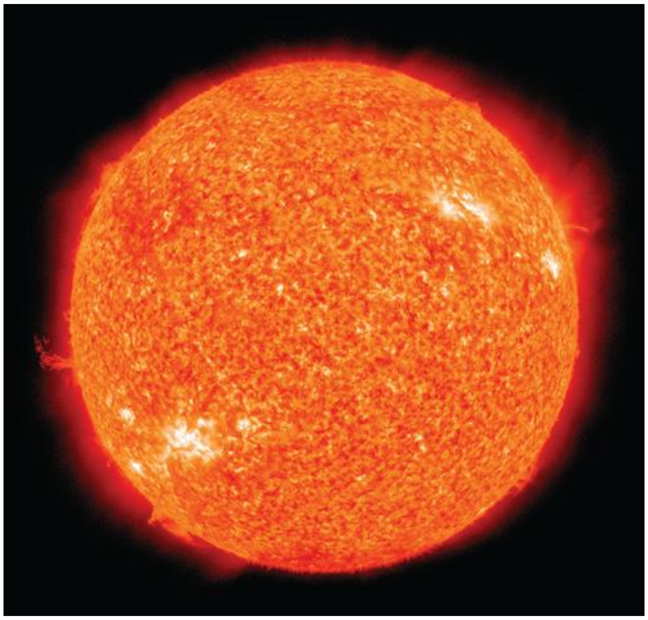
a **Determine** how many radioactive nuclei each human would have breathed in if all radioactive fission products were spread evenly among the human population at the time (2.4 billion). Hint: **calculate** how many atoms of U-235 are in 0.88 kg and double that to get the number of radionuclides. (4 marks)

b **Propose** why this is not a realistic calculation. Include an example to demonstrate your reasoning. (3 marks)

39 The Sun produces 1.86×10^{38} neutrinos per second. This is called the solar neutrino flux at its surface.

a **Determine** how many of these fall on Earth's surface per second. Hint: you will need to consider what fraction of the Sun's radiation will reach the Earth. Note: the distance between Earth and the Sun = 1.496×10^{11} m; diameter of Earth = 12,742 km; surface area of a sphere = $4\pi r^2$. (8 marks)

b **Deduce** how many neutrinos fall on a 1 cm^2 area of the Earth's surface per second. (6 marks)



40 **Evaluate** this statement: "Fusion of nuclides heavier than $^{56}_{26}Fe$ actually requires energy rather than produces energy, so will not proceed". (4 marks)

Data drill

Nuclide binding energy

The binding energy of a nuclide can be used to determine its relative stability and predict whether it is more likely to undergo a fission or fusion reaction.

Table 1 shows the binding energy for a selection of nuclides, as well as their atomic and mass numbers.

TABLE 1 Atomic number, mass number and binding energy for a selection of nuclides

Atomic number (Z)	Mass number (A)	Binding energy (MeV)
20	45	442.635
21	47	460.283
22	49	472.359
23	53	489.438
24	56	503.218
25	58	521.316
25	59	524.214
26	61	536.169
28	64	552.327
30	66	578.136

Apply understanding

1 **Calculate** the binding energy (in MeV) per nucleon for the nuclide $^{59}_{25}\text{Mn}$ (to 2 d.p.). (2 marks)

2 **Determine** the symbol for the final nuclide in the table in the $^{A}_{Z}\text{X}$ nomenclature. (2 marks)

Analyse evidence

3 **Identify** any trend in the relationship between mass number and binding energy for the given range. **Justify** your conclusion by reference to the data. (2 marks)

4 **Predict** the binding energy in MeV and MeV per nucleon for the nuclide $^{24}_{12}\text{Mg}$. **Justify** your answer, with reference to the data. (2 marks)

Interpret evidence

5 **Draw a justified conclusion** about which nuclide in the table is the most stable. (3 marks)

Module 6 checklist: Nuclear energy and mass defect

Quizlet: Revise key terms online to test your understanding

UNIT 1

Topic 2 review

Multiple choice

(1 mark each)

1 The nuclear model of an atom is best described as
- **A** a small nucleus compared to the size of the atom.
- **B** protons tightly bound to neutrons by the strong force.
- **C** a small package of protons, neutrons, and electrons.
- **D** electrons orbiting a small core of protons and neutrons.

2 The strong nuclear force can be described as being negligible at all but atomic ranges where it is
- **A** attractive and keeps electrons and protons together.
- **B** attractive and keeps nucleons together.
- **C** repulsive and keeps nucleons apart.
- **D** repulsive and keeps protons apart.

3 In the nomenclature for nuclides, ${}^{A}_{Z}X$, the symbols A, Z and X represent in order
- **A** mass number, symbol for the element, atomic number.
- **B** symbol for the element, mass number, atomic number.
- **C** mass number, atomic number, symbol for the element.
- **D** atomic number, symbol for the element, mass number.

4 The number of nucleons in the ${}^{22}_{10}\text{Ne}$ atom is
- **A** 10.
- **B** 12.
- **C** 22.
- **D** 32.

5 Mg-23 undergoes natural radioactive decay to form Na-23 and
- **A** ${}^{0}_{-1}e + \bar{\nu}_e$.
- **B** ${}^{0}_{+1}e + \bar{\nu}_e$.
- **C** ${}^{0}_{-1}e + \nu_e$.
- **D** ${}^{0}_{+1}e + \nu_e$.

6 Natural beta negative decay is shown by
- **A** ${}^{239}_{92}\text{U} \rightarrow {}^{240}_{92}\text{U} + {}^{-1}_{0}e + \nu_e + \gamma$.
- **B** ${}^{239}_{92}\text{U} \rightarrow {}^{240}_{92}\text{U} + {}^{-1}_{0}e + \bar{\nu}_e + \gamma$.
- **C** ${}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}e + \nu_e + \gamma$.
- **D** ${}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}e + \bar{\nu}_e + \gamma$.

7 The particles emitted in the decay of the nucleus ${}^{32}_{15}\text{P}$ into ${}^{32}_{16}\text{S}$ are
- **A** β^-, ν_e.
- **B** ${}^{0}_{-1}e$, $\bar{\nu}_e$.
- **C** ${}^{0}_{+1}e$, ν_e.
- **D** ${}^{0}_{+1}e$, $\bar{\nu}_e$.

8 A type of radioactive decay in which an energetic positron and associated neutrino are emitted from an atomic nucleus is
- **A** alpha radiation.
- **B** gamma radiation.
- **C** beta positive radiation.
- **D** beta negative radiation.

9 What type of nuclear reaction is represented by the following equation?

$$ {}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n} $$

- **A** Artificial transmutation
- **B** Radioactive decay
- **C** Nuclear fusion
- **D** Nuclear fission

10 The aluminium isotope Al-24 is unstable and undergoes beta positive (positron) decay. Which of the following reactions shows the decay reaction?

A $^{24}_{13}\text{Al} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{+1}\text{e} + \bar{\nu}_e$

B $^{24}_{11}\text{Al} \rightarrow {}^{24}_{12}\text{Mg} + {}^{0}_{+1}\text{e} + \nu_e$

C $^{24}_{12}\text{Mg} + {}^{0}_{+1}\text{e} + \nu_e \rightarrow {}^{24}_{13}\text{Al}$

D $^{24}_{13}\text{Al} \rightarrow {}^{24}_{14}\text{S} + {}^{0}_{-1}\text{e} + \bar{\nu}_e$

11 A Geiger counter registered an intensity of 2,400 counts per second from a sample that contained a radioactive isotope of polonium. After 13 minutes 40 seconds, the counter registered 75 counts per second. What is the half-life of this isotope in seconds?

A 137

B 205

C 164

D 464

12 Which of the following lists the particles associated with radioactive decay in order of increasing ionisation power?

A α, β, γ

B β, α, γ

C γ, α, β

D γ, β, α

13 Determine the mass defect in amu and joules for the following reaction and whether the energy is released or absorbed.

$$^{1}_{1}\text{H} + {}^{7}_{3}\text{Li} \rightarrow {}^{4}_{2}\text{He} + {}^{4}_{2}\text{He}$$

Some elementary particle masses and nuclide masses, including electrons, are shown in amu.

Elementary particle	Mass (amu)	Nuclide	Mass (amu)	Nuclide	Mass (amu)
e	0.000549	H-1	1.007825	He-4	4.002603
p	1.007276	H-2	2.014102	Li-6	6.015123
n	1.008665	He-3	3.016029	Li-7	7.016003

A 0.018622 amu, 2.78×10^{-12} J, released

B 4.080677 amu, 6.09×10^{-18} J, released

C 0.018622 amu, 1.67×10^{7} J, absorbed

D 4.080677 amu, 3.67×10^{19} J, absorbed

14 Natural radioactive decay by the emission of beta negative particles is generally the result of

A a large excess of protons over neutrons.

B a large excess of neutrons over protons.

C an excess of mass.

D a deficit of mass.

15 A nuclear reaction is represented by the following equation.

$$^{1}_{0}\text{n} + {}^{198}_{80}\text{Hg} \rightarrow {}^{197}_{79}\text{Au} + {}^{2}_{1}\text{H}$$

This reaction is an example of

A fusion.

B fission.

C natural transmutation.

D artificial transmutation.

Short response

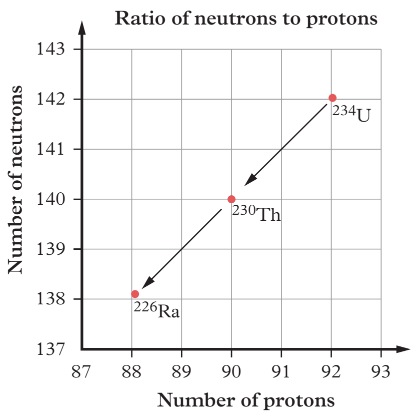
16 **Contrast** the properties of the strong nuclear force and the electromagnetic force as they apply inside a nucleus. (3 marks)

17 There are many isotopes of the element molybdenum (Mo). The isotope Mo-96 is stable, but Mo-91 and Mo-100 are both unstable.

- **a** **Describe** what the nuclei of different molybdenum isotopes have in common. (1 mark)
- **b** **Infer** the types of decay the two unstable isotopes undergo and **explain** how this achieves stability. (5 marks)

18 **Construct** a balanced equation for the alpha decay of Po-214. (3 marks)

19 Uranium-234 (U-234) is a radioactive element. The graph shows the number of protons and neutrons in the nuclei of the elements formed when uranium-234 decays.



- **a** **Explain** how the graph shows that uranium-234 and thorium-230 emit alpha particles. (2 marks)
- **b** After a series of more spontaneous decays, the final nuclide will have one particular property. **Describe** this property. (2 marks)
- **c** Radioactive decay may also produce gamma radiation. **Deduce** why the emission of gamma radiation does not cause a new element to be formed. (2 marks)

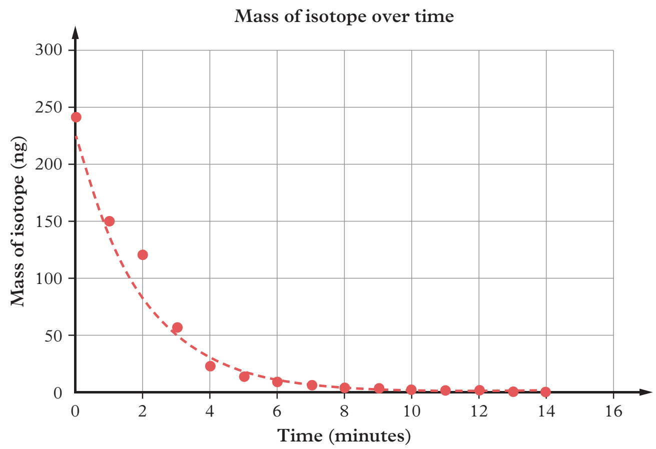
20 A researcher with a Geiger counter measures the intensity from a radioactive source at midday as 200 counts per minute. At 3:00 p.m., they find that this has dropped to 25 counts per minute. Assume background radiation had no effect. **Determine** the half-life of the radioactive source. (4 marks)

21 An isotope of neptunium is Np-241, which has a half-life of 14 minutes. A sample of Np-241 has an initial mass of 22×10^{-6} g.

- **a** **Sketch** a line to show the mass of the isotope at 0, 5, 10 and 14 minutes. (4 marks)
- **b** **Calculate** the mass of the Np-241 in the sample after 90 minutes. (2 marks)
- **c** **Deduce** the time that would have elapsed for the mass to be 2×10^{-6} g. (2 marks)

22 Commercial nuclear power stations produce a number of radioactive waste products. One of the radioactive products is iodine-138, which has a half-life of 6 seconds. A sample of radioactive material contains 2,000 atoms of iodine-138. **Determine** how long it will take for the number of iodine-131 atoms to decrease to 125. (4 marks)

23 The mass of a radioactive source was measured over a period of time and plotted as shown in the graph.



- **a** **Propose** why not all points are on the exponential trendline and **infer** what this says about the nature of radioactive decay. (1 mark)
- **b** **Determine** the half-life of the sample in minutes (1 d.p.). (4 marks)

24 The radioactive isotope technetium-99 can be injected into the bloodstream to trace the blood flow to the heart. Tc-99 emits only gamma rays.

a **Explain** what a gamma ray is. (1 mark)

b The amount of Tc-99 in a blood sample decreased from 856 nanograms per litre ($ng\,L^{-1}$) to 53 $ng\,L^{-1}$ in 24 hours. **Determine** the half-life of Tc-99 in hours (to the nearest whole number). (4 marks)

c **Determine** the concentration of the sample in $ng\,L^{-1}$ to the nearest whole number after another 12 hours. (2 marks)

d **Propose** one advantage of using Tc-99 to trace blood flow compared to using another isotope of technetium, Tc-97, which has a half-life of 97 days. (2 marks)

e **Propose** one advantage of using Tc-99 to trace blood flow compared to using Tc-100, which has a half-life of 3.3 μs. (2 marks)

25 At the very high temperatures in the Sun, hydrogen is converted into helium. It takes four hydrogen nuclei to produce one helium nucleus. The exact mass of a ${}^{1}_{1}H$ atom including electrons is 1.007825 amu, and the mass of a He-4 atom including electrons is 4.002603 amu.

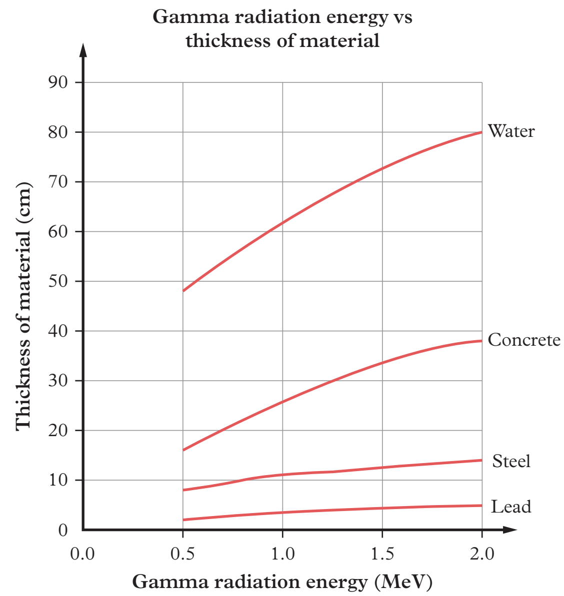
a **Propose**, with justification, whether the mass of the Sun would increase, decrease or stay the same as a result of the following reaction: (3 marks)

$$4\,{}^{1}_{1}H \rightarrow {}^{4}_{2}He$$

b **Determine** the energy lost or gained, in joule, for every helium nucleus produced. (2 marks)

26 Gold has a particular radioactive isotope, ${}^{196}_{79}Au$, which has a half-life of 6 days. A medical treatment involves injecting 100 μg of this isotope into the bloodstream and then measuring it some weeks later. **Determine** the amount of Au-196 present in the blood after 30 days have elapsed (2 s.f.). (2 marks)

27 The graph shows how the thickness of different materials needed to absorb 90% of the gamma radiation emitted by a source depends on the energy of the radiation. The energy of the gamma radiation is given in mega electron-volts (MeV).



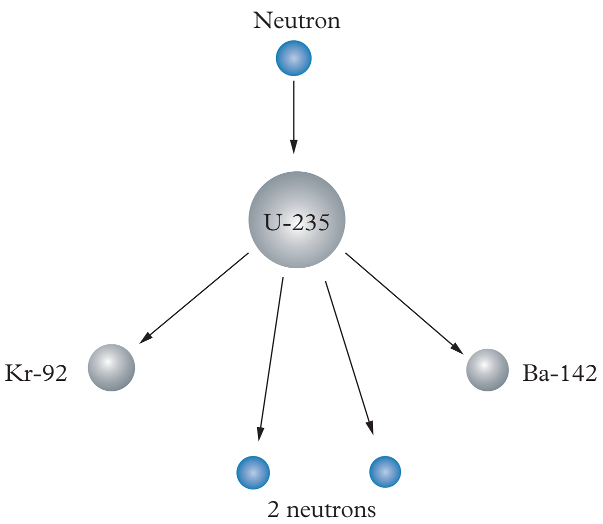
a **Identify** which of the materials shown is least effective at absorbing gamma radiation. **Justify** your answer. (3 marks)

b For gamma radiation of energy 1.5 MeV, **determine** how many times more effective steel is than water at absorbing the radiation. Show your working. (2 marks)

28 **Determine** the binding energy in MeV per nucleon for the nuclide germanium-76. The exact mass of the nuclide, including electrons, is 75.921403 amu. The masses of other subatomic particles are proton = 1.007276 amu, neutron = 1.008665 amu, electron = 0.000549 amu.

Express your answer to 3 s.f. (4 marks)

29 The diagram shows what can happen when the nucleus of a uranium atom absorbs a neutron.

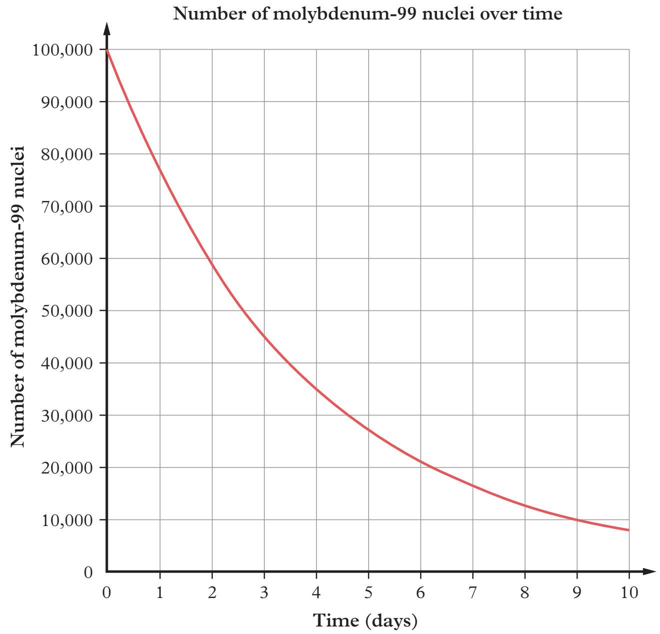


a **Identify** the name given to the process shown in the diagram. (1 mark)

b **Explain** how this process could lead to a chain reaction. (2 marks)

c **Explain** how the mass number of an atom changes when its nucleus absorbs a neutron. (1 mark)

30 Technetium-99 is used by radiologists as a medical tracer. In hospitals it is produced inside a technetium generator by the decay of molybdenum-99 nuclei. The graph shows how the number of nuclei in a sample of molybdenum-99 changes with time as the nuclei decay.



A technetium generator will continue to produce sufficient technetium-99 until 80% of the original molybdenum nuclei have decayed. **Determine** after how many days a source of molybdenum-99 inside a technetium-99 generator will need replacing. Show clearly your calculation and how you used the graph to obtain your answer. (3 marks)

TOTAL MARKS
/88

MODULE 7

Current, potential difference and energy flow

Introduction

When you run a comb through your hair you might hear some crackles, or your hair might stand up and "reach" for the comb! You have separated electric charges by friction in a process called "electrification".

Electric charge is responsible for many natural effects, such as lightning strikes, and much of our modern technology relies on making and controlling electric charges. To tinker with modern technology, we need to understand the nature of electric charge, current, energy and voltage. By the end of this topic you should be able to explain why a 6 V motorcycle battery can be more powerful than a 12 V car battery.

Prior knowledge

Prior knowledge quiz

Check your understanding of electricity before you start.

Subject matter

Science understanding

→ Describe electric charge as positive or negative.
→ Describe electric current as carried by discrete electric charge carriers.
→ Describe the law of conservation of electric charge.
→ Explain that electric charge is conserved at all points in an electrical circuit.
→ Describe the concepts of electrical potential difference and power within a circuit.
→ Solve problems involving electric current, electric charge and time using $I = \frac{q}{t}$.
→ Explain that the energy inputs in a circuit equal the sum of energy output from loads in the circuit.
→ Explain that the energy available to electric charges moving in an electrical circuit is measured using electrical potential difference.
→ Solve problems involving electrical potential difference using $V = \frac{W}{q}$.

- → Explain in qualitative terms why electric charge separation produces an electrical potential difference.
- → Solve problems involving power using $P = \frac{W}{t}$.
- → Describe the concept of resistance.
- → Solve problems using $V = IR$.
- → Discuss the differences between ohmic and non-ohmic resistors.
- → Interpret experimental data to determine the resistance across an ohmic resistor.

Science as a human endeavour

- → Appreciate the significant contributions of scientists such as Gustav Kirchhoff, Georg Ohm, Hertha Ayrton and Florence Violet McKenzie who furthered our understanding of electrical currents.

Science inquiry

- → Compare characteristics of ohmic and non-ohmic resistors experimentally.
- → Interpret graphical representations of electrical potential difference versus electric current data to find resistance using the gradient and its uncertainty.

Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 7.7 Finding resistance using current and voltage across an ohmic resistor

Lesson 7.8 Ohmic and non-ohmic resistors

Lesson 7.1
Charge

Key ideas

→ Charge is classified as positive and negative.
→ Conductors are substances that allow free movement of charge through them.
→ Insulators are substances that do not allow free movement of charge through them.

Learning intentions and success criteria

How is charge classified?

charge
a physical property of an object that causes it to experience a force when placed in an electric field; it can be negative, such as on an electron, or positive, such as on a proton

You may wonder who gave the electron a negative **charge**. For years you've learnt that electrons have a negative charge and protons have a positive charge. This is a convention, made up by people, but it has some logic.

The Greeks knew that taking a piece of amber (tree resin) and rubbing it with animal fur would cause feathers, hair and straw dust to stick to the amber. In 1733, French investigator Charles du Fay discovered two types of charge. He called them vitreous (glass rubbed by silk) and resinous (amber rubbed by fur) and noted that these two types of charge cancelled each other out.

The charges were given a name in 1747 by US scientist Benjamin Franklin. He knew that rubbing glass created a charge, and if you put your hand on the glass you acquired (received) the same charge. He said that you then had an excess of charge – that charge was added to you. Franklin said that as adding was positive (as in mathematics), the charge on the glass when rubbed with silk was positive (+). When a positively charged person touched the ground, the charge went away. Franklin said the ground must have an opposite charge that he called minus (–), which we now call negative.

When the electron was discovered by J. J. Thomson in 1897, it was shown to have the same charge as a plastic rod rubbed with fur – that is, a negative charge. So, electrons were considered to be particles with negative charge. When electrons are removed from an object such as glass, the glass is left with an excess of positive charges. The particle responsible for this positive charge was given the name "proton".

What carries charge?

You have learnt that atoms are the building blocks of all matter. An atom consists of a very small and dense central nucleus, which contains protons and neutrons, and a cloud surrounding the nucleus that contains electrons.

Figure 1 shows the location of the nucleus relative to the electron cloud and the relative diameters of a typical atomic nucleus and the outer electron cloud for a general atom. You can see the atom is about 100,000 times the diameter of the nucleus, so the atom is mostly empty space.

The particles in the nucleus are very tightly bound together, with the protons being positively charged and the neutrons being neutral (no net charge). The electrons, especially the outermost ones, are discrete (individual) particles and are very loosely bound to the nucleus in most atoms. "Discrete" means individually separate and distinct. Hence, discrete charge carriers are individual particles such as electrons and protons.

Any atom that has equal numbers of protons and electrons is said to be neutral as it has no net electric charge. Neutrons simply act as a part of the nuclear glue and do not alter the positive–negative balance of the atom. The hydrogen atom is the simplest atom in nature. It only has 1 electron and 1 proton, whereas lawrencium (Lw), a large atom, has 103 electrons, 103 protons and 157 neutrons. If an individual atom of any element is made to gain or lose some of its electrons, it is said to have become an **ion** (from the Greek "ienai", which means "to go"; coined in 1834 by Michael Faraday because ions move around, or "go"). An ion is also an example of a discrete charge carrier.

ion
an atom that has lost or gained electrons

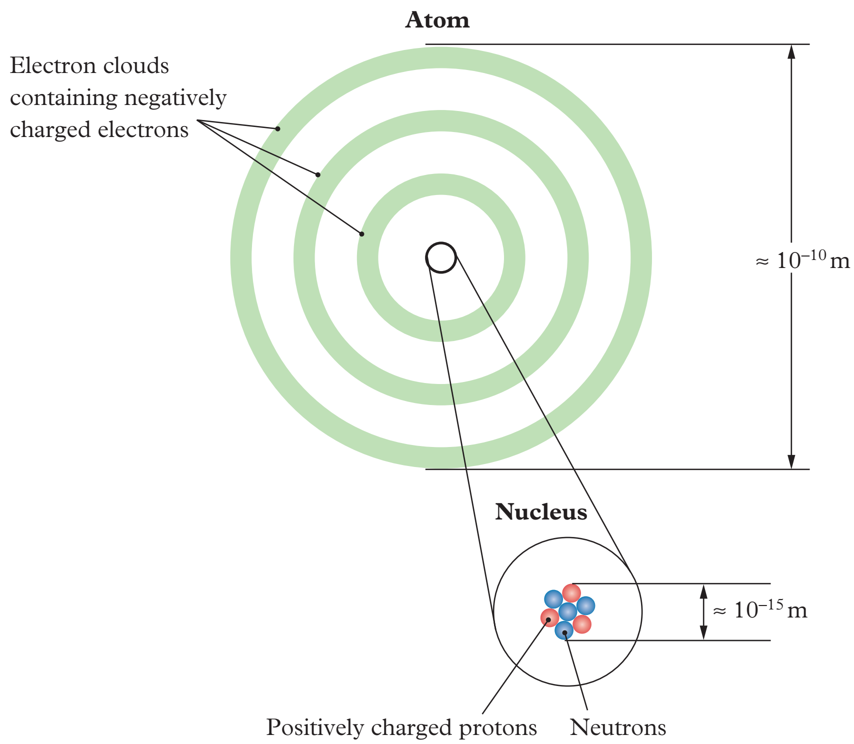


FIGURE 1 Simplified diagram showing the size of the atom and its constituents

coulomb
a measure of electric charge; one coulomb (C) is the charge on 6.24×10^{18} elementary charges

Positive ions have lost electrons and negative ions have gained electrons over and above the normal atomic number. Ions are important in various types of chemical reactions. You would have used tables of common ions in your earlier science work.

A lithium atom ($^{7}_{3}Li$) has 3 protons ($3p^+$) and 3 electrons ($3e^-$) and is electrically neutral. If one of the electrons is stripped away, the atom would still have 3 protons (+3) but only 2 electrons (–2). Its net charge would be the sum of +3 and –2, which is +1. It would have the formula Li^{1+} (or just Li^+). Likewise, a fluorine atom $^{19}_{7}F$ has 7 protons and 7 electrons ($7p^+$ and $7e^-$) and is electrically neutral. If it gains an electron, it will become an F^- ion.

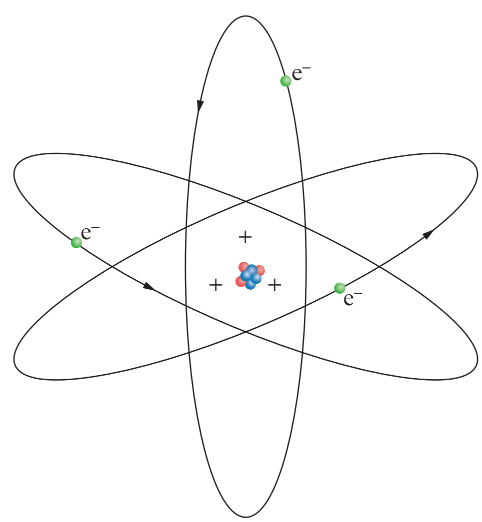


FIGURE 2 A simplified "planetary" model of an atom showing the positive central nucleus and orbiting electrons. Electrons don't really travel around in orbits like planets around the Sun, but the model helps explain the location of the two types of charge. Note that there are three positive charges in the nucleus, which are balanced by three negative charges in the electron cloud.

How do you measure charge?

Electric charge is measured in a unit called **coulomb** (symbol C). The unit is named after French physicist Charles-Augustin de Coulomb (1736–1806). One coulomb of electric charge is equivalent to the charge on 6.24×10^{18} electrons. If an electrified object has an excess of 6.24×10^{18} electrons or has lost this number of electrons,

Study tip

The symbol Q is the SI unit symbol for the quantity of charge on an object; however, it is common to use a lowercase q as well. You can use either. The symbol q_e (note the subscript e) stands for "elementary charge" and the magnitude of q_e is 1.6×10^{-19} C. The subscript e does not stand for electron.

it is said to have a charge of one coulomb (1 C) negative or positive respectively. An elementary charge (q_e) is the magnitude of the electric charge carried by a single proton or a single electron. The charge on a single electron can be calculated as $\frac{-1\text{ C}}{6.24 \times 10^{18}} = 1.6 \times 10^{-19}$ C.

An electron has a charge of $-q_e$ and a proton has a charge of $+q_e$. Note that we can only speak of "excess" charge as we don't know how many electrons and protons make up the object, just the number that are in excess one way or the other.

$$\text{Number of elementary charges} = \frac{\text{total charge}}{\text{elementary charge}}$$

$$n = \frac{q}{q_e}$$

Worked example 7.1A

Calculating particles in a charge

Calculate the number (n) of excess electrons in an object with a charge of –2.5 C (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$n = \frac{q}{q_e}$ (1 mark) $q = -2.5$ C $q_e = -1.6 \times 10^{-19}$ C
Step 3: Substitute the known values into the formula. Find the unknown.	$n = \frac{-2.5}{-1.6 \times 10^{-19}}$ $= 1.5625 \times 10^{19}$
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. You are requested to calculate the number of excess electrons and to express your answer to 2 s.f.	$n = 1.6 \times 10^{19}$ electrons (1 mark)

Your turn

Calculate the number (n) of excess elementary charges in an object with a charge of 15 μC (2 s.f.). Note: the prefix for the unit is "μ". (2 marks)

Fractional charge

All charged objects in nature are whole number multiples of the charge of an electron. However, you will see in Unit 4 that protons and neutrons are made up of more fundamental particles called "quarks". They can have fractional charges such as $\frac{1}{3}q_e$ and $\frac{2}{3}q_e$, which could be positive or negative.

What are the properties of atomic particles?

Table 1 summarises the properties of electrons, protons and neutrons that we've just learnt about.

Study tip

Information about producing a charge can be found on Oxford Digital.

TABLE 1 The properties of the three fundamental atomic particles

	Electron	Proton	Neutron
Relative charge	–1	+1	0
Coulomb charge	-1.6×10^{-19}	$+1.6 \times 10^{-19}$	0
Mass	9.11×10^{-31} kg	1.673×10^{-27} kg	1.675×10^{-27} kg
Atomic location	orbital cloud	nucleus	nucleus
Discovered	1897 by J. J. Thompson	1913 by E. Rutherford	1932 by J. Chadwick

What is the law of conservation of charge?

Frictional charging involves a transfer of negative charge or electrons from one object to another. Objects can never gain or lose protons in this process – they stay in place. It is the electrons that move. When a single electron leaves one object for a second object, the second has an excess of one electron (–1) and the first now has an excess of one proton (+1). The net amount of charge lost by one object of the pair is gained by the other. We can state a more general law called the **law of conservation of charge**:

law of conservation of charge
the net amount of charge produced in any transfer process is zero

The total charge before a transfer process equals the total charge after the process.

Look at Figure 3 and imagine rubbing a glass rod with a piece of silk, both of which are neutral. The diagram shows that 5 electrons have jumped from the glass to the silk, leaving the glass with a +5 charge, and the silk with a –5 charge, which add to zero. Charge is conserved, as the charge (before) of zero equals the charge (after) also of zero. The amount of charge produced (+5, –5) is zero, as the law states.

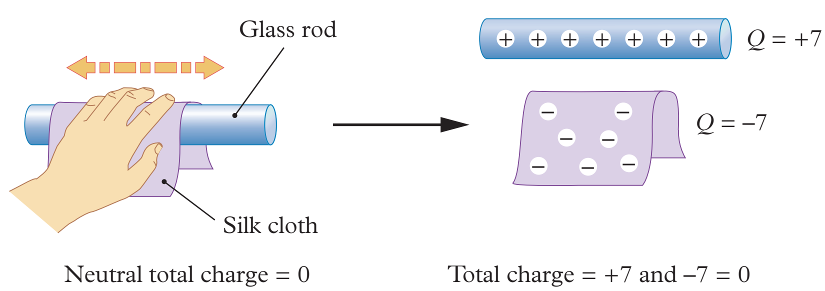


FIGURE 3 Loss of electrons by glass = gain of electrons by silk

What are conductors and insulators?

What is the difference between the way charge behaves in plastic and in metal? Plastic and metal are both solids, but they behave differently with electric charge. In solids, the atoms are generally arranged in a simple geometric pattern or lattice. In liquids and gases, the atoms are much freer to move.

A metallic solid has a regular lattice array (a fixed pattern) of atomic nuclei and the outermost electrons of each atom are easily able to move throughout this array (Figure 4). This type of arrangement is called metallic bonding. Metals are called good electrical **conductors** because any charge placed on them is free to move through the lattice. The mobile charge carriers are the electrons. In liquids that conduct electricity, the ions are the mobile charge carriers. For example, in a solution of sodium chloride in water, the ions involved are sodium ion (Na^+) and chlorine ion (Cl^-).

conductor
a substance that allows free movement of charge through it

Substances that do not allow free movement of charge, or whose atomic electrons are not free to move, are called **insulators**. The most common insulators used to prevent the flow

insulator
a substance that does not allow free movement of charge through it

of electric charge are rubber, plastics, paper, glass and ceramics. Charges placed onto any conductor will be free to evenly distribute over the surface of the conductor, while charge placed onto the surface of any insulator will stay in the same place.

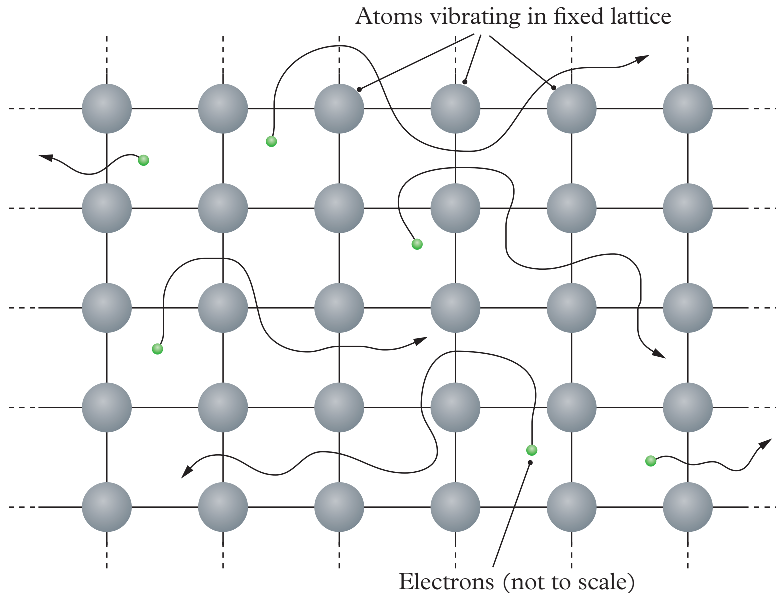


FIGURE 4 Lattice of fixed atoms and their mobile electrons

Check your learning 7.1

Check your learning 7.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** the concept of charge and how it can be classified. (3 marks)

2 **Describe** the difference between an insulator and a conductor. (2 marks)

3 **Calculate** the number of excess elementary particles in the following charges.
  a $+10.0\,C$ (2 marks)
  b $1.45\,\mu C$ (2 marks)
  c $-15\,pC$ (2 marks)

4 **Calculate** the magnitude of the charge in coulombs in the following.
  a 1.25×10^{25} electrons (2 marks)
  b 6.02×10^{23} electrons (2 marks)

5 **Explain** whether you can have an object with a charge of $3 \times 10^{-20}\,C$. (2 marks)

6 **Identify** whether each of the following statements is true or false regarding why metals are good conductors.
  a Metals contain free electrons. (1 mark)
  b The atoms in metals vibrate more easily than in non-conductors. (1 mark)
  c Metals have bigger gaps between their atoms than do insulators. (1 mark)
  d The atoms in metals can move about. (1 mark)

Analytical processes

7 **Categorise** the following materials into electrical conductors and electrical insulators: copper, PVC plastic, aluminium, silver, polythene, dry air, glass, carbon, salt solution, sugar solution. (2 marks)

8 A plastic rod is rubbed with fur and the rod acquires a $+50\,\mu C$ charge. **Deduce** the charge on the fur. (1 mark)

9 Two objects with different initial quantities of charge are brought together and the charge redistributes, as shown by the final state in the table. **Determine** the charge on the second object in each of these three cases, using the law of conservation of charge. (1 mark per row)

	Initial state (μC)		Final state (μC)	
	Object A	Object B	Object A	Object B
a	+10	−6	+4	?
b	+20	?	0	−20
c	+5	?	+2	−10

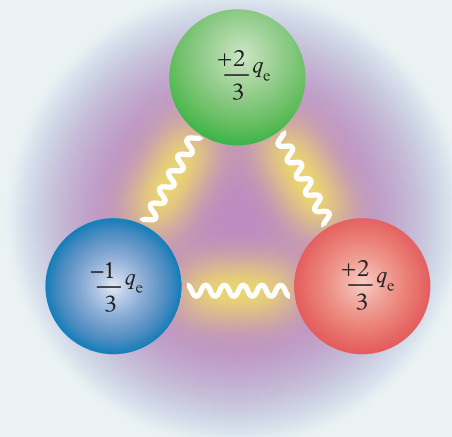
10 When a glass rod is rubbed with silk it becomes positive and the silk becomes negative, yet both attract dust. **Explain** whether dust has a third type of charge that is attracted to both positive and negative charges. (3 marks)

11 A neutral helium atom is stripped of all its electrons. **Calculate** the overall charge, in coulombs, on the resulting particle. (2 marks)

12 An atom of oxygen has 8 protons, 8 neutrons and 8 electrons. In a reaction, it gains electrons and finishes up with 10 electrons. **Calculate** the final overall charge. (2 marks)

Knowledge utilisation

13 The figure shows the three quarks that make up a proton. **Demonstrate** that the sum of the charges adds up to the charge on the proton. (1 mark)



14 **Propose** why a car always attracts dust immediately after it is polished. Note: car wax and car tyres are insulators. (2 marks)

Lesson 7.2

Current and electron flow

Key ideas

→ Electric current is the rate of movement of electric charge carriers from one part of a conductor to another.

→ Electron flow is the flow of electrons in a circuit and is opposite to electric current.

Learning intentions and success criteria

What is electric current?

In Lesson 7.1 we saw that charge can reside on an object. It just sits still. Charge residing on an object is described as electrostatic because "static" means to stay in place. But charge can also move. When a battery is connected across a light bulb with wires, charge flows through the wires (Figure 1). This is called the **electric current**, from a Latin word meaning "to run". It is a little like running – different amounts of electric charge can run and electric current can run at different speeds. The actual electric current I in the wire is

electric current the rate of motion of electric charge carriers from one part of a conductor to another (symbol: I; SI unit: ampere; unit symbol: A)

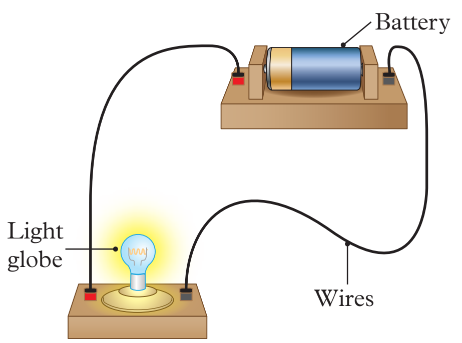


FIGURE 1 When a battery is connected to a light bulb, charge flows through the wires.

the total amount of charge q (measured in coulombs) passing any given point in the wire in a time period t.

$$I = \frac{q}{t}$$

The symbol for current is I, and the unit of electric current is the ampere, with the symbol A. One ampere of electric current is thus a flow of charge of 1 coulomb per second ($1\,\mathrm{C\,s^{-1}}$). The term "ampere" is unofficially shortened to "amp" or "amps". Sometimes, Q is used for the charge on an object to distinguish it from another object with charge q. Either can be used.

$$\begin{aligned} 1\,\mathrm{A} &= 1\,\mathrm{C\,s^{-1}} \\ &= 6.24 \times 10^{18} \text{ electrons per second passing a given point} \end{aligned}$$

One ampere of current is quite large. Household appliances use from a fraction of an ampere up to about 20 A. For instance, a light bulb uses about 0.25 A, a microwave oven 3 A, and a stove about 20 A. Inside electronic devices, currents of microamps (μA) or milliamps (mA) are more common. Electric current is measured with an ammeter.

Table 1 summarises the units and symbols related to electric current.

TABLE 1 Units and symbols related to electric current

Physical quantity	Quantity symbol	Unit	Unit symbol
Electric charge	q	coulomb	C
Current	I	ampere	A

Worked example 7.2A

Calculating the current of a moving charge

A charge of 30 C passes through a light bulb in 1 minute. **Calculate** the current in the bulb (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$I = \frac{q}{t}$ $q = 30$, $t = 1$ minute
Step 3: Substitute the known values into the formula. Find the unknown. In this case, remember to convert time to seconds.	$I = \frac{q}{t}$ (1 mark) $= \frac{30}{1 \times 60}$ $= 0.5$
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Current is measured in ampere (A), and you are required to express your answer to 2 s.f.	$I = 0.50\,\mathrm{A}$ (1 mark)

Your turn

In a time of 2.00 minutes, it was found that 120 C of charge had passed through a solution. **Calculate** the current in ampere (2 s.f.). (2 marks)

Worked example 7.2B

Calculating the charge moving through a conductor

A current of 2.0 A passes through a light bulb in a torch. **Calculate** how many

a coulombs of charge pass in 1.0 s (1 s.f.) (2 marks)

b electrons pass in 1.0 s. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate equation and use it to find an answer.
Step 2: For part **a**, identify the appropriate formula and gather any data that you require.	**a** $I = \frac{q}{t}$ (1 mark) $I = 2.0\,\text{A}$, $t = 1.0\,\text{s}$
Step 3: Rearrange the formula so that you can calculate the unknown value. In this case, we need to give q as the subject (unknown value).	$q = It$
Step 4: Substitute the known values into the formula. Find the unknown.	$q = 2.0 \times 1.0$ $= 2.0$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. In this case, your answer should be given in coulombs (C) and expressed to 1 s.f.	$q = 2\,\text{C}$ (1 mark)
Step 6: For part **b**, identify the appropriate formula and gather any data that you require.	**b** $n = \frac{q}{q_e}$ $q = 2.0$ (from answer to part **a**)
Step 7: Substitute the known values into the formula. Find the unknown.	$n = \frac{q}{q_e}$ (1 mark) $= \frac{2}{1.6 \times 10^{-19}}$ $= 1.25 \times 10^{19}$
Step 8: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. In this case, you are required to calculate number of electrons and to express your answer to 2 s.f.	$n = 1.3 \times 10^{19}$ electrons (1 mark)

Your turn

Calculate the number of electrons that pass through a transistor in 2.0 minutes if it has a current of 15 mA passing. (2 marks)

What makes an electrical circuit?

You probably have heard the word "circuit" used in reference to things like a cross-country circuit, or the Bathurst 1,000 Mount Panorama motor racing circuit. "Circuit" comes from the Latin "circumire", meaning "to go around" – hence the words circle, circumference and circus (horses and chariots go around the ring). Here we'll be talking about electrical charge going in a **circuit** from one battery terminal to the other.

circuit
a closed loop of conducting material through which electric charge can flow

What is conventional current?

Experiments were carried out with electricity and electrostatic charge long before the nature of electrons was discovered. In the 1730s, Benjamin Franklin used the term "positive charge" in his early experimental work on electric current. He assumed that the charges in motion in conductors were positive charges and that they flowed along conductors from the positive terminal to the negative terminal (a little like water naturally flowing downhill). This arrangement is called a "circuit".

conventional current
the direction in which positive charges flow; opposite to electron flow

Study tip

In physics, "electric current" means conventional current unless otherwise specified.

electron flow
the direction of electron motion in a conductor from negative to positive

It is still common in physics and electrical circuit analysis to refer to **conventional current** as the motion of positive charges from the positive terminal of a battery to the negative terminal. This is the convention used in this textbook and, although physically incorrect (as we now know it is the electrons in a wire that move) it is accepted as the international convention. This ensures clear communication of ideas and findings around the world. So, in physics, "electric current" means conventional current.

The term we use for electron movement is "**electron flow**" and it is the direction of electron motion in a conductor from negative to positive. One amp of (conventional) current in one direction is the same as one amp of electron flow in the opposite direction.

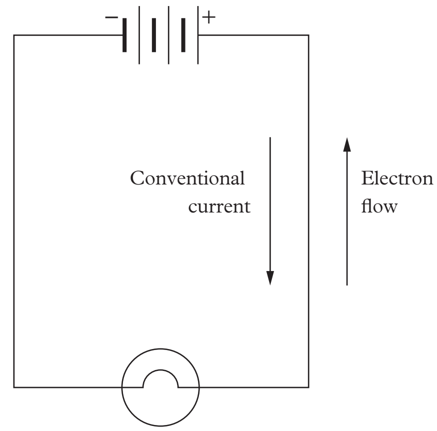


FIGURE 2 Conventional current is opposite to electron flow. We use the term "current" to mean conventional current.

Direct current

direct current
electrical current in which the flow of charge is in one direction only

When electric charge flows from the source of charge around a circuit in the one direction (as in Figure 3B), the type of current is called **direct current** (DC). Batteries provide DC. The current may vary but is always in the same direction.

When considering the flow of electric charge, a water model can be a useful analogy (Figure 3). The water pump is the equivalent of the electric battery. The water pipes are the equivalent of the electrical conductors, and the water itself is analogous to the electric charges in motion (the current). Note that as the water flows around the pipe circuit, it can provide energy to run a water wheel – just as charge flowing around an electrical circuit can provide energy to operate a light bulb. In the water pipes, water never gets used up – it just keeps getting recycled. The same thing occurs with electric charge. The electric charge doesn't get used up – it just gives up its energy but keeps flowing until the battery energy is reduced to zero as a result of energy being transferred to the light bulb.

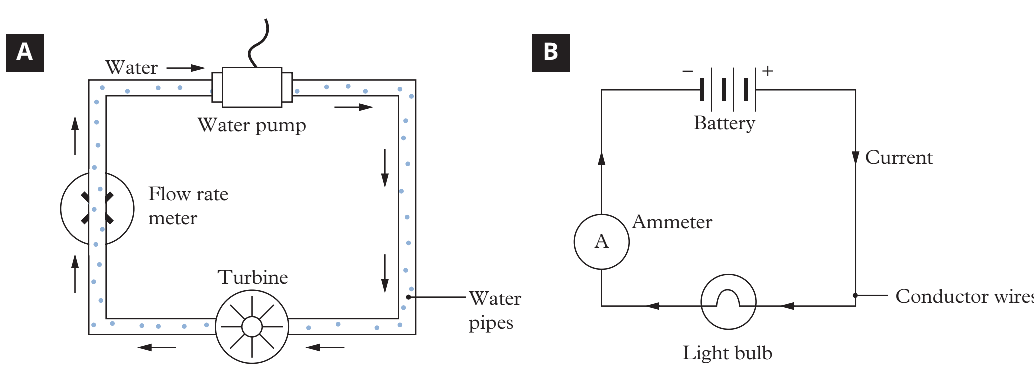


FIGURE 3 (A) A water model can be a useful analogy for (B) the flow of electric charge in a circuit.

Open circuits and electric currents

An electrical circuit must be a complete closed-loop path. The charges will flow from the battery through the conductors to the light bulb and deliver the energy given to them by the battery. This is called a **closed circuit** and the switch is turned "on". The opposite is an **open circuit**, which means the switch is turned "off". If the path is not complete, charge will not flow and the current stops.

If the battery terminals are connected directly together without the circuit containing a device to restrict the amount of charge flowing (such as a light bulb), then a short circuit occurs. This is a potentially dangerous situation as the very large current that may flow can cause heating of the conductors and subsequent fires. It is possible to cause sparking and welding (joining) of the metal conductors when very large batteries are short circuited.

closed circuit
a complete electrical circuit in which charge can flow; switch is "on"

open circuit
an incomplete electrical circuit in which no charge can flow; switch is "off"

Alternating current

In DC, the direction of the flow of charge, and thus the current, is constant over time. Figure 4A illustrates this *I–t* relationship graphically. However, if the electricity is produced by a generator that uses rotating coils of wire in a magnetic field, it will produce currents that vary in both magnitude and direction many times per second. This regular back and forth motion of the current in a conductor is called **alternating current** (AC) and is represented graphically in Figure 4B. Industrial and household electricity is distributed via this type of current. The overhead wires on the street outside your home have alternating current.

alternating current
electric current that periodically reverses direction and changes its magnitude continuously with time, in contrast to direct current which flows only in one direction

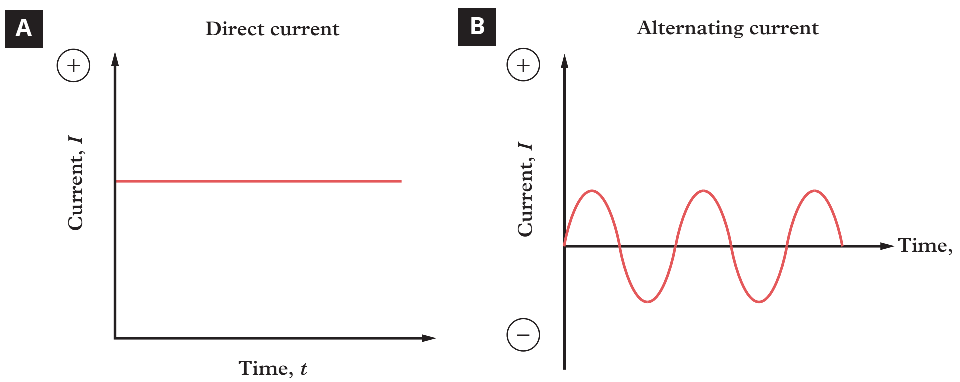


FIGURE 4 (A) In DC current, the direction of current is constant over time. The magnitude of the current may also be constant, as shown here, but can vary. (B) In AC current, both the magnitude and direction of the current are alternating over time.

How do you measure current?

When charge moves through a metallic conductor, an electric current is produced. In practice, very large numbers of electrons are moved. Power supplies in your high school laboratory can deliver up to 5 amperes (5 A), which is 5 coulombs per second ($5\,C\,s^{-1}$). By definition, if 1 coulomb of electrons passes any given point in a conductor (such as a wire) per second, then a current of 1 ampere (1 A) is passing. The current can be measured with an **ammeter** (Figure 5).

ammeter
a device for measuring the rate of flow of charge (current) in a circuit

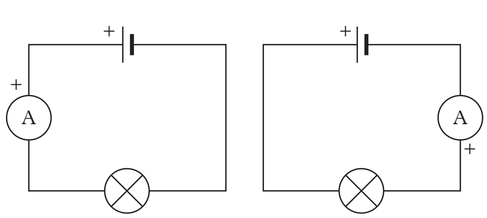


FIGURE 5 An ammeter is connected in series with the circuit device (a bulb in this case). It can be connected on either side of the device. The connecting leads must be connected the correct way; otherwise the pointer on an analogue meter will try to go backwards, and a digital meter will give a negative reading. The positive terminal of the ammeter must be connected to the positive side of the circuit.

FIGURE 6 An analogue ammeter uses a printed scale and a pointer. It is connected to the 500 mA scale and thus the reading is 100 ± 5 mA.

Ammeters

Ammeters measure the electric current (rate of flow of charge) past a given point, so an ammeter should be connected in **series** with the circuit device (such as a bulb or resistor). There are two types of ammeters available in laboratories: analogue and digital.

series
describes an electrical circuit in which components are connected along a single path, so the same current flows through all of the components

Analogue ammeters

Analogue meters have a printed scale and a needle or pointer to indicate the reading. In Figure 6, the analogue ammeter is reading 100 mA. If you said 1 A or 10 mA, you are using the wrong scale. The wire is connected at the bottom to the 500 mA terminal, so you read off the 500 mA scale. On this scale there are 10 divisions for each 100 mA, so the scale reading division is 10 mA. Because of this, the half-scale division is 5 mA, and so the scale reading uncertainty is ± 5 mA.

Figure 7 shows an analogue ammeter connected to the 50 mA scale (the top scale). In this case, the pointer is between 12 mA and 13 mA. The scale divisions are 1 mA apart, so the half-scale divisions are 0.5 mA. When an ammeter pointer is between readings, you should read to the nearest half-scale division, which appears to be 13.0 mA. Thus, our best estimate for the reading in Figure 7 is 13.0 ± 0.5 mA.

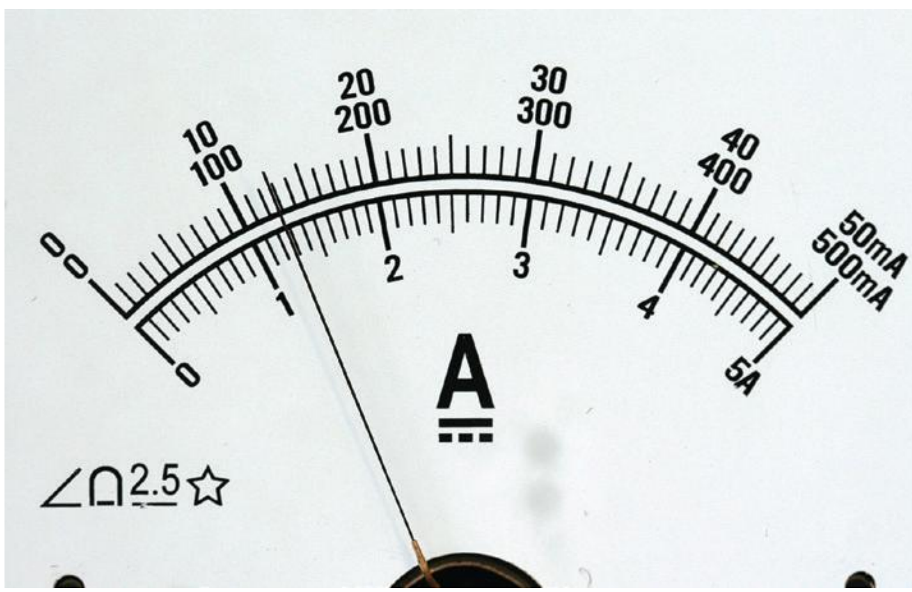


FIGURE 7 An ammeter connected to the 50 mA scale. The reading on this ammeter is 13.0 ± 0.5 mA.

Digital ammeters

A common digital meter used in schools is the digital multimeter (DMM). It can be used as an ammeter, voltmeter and ohmmeter (for resistance). The DMM in Figure 8 reads 2.59 mA. The rule for scale reading uncertainty (or "resolution") for a digital scale is ± the final decimal place. Thus, the reading on the meter would be stated as 2.59 ± 0.01 mA.

Most experiments in senior Physics are likely to have currents in the order of several amps. The DMM shown is measuring the current in a red light-emitting diode (LED), which is a highly efficient device for converting electricity into light, so the currents are small.

Some schools have digital ammeters and digital voltmeters as separate devices. Many schools use analogue meters as well, depending on the year level and whether it is a classroom practical or a student experiment.

FIGURE 8 A DMM is being used as an ammeter to measure the current through a red LED. The reading is 2.59 mA. The uncertainty is ± 0.01 mA.

How fast do electrons move?

To examine what is happening at an atomic level inside a wire conducting a current, we need to consider it in terms of electrons, as they are the mobile charges that actually move.

Let's consider a piece of copper wire. The two outermost electrons of copper atoms in the metallic lattice are constantly moving about in random directions. Chemists call it a "sea" of electrons. They have no net velocity in any particular direction. If a battery is connected across the ends of the wire, then the free electrons will move under the repulsion from the negative terminal of the battery and be attracted to the positive terminal (Figure 9).

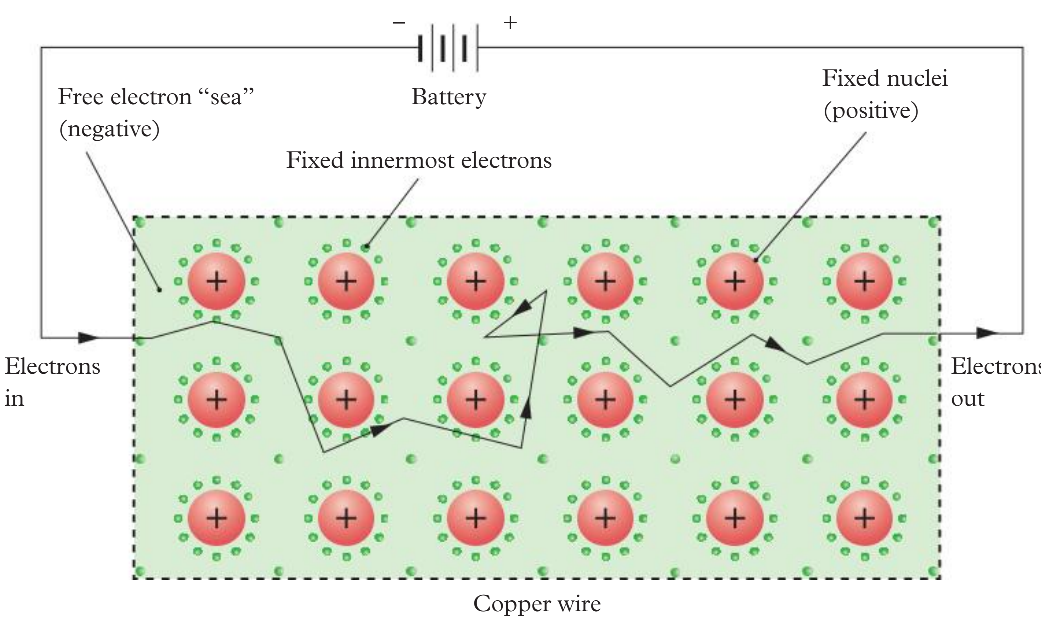


FIGURE 9 Electron flow in a copper wire connected across battery terminals

Because the metallic lattice contains large numbers of nuclei, the electrons in motion undergo collisions that slow their progress. This is called "resistance", and will be discussed in Module 8.

When you turn a light switch "on", the bulb lights up almost instantaneously. A wave of repulsions travels along the wire under the influence of the battery, and this happens at lightning speed. You can imagine an electron entering one end of the wire and, almost instantaneously, another electron being repelled from the opposite end of the wire. Although it is not instantaneous, it occurs at close to the speed of light ($3 \times 10^8\,\mathrm{m\,s^{-1}}$). The electrons, themselves, do not move as fast.

Check your learning 7.2

Check your learning 7.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** electric current in the context of a battery making a light bulb glow. (2 marks)

2 **Calculate** the electric current in the following cases.

a 20 C of charge passes through an ammeter in 5 s. (2 marks)

b 5 C of charge passes through an ammeter in 20 s. (2 marks)

c 200 C of charge passes through an ammeter in 3 minutes. (2 marks)

3 **Calculate** how many electrons are in a lightning bolt that moves 10.0 C of charge. (2 marks)

4 A torch runs for 1 hour and 6.75×10^{21} electrons flow through the filament.

a **Calculate** how many coulombs of charge this is. (1 mark)

b **Calculate** current in amperes for the movement of charge above. (2 marks)

5 **Describe** what is meant by conventional current. (1 mark)

Analytical processes

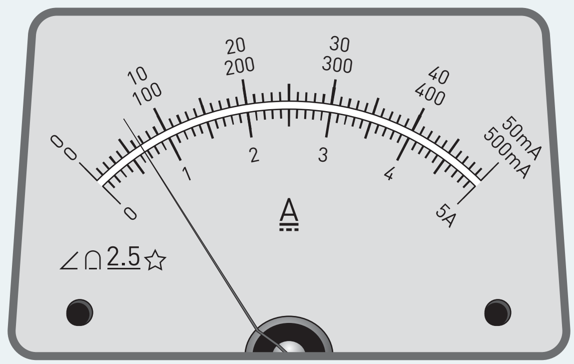
6 Consider the following charged and uncharged objects.

a **Calculate** how many electrons are needed to form a charge of –5.00 nC. (2 marks)

b **Determine** how many electrons must be removed from a neutral object to leave a net charge of +0.20 μC. (2 marks)

7 When sounding a car horn, the car battery moves 5×10^{20} electrons through the horn. **Determine** how many coulombs of charge were moved. (2 marks)

8 The ammeter shown is connected to the 500 mA scale.



a **Determine** the best estimate reading on the meter. Include the scale reading uncertainty (±) for this scale. (2 marks)

b **Deduce** the best estimate and uncertainty for the reading if the ammeter was connected to the 50 mA scale. (2 marks)

Lesson 7.3
Voltage and sources of potential energy

Learning intentions and success criteria

Key ideas

→ Electrical potential is the amount of work needed to move a unit of charge from one point to another.

→ Electrical potential energy is the energy stored in a charge and circuit system.

What are volts?

You are probably familiar with the term "volt". Your power supply at home is 230 volts, the battery in a car is 12 volts, or about 400 volts if it is an electric vehicle, and the cell in a torch is 1.5 volts. A **volt** is a unit of electrical potential or voltage, and **voltage** is a measure of electrical potential energy. So how did these power sources come about and what does the number of volts mean – is it energy or something else?

volt
a unit of electrical potential or voltage, equivalent to 1 joule per coulomb of charge

voltage
a measure of electrical potential energy per unit charge, measured in joules per coulomb; often referred to as electrical potential

The electrical age began around 250 years ago when it was discovered how to store electrical charge, and thus control it rather than just deal with its electrostatic effects. Italian scientists Luigi Galvani (1737–1798) and Count Alessandro Volta (1745–1827) experimented with electrical effects in animal tissues, showing that the nervous system is electrically operated. Volta was able to produce the first example of an electric battery, which he called a "pile", constructed from a series of pairs of zinc and copper electrodes separated by moist cloth layers. Today we call this apparatus a voltaic battery or just a battery.

In an electrical circuit, the battery provides potential energy to electrons, and devices such as bulbs and resistors transform that energy to other forms of energy, such as heat and light. Electrical energy is very important in our lives. The great explosion in technology in the twentieth century has been almost solely due to applications of electrical energy. Our information age would not be possible without electricity.

What are electrical potential and electrical potential energy?

The gravitational model is a good analogy to describe energy stored between charges. Consider a 1 kg block of wood on a bench. Earth exerts a gravitational force on the block. When you lift the block up against gravity, you need to do work on the block (with your muscles) and energy gets transferred to the block-and-Earth system. We say the system has acquired more gravitational potential energy (GPE). The block now has the ability to do work. If you let it go, it can do work. This is what Joule did in his experiment (Module 4) in which he let a falling block turn a paddlewheel and heat up some water. Rather than say the block–Earth system did work, we simplify this and say the block acquired more GPE and did work. It is not strictly correct, but the meaning is understood.

For a block of wood being lifted up, the increase in gravitational potential energy is equivalent to the work done, W, and is calculated using $W = mgh$. Similarly, with electricity, it requires work, W, to be done to pull a positive charge away from a negative charge. The work done is given by:

$$W = qEd$$

where E is a measure of the electric field strength in the wire (just as the acceleration due to gravity, g, is a measure of gravitational field strength) and d is distance (similar to height). Note that this is not a required formula but we note it here for comparison.

If we do 1 joule of work, W, on 1 coulomb of charge, q, we say that we have increased the **electrical potential**, W, of the charge by 1 volt. One joule per coulomb is known as a volt: 1 volt (V) = 1 J C^{-1}.

electrical potential
the amount of work needed to move a unit (1 C) of charge from one point to another, or the electrical potential energy per unit of charge (symbol: V; SI unit: volt; unit symbol: V)

We can also say we have increased the **electrical potential energy**, U, of the charge by 1 joule. That is, $\Delta U = 1$ J. The change in electrical potential energy is equal to the work done on the charge: $\Delta U = W$.

electrical potential energy
the energy stored in a charge and circuit system, or the capacity of the charge carriers to do work due to their position in an electrical circuit (symbol: U; SI unit: joule; unit symbol: J)

We can also apply this to an electrical circuit of cells and wires. As soon as a source of electrical potential (a battery) is connected to the wires in a circuit, an electric field is created along the surface of the wire from one end of the battery to the other. It is this electric field that interacts with the charge and pulls it through the wire. The charge goes from a region of high potential to a region of low potential as it does work and has a decrease in potential energy.

For instance, if 10 J of work was needed to shift a 2 C charge from A to B, we would say its electrical potential energy has changed by 10 J ($\Delta U = 10$ J), but that its electrical potential has changed by 5 joules per coulomb or 5 volts ($\Delta V = 5\,\text{J}\,\text{C}^{-1}$, or 5 V). This is a subtle but critical difference.

$$\text{Electrical potential} = \frac{\text{work}}{\text{charge}}$$

$$V = \frac{W}{q}$$

Electrical potential, V, is a scalar quantity and is measured in units of joules per coulomb, $\text{J}\,\text{C}^{-1}$, or volts, V.

Summary

In summary, electrical potential defines a region of space or position in a circuit irrespective of whether there is any charge there or not. It just says that if there was charge at that point, it would have this electrical potential value.

Electrical potential energy refers to the energy of the charge if it was actually there. In terms of an electrical circuit, when a charge of 1 C passes through a light bulb and does 1 J of work by giving off that amount of energy as light and heat, we say the electrical potential of the charge has dropped by 1 V across its journey through the bulb. The change in electrical potential is called the electrical potential difference.

Table 1 summarises the units and symbols related to electrical potential.

TABLE 1 Units and symbols related to electrical potential

Quantity	Quantity symbol	Unit	Unit symbol
Electrical potential	V	volt	V
Electrical potential energy	U	joule	J
Work	$W\ (= \Delta U)$	joule	J

Worked example 7.3A

Calculating electrical potential and work

An electric charge of 15 C is able to do 30 J of work as it passes through a light bulb. **Calculate** its electrical potential at the start (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula, substitute values and solve the equation to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$V = \frac{W}{q}$ (1 mark) $q = 15\,\text{C}$, $W = 30\,\text{J}$
Step 3: Substitute the known values into the formula. Find the unknown.	$V = \frac{30}{15}$ (1 mark) $= 2$
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Note that this is the initial electrical potential and will be at zero electrical potential at the end. We can say its potential difference is 2.0 V.	$V = 2.0\,\text{V}$ (1 mark)

Your turn

Calculate the work that can be done by 20 mC of charge at an electrical potential of 5.0 V (2 s.f.). (3 marks)

What is potential difference?

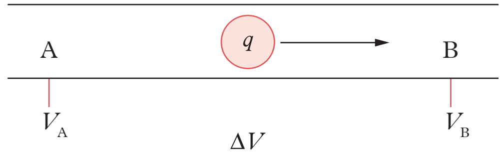


FIGURE 1 Moving a charge q from A to B

We have been talking about the electrical potential, V, of a charge, q, and how it has the capacity to do work, W. When it does work and its potential energy decreases, we say it experiences a potential difference. **Potential difference** is the difference in electrical potential between two points in a circuit. Imagine moving a charge Q from point A to point B (Figure 1) by doing work on it.

The potential difference is the difference between the two electrical potentials and has the symbol ΔV. It is common to assign one of the points as zero potential, so instead of ΔV we can just use V for potential difference.

Potential differences become useful in electrical circuit questions (to be discussed in the next module). If the two ends of an electrical conductor are held at different electrical potentials (such as by connecting them to the terminals of a battery), then a potential difference is set up across the conductor. The subsequent electric field within the conductor will allow free electrons to flow. We picture this as positive charge flowing in the opposite direction. This is the electric current within the conductor.

potential difference
the change in potential energy per unit charge between two defined points in a circuit ΔV; the unit of electrical potential difference is the volt, V; sometimes referred to as the voltage

Study tip

Despite its name, electromotive force is not a force. It is not expressed using newtons, but instead in volts.

What are the sources of electrical potential?

In Lesson 7.2 we said that a battery can supply direct current (DC). Let us take this idea further to see why this is possible. A simple cell consists of two dissimilar metals separated by a conducting solution. The familiar carbon–zinc dry cell (carbon = positive electrode, zinc case = negative electrode) produces a potential difference of about 1.5 V.

Chemical reactions in a copper–zinc cell (Figure 2) convert the chemical potential energy of the system to electrical energy and do work on the charge inside the battery to cause the copper electrode to become positively charged and the zinc electrode to become negatively charged with a potential difference of about 1.5 V.

When a simple cell is constructed, the metal plates are separated by a salt solution or a conducting paste. The electrical potential difference still exists between the positive and negative metal electrodes of the cell. This potential difference is measured in volts (V) and is usually referred to as the voltage of electrical potential of the cell (or battery) but is more correctly called the **electromotive force** (EMF) of the cell. This EMF term is not necessary here but will be used in Unit 3 on electromagnetism. The symbols used for cells are described in the next module.

electromotive force
a difference in potential that tends to give rise to an electric current (symbol: EMF; SI unit: volt; unit symbol: V)

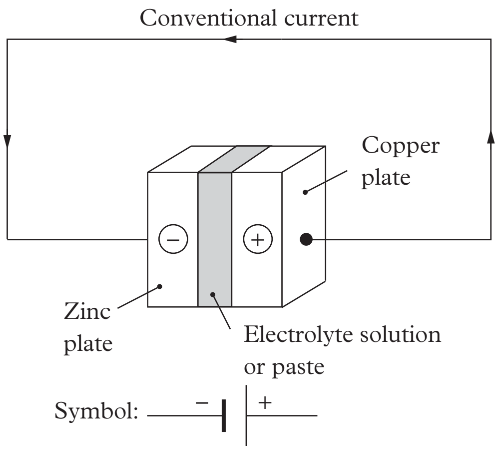


FIGURE 2 A copper–zinc cell

FIGURE 3 You can get electrical energy out of a circuit that uses a lemon with a piece of copper and a piece of zinc, but it is not practical to use it to power a phone or a dishwasher.

Study tip

A useful statement worth learning is "electrical potential difference of a cell is the result of work done to cause charge separation".

Internal energy and electrical potential energy in a cell

In Module 2 you saw that internal energy is the sum of microscopic forms of energy including the bonds between and within chemicals. A fully charged battery will have more internal energy than a flat battery. To separate the positive from negative charge as happens in a cell, work must be done on the charges. The energy required for the separation of electric charge produces an electrical potential difference.

Combination of cells

If several simple cells are joined together, the combined arrangement is called a battery. A normal 12 V car battery usually has six individual cells, each of 2 V, connected together in series. Notice that the battery symbol (Figure 4A) actually consists of four separate cells connected together so that positive electrodes are directly connected to negative electrodes. This type of connection is called a **series connection** of the cells, and the total voltage is the sum of the voltages of each cell.

series connection one in which the components are connected along a single path

Series connection:
total voltage = sum of voltages of individual cells

Individual cells may also be connected so that all positive electrodes are connected together and all negative electrodes are connected together. This is called a **parallel connection**, and the total voltage is then the same as that of each individual cell. In a parallel connection, a battery cannot supply more energy to each charge. However, it can supply a greater quantity of charge per unit time or a greater current in any external circuit (Figure 4B).

parallel connection one in which the components are connected along multiple paths

Parallel connection:
total voltage = individual cell voltage

Note that only cells with equal values of voltage should be connected in parallel.

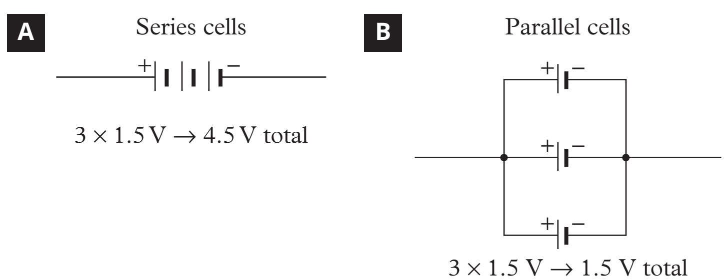


FIGURE 4 Cells in a (A) series connection provide greater voltage than cells in a (B) parallel connection.

Study tip

If you were asked to compare the voltages of two cells, what would you say? "Compare" means to state the similarities and differences and their significance. You would need to state that a similarity was that one end of each cell was positive and the other end negative; the difference being the voltage value of each cell with reference to the negative end.

What happens when electrical potential in a circuit changes?

The battery in a circuit is the energy pump that raises the charge to a higher electrical potential at the positive terminal. Positive conventional current will flow from the positive terminal of the battery, through the external circuit conductors, and back to the negative battery terminal. Along this pathway, the charge loses electrical potential as it does work in various circuit elements such as resistors, bulbs and motors.

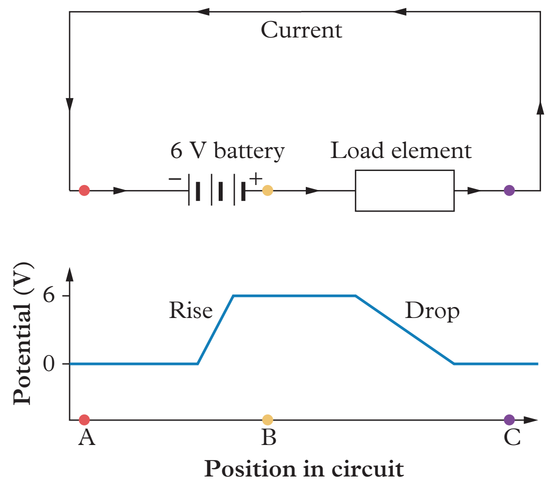


FIGURE 5 The battery provides the electric current for the circuit; the current will flow from the positive terminal, through the circuit and back to the negative terminal. During this process, some potential energy will be converted to other forms of energy.

Study tip

You may be asked to "distinguish" between series and parallel circuits. This means you should be able to recognise them as different and note points of difference between them. For batteries, the main difference is the way they are connected: **series** means they are joined positive to negative, whereas **parallel** means the positive terminals are connected together, and the negative terminals are connected together.

In the circuit, potential energy of the charge is converted to other forms of energy such as thermal, kinetic or light energy. In this process of energy conversion, the charge is not destroyed or used up – its electrical potential energy is reduced back to zero as it reaches the negative battery terminal. The battery will restore the electrical potential energy of the charges back to a high value.

This is similar to lifting a ball in the air. As you lift the ball, you increase its potential energy (like a battery). When the ball falls, its potential energy decreases. The ball still exists (like the charge does), but it has reduced potential energy. Strictly speaking, it is the ball–Earth system that stores the energy, not just the ball. Likewise, electrical potential energy is stored in the system of positive and negative charges, not just the one charge flowing in the circuit. To make it simpler, we just say Earth has zero joules of gravitational potential and the negative terminal of an electric cell has zero volts of electrical potential.

How do you measure voltage?

Voltmeters

A **voltmeter** is used to measure the voltage difference in a circuit. Reading a voltmeter is similar to reading an ammeter. However, a voltmeter measures the potential difference **between** two points in a circuit, so it must be connected "across" (one lead either side of) a circuit device such as a bulb. A voltmeter is connected in parallel with a circuit device. The symbol for a voltmeter is a circle with a "V" inside.

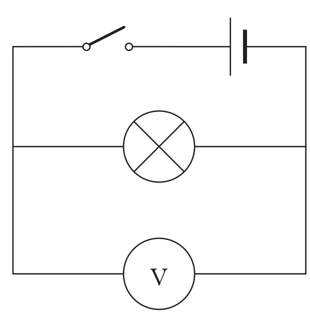


FIGURE 6 The voltmeter (circle with a "V") is connected in parallel with a circuit device such as a bulb (circle with the cross). The voltmeter is said to be connected "across" the device. This diagram also includes an open switch, and a cell. Symbols used here are described in detail in the next module.

voltmeter
an instrument used for measuring electrical potential difference between two points in an electrical circuit

Analogue voltmeters

The voltmeter in Figure 7 is connected to the 30 V scale. The scale division is 1 V, so the half-scale division is 0.5 V. As for an ammeter, it is usual to read to the nearest half-scale division. Close inspection suggests the needle is closer to 17.0 V than 17.5 V, so our "best estimate" is 17.0 ± 0.5 V.

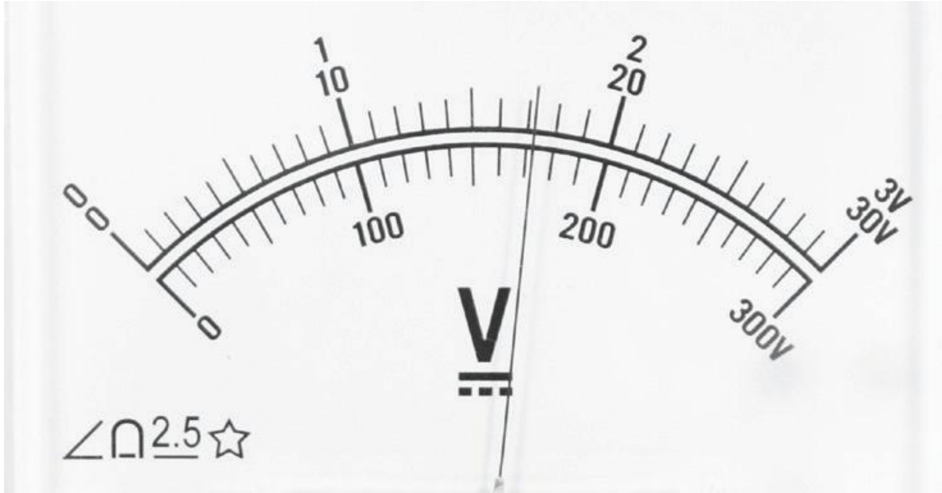


FIGURE 7 The voltmeter was set to the 30 V scale, and the reading is 17.0 ± 0.5 V.

Digital voltmeters

As with digital ammeters, digital voltmeters have the same rule for their uncertainty – the uncertainty is the last decimal place to the right, which is the least significant decimal place. The digital voltmeter connected to a lemon in Figure 8 has the knob set to the 2 V scale, so any reading is in volts (not mV). Thus, the reading is 0.888 V. The uncertainty is 0.001 V, so the "best estimate" is 0.888 ± 0.001 V.

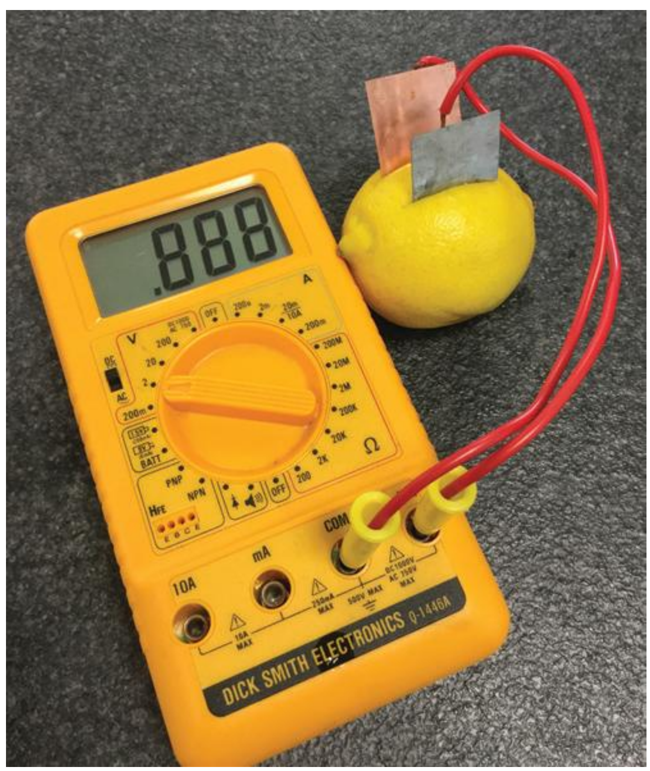


FIGURE 8 A digital multimeter set to read voltage. It's on the 2 V setting so it can read up to 2 V. This reading would be stated as 0.888 ± 0.001 V.

Check your learning 7.3

Check your learning 7.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** electrical potential energy in terms of charge moving though a light bulb in a circuit. (2 marks)

2 **Describe** electrical potential difference. (2 marks)

3 **Calculate** the electrical potential (voltage) if 60 J of energy is available for every 15 C of charge. (2 marks)

4 When 15 C of charge is moved between two points in an electric field, 20 J of work is done by the charge.

a **Calculate** the potential difference between the two points. (2 marks)

b **Explain** whether the charge moves from high to low electrical potential, or from low to high electrical potential. (3 marks)

Analytical processes

5 A charge of 2.00 C passes through the solar cells of a pocket calculator in 2.00 h. The voltage output of the calculator is 4.5 V. **Calculate** the work done on the charge. (2 marks)

Knowledge utilisation

6 You have three cells, each with a voltage of 2 V.

a **Determine** how you would arrange them to produce

i 6 V (1 mark)

ii 2 V. (1 mark)

b **Infer** the advantage of using three 2 V cells in parallel rather than just one 2 V cell by itself considering they give the same voltage. (1 mark)

7 The chemicals in an electric cell do 1.5 J of work on the charge entering the negative terminal of a cell. **Determine** whether the electrical potential of the charge increases or decreases when this happens. (3 marks)

Lesson 7.4
Power

Key ideas

→ Power is a measure of the rate at which work is done or the rate at which energy is transferred or transformed.

Learning intentions and success criteria

What is power?

You often hear about one car being more powerful than another, or of a more powerful runner in a race. But what do we mean by **power**? Let's explain with an example. A student walks up a flight of stairs one day but the next they run up. In which case do they use more energy, and in which case do they have a bigger power output? The answer is that they use the same energy in each case because the change in gravitational potential energy ($E_p = mgh$) is the same. However, when the student runs up the stairs, they use the energy in a shorter amount of time, so we say they had a higher power output.

power
the rate at which work is done or the rate at which energy is transferred or transformed

What is the power formula?

Power can be expressed by the formula:

$$\text{Power (in watts, W)} = \frac{\text{work (in joules, J)}}{\text{time (in seconds, s)}}$$

$$P = \frac{W}{t}$$

Units and symbols related to power often confuse students, as the letter "W" represents two things, as shown in Table 1. The symbol W is used for the quantity work (in italics, W), and also for the unit watt. For example:

$$\text{Work} = 1{,}000 \text{ joules } (W = 1{,}000\,\text{J}); \text{ power} = 50 \text{ watts } (P = 50\,\text{W})$$

TABLE 1 Units and symbols related to power

Quantity	Quantity symbol	Unit	Unit symbol
Work (energy)	W	joule	J
Power	P	watt	W
Time	t	second	s

Common multiples of the watt in electrical circuits are milliwatts (mW) and kilowatts (kW). For power stations, the multiples are megawatts (MW) for a million (10^6) watts, and gigawatts (GW) for a billion (10^9) watts. Power consumption in electrical circuits will be discussed in Module 8.

Worked example 7.4A

Calculating power output

An electric heater has a power rating of 2.0 kW.

a **Express** the power of the heater in watts, using scientific notation. (1 mark)

b **Calculate** how much energy the heater will use in 10.0 minutes. Express your answer in megajoules. (2 marks)

Think	Do
Step 1: For part **a**, look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Express" means to convey, show or communicate something. We must "communicate" the power of the heater in watts, using scientific notation.
Step 2: Gather any data that you require.	$P = 2.0\,\text{kW}$
Step 3: Convert 2.0 kW to watts. Kilo, "k", means 10^3.	**a** $2.0 \times 10^3 = 2{,}000\,\text{W}$
Step 4: Finalise your answer and make sure you have included the correct units, used scientific notation and expressed your answer to the correct number of significant figures. In this case, you are required to use watts (W) and use scientific notation to express your answer to 2 s.f.	$P = 2.0 \times 10^3\,\text{W}$ (1 mark)
Step 5: For part **b**, look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must apply the appropriate formula to find an answer.
Step 6: Select the appropriate formula and gather any data that you require. Recognise that time t will need to be converted to seconds in the calculation.	**b** $P = \frac{W}{t}$ $P = 2.0 \times 10^3\,\text{W}$; $t = 10.0$ minutes (1 mark)

Think	Do
Step 7: Rearrange the formula so that you can calculate the unknown value. In this case, we need to calculate work (energy) so we need to make W the subject of the equation. Convert minutes to seconds by multiplying by 60.	$W = Pt$
Step 8: Substitute the known values into the formula. Find the unknown.	$W = 2{,}000 \times (10.0 \times 60)$ $= 1{,}200{,}000\,\text{J}$
Step 9: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. In this case, the question requires a response in megajoules expressed to 2 s.f.	$1{,}200{,}000\,\text{J} = 1.2 \times 10^6\,\text{J}$ $= 1.2\,\text{MJ}$ (1 mark)

Your turn

Calculate the energy output of a generator that delivers 1.5 kW of electrical power for 5.0 minutes. (2 marks)

Additional power formulas

There are many variables used in describing electrical circuits. For instance: work, energy, power, charge, voltage, current and time. They are all interrelated by formulas we have described so far and which are listed in the QCAA Formula and data book. For calculating power (P), these variables can be brought together into two new combinations depending on what quantities are given.

Power formula 1: This is the basic formula:

$$P = \frac{W}{t}$$

Power formula 2: We can expand the basic formula for power (above) by replacing W with $V \times q$, as outlined in Lesson 7.3:

$$P = \frac{V \times q}{t}$$

We also know that $I = \frac{q}{t}$, so our formula for power becomes:

$$P = VI$$

Power formula 3: In Lesson 7.5 you will see that a rearrangement of Ohm's law gives $V = \frac{I}{R}$, so we can substitute this for V in the formula above to get:

$$P = I^2 R \text{ or } P = \frac{V^2}{R}$$

Worked example 7.4B

Calculating current from power output

Calculate the current in a toaster that has a power rating of 1200 W and is connected to the 240 V home supply (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$P = VI$ $P = 1200\,\text{W}$, $V = 240\,\text{V}$
Step 3: Rearrange the formula so that you can calculate the required value. In this case we are required to calculate current, so we need to make I the subject of the formula.	$I = \frac{P}{V}$ (1 mark)
Step 4: Substitute known values into the formula. Find the unknown.	$I = \frac{1200}{240}$ $= 5$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The unit for current is ampere (A) and the question requires a response correct to 2 s.f.	$I = 5.0\,\text{A}$ (1 mark)

Your turn

Calculate the power consumption of a microwave oven that draws a current of 4.5 A from a 240 V supply. (3 marks)

Worked example 7.4C

Calculate energy consumption using power data

Calculate how many joules of electrical energy are transformed in 60 seconds by a 6.0 V, 0.50 A lamp (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must apply the appropriate formula to find an answer.
Step 2: Identify the appropriate formula(s) and gather any data that you require.	$P = \frac{W}{t}$ $P = VI$ $t = 60\,\text{s}$, $V = 6.0\,\text{V}$, $I = 0.5\,\text{A}$
Step 3: Rearrange the formulas so that you can calculate the unknown value. In this case, you need to calculate power consumption (work or energy), so rearrange and combine the equations to make W the subject.	$W = P \times t = VI \times t$ (1 mark)
Step 4: Substitute the known values into the formula. Find the unknown.	$W = VIt$ $= 6.0 \times 0.5 \times 60$ (1 mark) $= 180$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The unit for work (energy) is joules and the question requires a response expressed to 2 s.f.	$W = 180\,\text{J}$ (1 mark)

Your turn

An electric kettle heater draws a current of 8.5 A from a 240 V supply. It is used for 2.5 minutes to boil some water.

a **Calculate** the power consumption (2 s.f.). (2 marks)

b **Calculate** the electrical energy consumed in joules (2 s.f.). (3 marks)

Check your learning 7.4

Check your learning 7.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** power in the context of an electric room heater. (1 mark)

2 **Calculate** the power consumption of a lamp labelled as "12 V, 2 A". (2 marks)

3 **Calculate** how many watts of power are used by a torch that has 6.00×10^2 C pass through it in a half-hour if its voltage is 4.5 V. (2 marks)

4 **Calculate** how much energy is produced by a lightning bolt having a 20 kA current, a voltage of 125 MV and a duration of 2.00 ms. (2 marks)

Analytical processes

5 A 10 W night light is on from 6 p.m. to 6 a.m. **Determine** how much electrical energy it uses. (2 marks)

6 **Deduce** how much electrical energy is needed to make a slice of toast with a 1,200 W toaster if the cooking time is 1.5 minutes. (2 marks)

7 **Deduce** the power consumption in kilowatts for Queensland's old train network that ran at 1,500 V DC. Typically, under full acceleration, a train would draw 250 A. (2 marks)

8 In an internal combustion car engine, the starter motor draws a huge current as it must crank the engine to get it started. It takes 5 seconds to start the engine. Typically, a starter motor draws an initial current of 150 A from a 12 V DC battery. **Determine** (2 s.f.) the

a power consumption (1 mark)

b amount of energy used in the time it takes to start the engine (1 mark)

c amount of charge (in coulombs) passing through the wire in the 5 s (1 mark)

d number of electrons leaving the battery in the 5 s. (1 mark)

9 It takes 168 kJ to heat 500 mL of water (2 cups) from 20°C to 100°C. **Determine** how long it would take an electric kettle to do this if it has a power output of 2000 W (2 s.f.). (2 marks)

10 An electric car under full acceleration draws 1500 A for 3.0 s. **Calculate** the power the battery is delivering (2 s.f.). (2 marks)

Lesson 7.5
Resistance

Key ideas

→ Resistance is the opposition to the flow of electric current through a conductor and is measured in units called ohms.

→ Resistance is dependent on length, area and material.

Learning intentions and success criteria

What is resistance?

We can divide matter into two categories: conductors and insulators. As you have learnt in Lesson 7.1, conductors have low resistance to the flow of charge, and insulators have extremely high resistance. But some metals are better conductors than others, and you can blend metals to change their resistance. In this lesson we will investigate "resistance". An analogy for resistance is water coming out of a hose – putting some steel wool up the hose would reduce the flow of water. The steel wool would increase the resistance to the flow of water inside the hose and the water would move more slowly through the entire length of the hose.

When a battery is connected across the ends of a metal wire, it applies a potential difference, V, that creates an electric field from one end to the other. The electric field in turn exerts a force on the electrons in the wire, causing an electric current. Although the electrons are accelerated by the applied electric field due to their small mass, they very quickly collide with the lattice of positive metal ions in the conductor and lose energy, but are then accelerated again by the field. The effect of the collisions within the lattice is to reduce the current. Every time an electron collides with one of the metal ions in the lattice, it loses energy, which is transferred to the lattice as heat and vibrational energy – as internal energy. This means the temperature of the conductor increases.

electrical resistance opposition to the flow of current in a circuit or component measured as the ratio of the voltage applied to the current that flows through it

This opposition to the flow of charge that any conductor produces is called its **electrical resistance**. The larger the resistance, the smaller the current as a result of any given applied voltage. Resistance is calculated using the following formula:

$$R = \frac{V}{I}$$

Resistance is measured in the unit ohm, named after German physicist Georg Simon Ohm (1787–1854). Its symbol is the Greek letter omega (Ω). For example, the resistance of a heating element in a toaster is about 50 Ω.

What affects resistance?

Three factors determine the resistance of a conductor: length, area and material. The first two are related to shape.

Length

The longer the length (L) of a conductor, the greater the number of collisions occurring and therefore the greater the resistance. Mathematically, resistance is found to be directly proportional to the length ($R \propto L$).

Cross-sectional area

The smaller the cross-sectional area (A) of a conductor, the less space the electrons have for movement and hence the greater the resistance. Mathematically, the resistance is inversely proportional to the cross-sectional area $\left(R \propto \frac{1}{A}\right)$.

Table 1 shows classroom results for the resistance (R) of some nichrome wire of different length (L) and diameter (d). (Nichrome is a metal alloy often used to control resistance in a circuit). Standard wire gauge (SWG) is related to the wire's diameter – bigger diameter means smaller gauge. Figure 1 shows graphs of the data in Table 1.

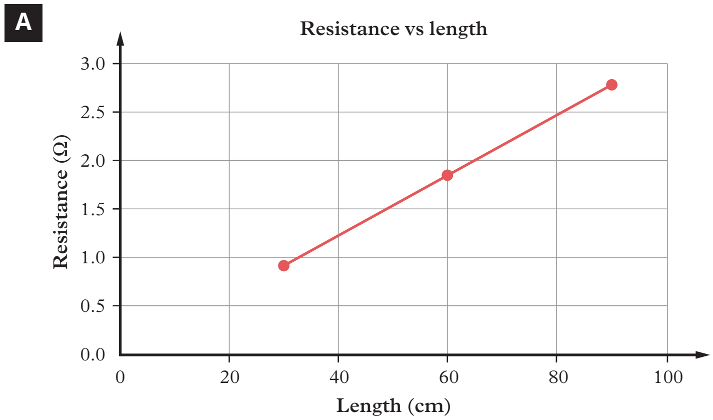
TABLE 1 Classroom resistance results for different (a) lengths and (b) area

a

L (cm)	R (Ω)
30	0.90
60	1.9
90	2.8

b

SWG	d (mm)	A (× 10^{-7} m^2)	$\frac{1}{A}$ (× 10^6 m^{-2})	R (Ω)
26	0.43	1.5	6.9	8.3
24	0.56	2.5	4.1	5.0
22	0.71	4.0	2.5	3.1



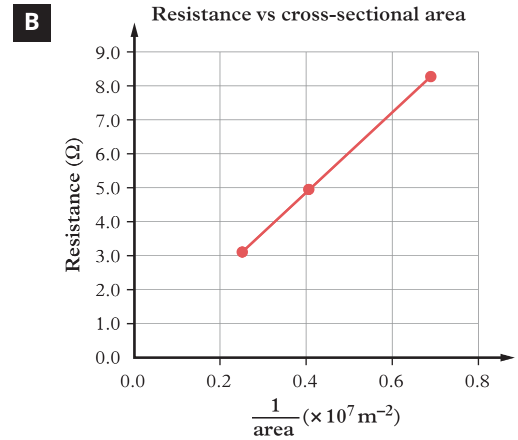


FIGURE 1 (A) Length and resistance vary in direct proportion. (B) When the resistance of three different gauges (thicknesses) of nichrome wire (1.0 m long) is plotted against the reciprocal of their cross-sectional area, a linear graph is obtained. This confirms that $R \propto \frac{1}{A}$.

Material

The third factor affecting resistance is material. Different types of metals will have varying lattice types. For example, nichrome wire heats up more than copper wire. It is harder for the current to pass through the nichrome because it is an alloy of two metals: nickel and chromium. These metals are slightly different from each other. As a result, instead of the electrons flowing smoothly through the material, the electrons frequently bounce off the unevenness that the mixed-up nickel and chromium atoms make.

If the atomic lattice is irregularly or tightly packed, more collisions are likely, and more energy is lost by the charge – thus, the greater the resistance.

For non-metals, the resistance depends on how strongly the electrons are held in bonds. In plastic and ceramics, the electrons are held very tightly in the bonds so none are free to move throughout the material. This means there will be no current despite being connected to a battery, so we say resistance is high. In graphite – a material made from carbon – there are some weakly held electrons so it can act as a conductor, although not a good one.

Summary

Resistance is dependent on length, area and material. Resistance will be **greater** if:

- length (L) is increased
- cross-sectional area (A) is decreased
- lattice is irregular or tightly packed, or electrons are tightly held in bonds.

Worked example 7.5A

Calculating changes to resistance

A length of tungsten light bulb filament wire has a resistance of 0.35 Ω. **Calculate** the resistance if

a the length is doubled (keeping cross-sectional area the same) (2 marks)

b a similar wire with half the cross-sectional area was used (keeping length the same). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.

Think	Do
Step 2: For part **a**, identify the appropriate formula and gather any data that you require. Let the length of the original wire be L, and the length of the wire when doubled be L_1.	**a** $R \propto L$ $L_1 = 2L$ (1 mark) $R = 0.35\,\Omega$
Step 3: Substitute the known values into the formula. Find the unknown. Recall the effect of length (L) on resistance (R). Doubling L will double R.	$L_1 = 2L$ $R_1 = 2 \times 0.35$ $R_1 = 0.70$
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance is expressed in ohm (Ω).	$R_1 = 0.70\,\Omega$ (1 mark)
Step 5: For part **b**, select the appropriate relationship for area. Let the area of the original wire be A, and the area of the wire when halved be A_1.	**b** $R \propto \frac{1}{A}$ $A_1 = \frac{1}{2}A$ $R_1 \propto \frac{1}{\frac{1}{2}A} \propto 2\frac{1}{A}$ $R_1 = 2R$
Step 6: Determine the effect of area (A) on resistance (R). Halving A will double R.	$R_1 = 2R$ (1 mark) $= 2 \times 0.35 = 0.70$
Step 7: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance is expressed in ohm (Ω). You must express your answer to 2 s.f.	$R = 0.70\,\Omega$ (1 mark)

Your turn

A piece of nichrome wire has a resistance of $24.0\,\Omega$. **Calculate** the resistance of a similar piece of wire that is

a a quarter of the length (3 s.f.) (2 marks)

b three times the cross-sectional area (3 s.f.). (2 marks)

Sometimes you may want to make simple changes to both the length and area at the same time. The equation we already have is:

$$R \propto \frac{1}{A} \text{ and } R \propto L$$

We can put these together and get $R \propto \frac{L}{A}$.

How can we change area and length together?

We don't always want to make simple multiples of the area and length of a piece of resistance wire. For example, we may want to make a wire coil of a certain resistance but don't have the exact length and diameter of wire we need. In that case we can apply our formula to make adjustments. The equation we already have is:

$$R \propto \frac{L}{A} \text{ or } R = \text{constant} \times \frac{L}{A}$$

This can be rearranged to give: constant $= \frac{RA}{L}$

For two wires of the same material at the same temperature we can now say:

$$\text{Constant} = \frac{RA}{L} = \frac{R_1A_1}{L_1}$$

where R, A and L are for the first wire, and R_1, A_1 and L_1 are for the second wire.

Worked example 7.5B

Calculating changes to resistance

A 25.0 cm length of nichrome wire of diameter 0.315 mm has a resistance of 3.44 Ω. **Calculate** the resistance for a 10.0 cm length of the same type of wire but with a diameter of 0.710 mm (3 s.f.). The temperature remains constant. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require. This is a question about the effect of change of size on the resistance of a wire.	Constant $= \frac{RA}{L} = \frac{R_1A_1}{L_1}$ (1 mark) $R = 3.44\,\Omega$, $L = 25.0\,\text{cm}$, $d = 0.315\,\text{mm}$, $L_1 = 10.0\,\text{cm}$, $d_2 = 0.710\,\text{mm}$
Step 3: Rearrange the formula so that you can calculate the unknown value. Here, we need to make R_1 the subject.	$\frac{RA}{L} = \frac{R_1A_1}{L_1}$ $R_1 = \frac{RA_1L}{L_1A}$
Step 4: Substitute the known values into the formula. Find the unknown.	$R_1 = \frac{RAL_1}{LA_1}$ $= \frac{3.44 \times \pi\left(\frac{0.315}{2}\right)^2 \times 10.0}{25.0 \times \pi\left(\frac{0.710}{2}\right)^2}$ $= \frac{3.44 \times (0.315)^2 \times 10.0}{25.0 \times (0.710)^2}$ $= 0.271$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance is expressed in ohms (Ω) and you are requested to express your answer to 3 s.f.	$R_1 = 0.271\,\Omega$ (1 mark)

Your turn

A 2.45 m length of nichrome wire of 0.25 mm diameter has a resistance of 50.0 Ω at room temperature. **Calculate** the length of similar wire but of 0.445 mm diameter required to make a coil of the same resistance at the same temperature (3 s.f.). (2 marks)

Skill drill

Factors affecting resistance

Science inquiry skills: Processing and analysing data (Lesson 1.7)

An experiment was conducted to address the following research question:

"What is the relationship between resistance and cross-sectional area of nichrome wire?"

Students measured the resistance of four 1.00 m lengths of nichrome wire of different diameters using a digital multimeter (DMM) set on the resistance scale (Figure 2).

FIGURE 2 DMM measuring resistance of a 1 m length of nichrome wire

The experimental data was collected and processed, and is presented in Table 2.

TABLE 2 Results from the resistance experiment

Trial	Diameter ($\times 10^{-3}$ m)	Area ($\times 10^{-8}$ m^2)	Resistance, R (Ω)				
			Test 1	Test 2	Test 3	Mean	$\delta x \pm$ (Ω)
1	0.113	1.00	105.0	100.1	95.0	100.0	5.0
2	0.160	2.00	47.8	49.9	52.5	50.0	2.4
3	0.226	4.00	26.3	25.1		25.0	1.3
4	0.276	6.00	17.5	16.8	15.8	16.7	0.8

Practise your skills

1 **Calculate** the missing value for resistance in Trial 3. (1 mark)

2 **Identify** the relationship between the cross-sectional area, A, and the resistance, R, of the wire. **Use** evidence from Table 2 to support your answer. You are not required to plot a graph. (2 marks)

3 **Predict** the resistance of the wire when the cross-sectional area is 8×10^{-8} m^2. Show your working. (2 marks)

How do we use resistors?

resistor
a device that reduces the flow of charge (current) in a circuit

Resistors are simple devices used to control the flow of electric current as well as to divide up a voltage into several smaller values. For example, your computer may have an input voltage of 12 V but some components may need just 0.6 V, so a resistor is used to reduce the voltage for that part of the circuit.

Resistors are generally of two types: fixed and variable. They differ considerably in physical size due to the total electrical power they are required to handle. We will only be dealing with fixed resistors – those that have a fixed resistance.

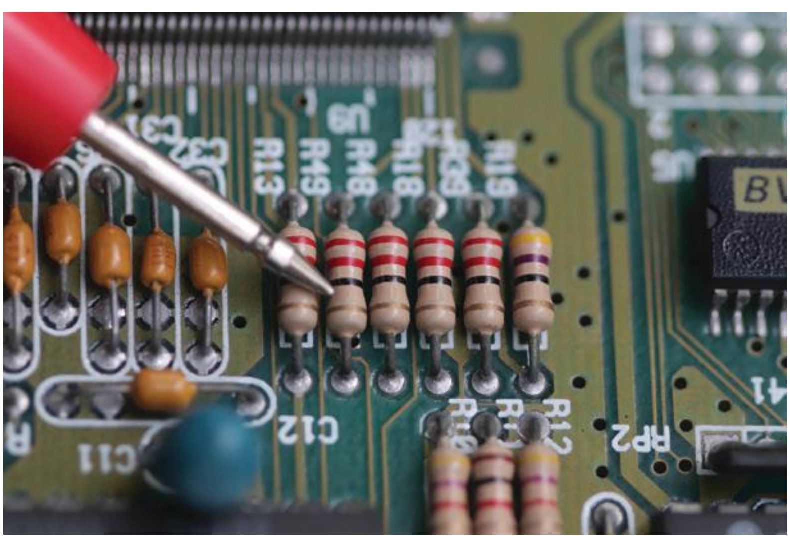


FIGURE 3 A probe points to resistors on a circuit board. The bands of colours indicate the resistance. In this case they are red, red, black, gold, which represent 22 Ω ± 5%.

Fixed resistors

Resistors are usually made of some form of carbon mixture. The simplest type of resistor is the carbon composition resistor, which is made of finely divided graphite carbon mixed with a powdered insulating medium, such as crushed clay, in a defined proportion. For example, if the voltage on one part of a circuit board in a computer needs to be dropped to, say, 0.7 V, then a resistor of perhaps 330 Ω is used. It all depends on the current, of course, so electrical engineers design circuits with all these complexities in mind. Figure 3 shows fixed resistors on a circuit board.

The mathematical relationship between voltage, current and resistance will be discussed in the next lesson.

Check your learning 7.5

Check your learning 7.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** resistance in the context of a short length of nichrome wire. (2 marks)

2 **Explain** how length, cross-sectional area and material can affect resistance. (3 marks)

3 **Calculate** the cross-sectional area of a 50 cm length of nichrome wire of diameter 0.43 mm. Give your answer in square metres (m^2). (2 marks)

4 **Calculate** the resistance of a 1.50 m length of nichrome wire of diameter 0.015 mm if a 3.0 m length of the same diameter and temperature has a resistance of 12.0 Ω. (4 marks)

5 Students find a 30 cm length of nichrome wire that has a resistance of 8.5 Ω. **Calculate** the resistance of a similar wire at the same temperature if its cross-sectional area was twice as big and its length was half. (4 marks)

6 Students want to use a piece of nichrome wire to make a 10.0 Ω heating element for an experiment. They have wire of diameter 0.376 mm and find that 50.0 cm is required to achieve the desired resistance. **Calculate** the length they should use if they have only 0.520 mm diameter wire of the same type available. Assume the temperature will be the same. (4 marks)

Knowledge utilisation

7 Students have a piece of wire of length 2.0 m and a diameter of 0.58 mm, with resistance of 11.3 Ω at 20°C.

a **Calculate** the length of wire needed to make a coil of resistance 10.0 Ω at the same temperature if they have to use wire of 0.25 mm diameter. (6 marks)

b **Calculate** how much time it would take to heat a cup of water (250 mL) from 20°C to boiling point if this 10.0 Ω wire (as used in part **a**) was connected to a 12.0 V laboratory power supply. (4 marks)

c **Assess** the effect on their experiment if students noticed that some of the loops in the coil were touching each other. (2 marks)

8 You have three 1.0 m lengths of nichrome wire of diameters 0.1 mm, 0.2 mm, and 0.3 mm. The 0.1 mm wire has a resistance of 20.0 Ω.

a **Predict** the shape of a graph of resistance (vertical axis) vs diameter (horizontal axis) for these three pieces of wire. (1 mark)

b **Explain** how you would linearise this relationship. (2 marks)

Lesson 7.6
Ohm's law

Key ideas

→ Ohm's law states the relationship between voltage, current and resistance.

→ Problems involving voltage, current and resistance can be solved using Ohm's law.

→ Ohmic and non-ohmic resistors have different voltage/current characteristics.

→ The resistance across an ohmic resistor can be interpreted using experimental data.

Learning intentions and success criteria

In 1825 and 1826, Ohm set up simple electrical circuits containing a length of resistance wire such as nichrome wire, as shown in Figure 1. He varied the voltage and noted the current through an ammeter (although he used slightly different terms at the time).

Ohm found that the current through the resistance wire was proportional to the voltage across it, provided he kept everything else the same (length, area and temperature).

$$I \propto V$$

After Ohm published his work, other scientists expanded on his findings and defined the ratio of V to I (which is a constant) as the electrical resistance, R:

$$\frac{V}{I} = R$$

Ohm's law
electric current is proportional to voltage and inversely proportional to resistance

This relationship between voltage, current and resistance can be rearranged to give a formula now recognised as **Ohm's law**: Electric current is proportional to voltage and inversely proportional to resistance.

$$I = \frac{V}{R}$$

Worked example 7.6A

Using Ohm's law in calculations

Calculate the

a resistance of a car horn if 1.50 A flows when 12.0 V is applied across it (2 marks)

b voltage across the same car horn when 250 mA is flowing. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: For part **a**, identify the appropriate formula and gather any data that you require. This is an Ohm's law question.	**a** $I = \frac{V}{R}$ $I = 1.50\,\text{A}$, $V = 12.0\,\text{V}$
Step 3: Rearrange the formula so that you can calculate the unknown value. Here, we need to make R the subject.	$R = \frac{V}{I}$ (1 mark)
Step 4: Substitute the known values into the formula. Find the unknown.	$R = \frac{12.0}{1.50}$ $= 8$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance is expressed in ohms (Ω). Because the least precise value in the question has 3 s.f, you must express your answer to 3 s.f.	$R = 8.00\,\Omega$ (1 mark)
Step 6: For part **b**, rearrange the formula so that you can calculate the unknown value. Here, we need to make V the subject.	**b** $V = IR$ (1 mark) $= 0.250 \times 8.0$ $= 2.0$
Step 7: Finalise your answer and make sure you have included the correct units. The unit for voltage is volts (V). Because 250 mA has 2 s.f. you must express your answer to 2 s.f.	$V = 2.0\,\text{V}$ (1 mark)

Your turn

Calculate the current that will flow in a 330 Ω resistor when placed across a 1.5 V cell (2 s.f.). (2 marks)

Ohm's law graphs

A graph of current (y-axis) versus voltage (x-axis) will give a linear relationship that passes through the origin (0, 0) and is thus directly proportional. The gradient $\frac{I}{V}$ is the reciprocal of the resistance:

$$\text{Gradient} = \frac{I}{V} = \frac{1}{R}$$

This relationship enables us to calculate the resistance of a conductor providing its graph is directly proportional: $R = \frac{1}{\text{gradient}}$ (Figure 1).

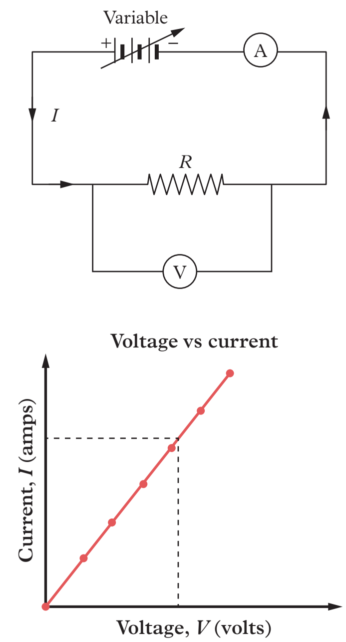


FIGURE 1 Ohm's law circuit and a graph of the results

What is the difference between ohmic and non-ohmic devices?

If an electrical component follows Ohm's law, we say it is "ohmic". If it doesn't follow Ohm's law, we say it is "non-ohmic".

Ohmic devices

Nichrome wire is a good example of an ohmic resistor (Figure 2).

If a current through a 17.0 cm length of nichrome wire of diameter 0.274 mm was measured as the voltage increases, the results would be similar to those in Table 1.

FIGURE 2 Nichrome wire is considered ohmic.

TABLE 1 Voltage and current through nichrome wire

Voltage (V)	0.0	1.0	2.0	3.0	4.0	5.0
Current (A)	0.0	1.2	2.4	3.6	4.8	6.0

When the results are plotted, a graph similar to Figure 3 would be produced.

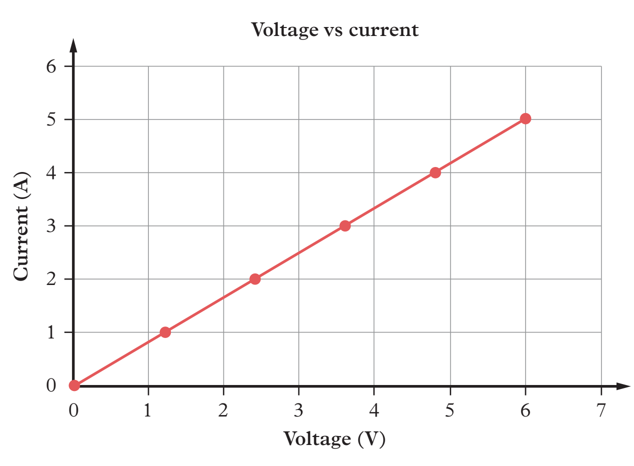


FIGURE 3 Graph of voltage (horizontal axis) vs current (vertical axis) for a piece of nichrome wire

Devices that have a directly proportional relationship for I vs V are said to be **ohmic devices**. A directly proportional graph is one that is linear and also passes through the origin (0,0). You can see that the nichrome wire graphed in Figure 3 is ohmic.

ohmic devices
those that follow Ohm's law

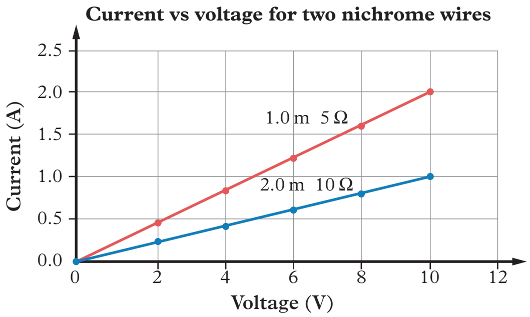


FIGURE 4 Voltage–current characteristics for 1 m and 2 m lengths of nichrome wire. When voltage is plotted on the horizontal axis, the steeper the line, the smaller the resistance.

Comparison of ohmic resistors

When different resistors are used, we still observe straight lines on a voltage–current graph, but the gradient changes. If a 1.0 m length of the nichrome wire and also a 2.0 m length of the same wire were used in a similar experiment to before, the graph of results would look like Figure 4. Both wires show a linear relationship, so they are both ohmic, as expected. However, the 1.0 m length of wire has a gradient of $\frac{2.0}{10} = 0.20$, so the resistance is the reciprocal of this: $\frac{1}{0.20}$ equals a resistance of 5 Ω, whereas the 2.0 m length has a gradient of 0.10 and this a resistance of 10 Ω. Recall that the gradient equals the reciprocal of the resistance.

Worked example 7.6B

Using experimental data to determine resistance

A 560 Ω resistor with a percentage uncertainty (tolerance) of ±10% was connected across the output of a laboratory power supply set to DC. Voltage and current readings were observed on the analogue meters shown in Figure 5. The voltage scale is 0–30 V and the current scale is 0–50 mA.

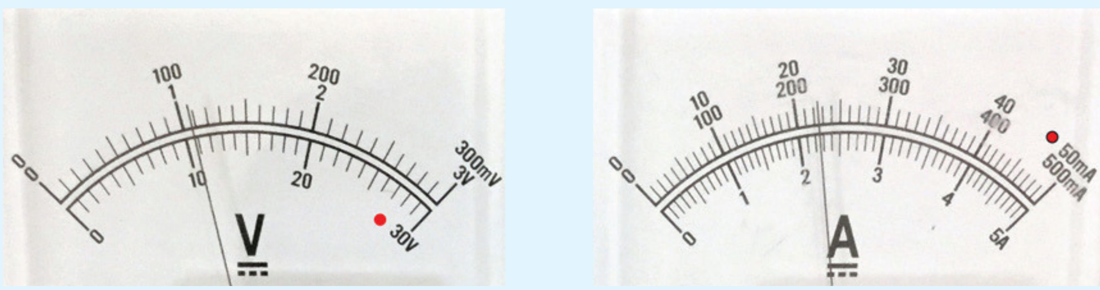


FIGURE 5 Voltmeter and ammeter readings

a **Determine** the voltage and current from the meters and include the “half-scale division” uncertainty, $\delta\bar{x}$. (4 marks)

b **Calculate** the experimental value for resistance including the percentage and absolute uncertainty. (4 marks)

c **Identify** whether this is within the stated range of ±10% for the resistor. (1 mark)

d **Calculate** the absolute and percentage errors (E_a, E%) (2 s.f.). (4 marks)

Think	Do
Step 1: For part **a**, look at the cognitive verb and mark allocation to determine what the question is asking.	“Determine” means to conclude after a calculation. We must look at the meters and read the values, calculate something and reach a conclusion.
Step 2: Gather any data that you require and perform any calculations. In this case, read the voltage and current from the meters and calculate the uncertainty.	**a** Voltage: 10.8 V, δ = 10.8 ± 0.5 V (1 mark) $\delta\% = \frac{0.5}{10.8} \times 100 = 4.6\%$ Current: 22.4 mA, δ = ± 0.5 mA (1 mark) $\delta\% = \frac{0.5}{22.4} \times 100 = 2.2\%$
Step 3: Finalise your answer and make sure that you have included the correct units. Voltage is expressed in volts (V) and current is express in ampere (A).	Voltage = 10.8 V ± 4.6% (1 mark) For current, convert mA to A (divide by 1,000). ∴ Current = 0.0224 A ± 2.2% (1 marks)

Think	Do
Step 4: For part **b**, look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 5: Identify the appropriate formula and gather any data that you require. Here, we first need to calculate resistance.	**b** $R = \frac{V}{I}$ $V = 10.8 \pm 4.6\%$, $I = 0.0224 \pm 2.2\%$
Step 6: Substitute the known values into the formula. Find the unknown.	$R = \frac{10.8 \pm 4.6\%}{0.0224 \pm 2.2\%}$ $= 482.1 \pm (4.6 + 2.2)$ (1 mark) $= 482.1\,\Omega \pm 6.8\%$ (1 mark)
Step 7: Convert percentage uncertainty back to absolute uncertainty.	$\delta\overline{x} = \frac{\Delta\%}{100} \times R$ $= \frac{6.8}{100} \times 482.1$ $= 54.8\,\Omega$ This gives a range of $482.1 \pm 54.8\,\Omega$. (1 mark)
Step 8: Finalise your answer and make sure to include the correct units.	The minimum and maximum values are $427.3\,\Omega$ and $536.9\,\Omega$. (1 mark)
Step 9: For part **c**, look at the cognitive verb and mark allocation to determine what the question is asking.	"Identify" means to recognise and name something.
Step 10: Finalise your answer.	**c** Note that the stated value of $560\,\Omega \pm 10\%$ ($504\,\Omega$ to $616\,\Omega$) overlaps with the range of the experimental value of the resistor. Therefore yes, it is within the tolerance range. (1 mark)
Step 11: For part **d**, look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. So we must identify the appropriate formula and use it to find an answer.
Step 12: Identify the appropriate formulas for E_a and $E\%$. Gather any data that you require and perform the calculations. Make sure you include the correct units and expressed to the correct number (2) of s.f.	**d** $E_a = \lvert x_O - x_A \rvert$ $= \lvert 482.1 - 560 \rvert$ (1 mark) $= 77.9\,\Omega$ (1 mark) $E\% = \frac{E_a}{A} \times 100$ $= \frac{77.9}{560} \times 100$ (1 mark) $= 13.9\%$ $= 14\%$ (2 s.f.) (1 mark)

Your turn

A resistor has a stated value of $100\,\Omega \pm 5\%$. Voltage and current readings for the resistor were taken on the analogue meters shown in Figure 6. The voltage scale is 0 to 30 V and the current scale is 0 to 50 mA.

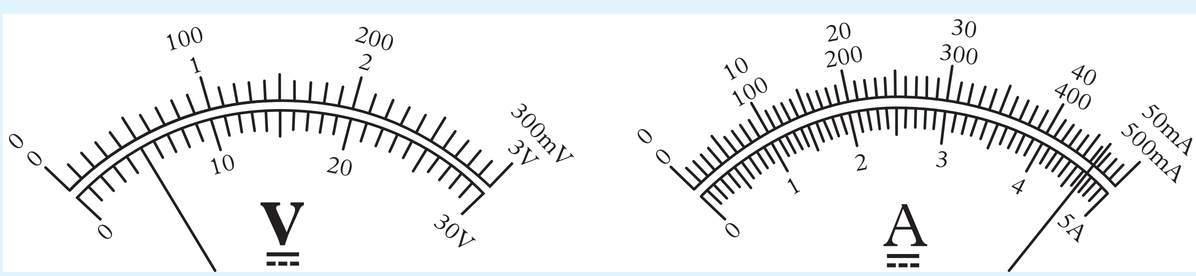


FIGURE 6 Voltmeter and ammeter readings using the 0 to 30 V scale and the 0 to 50 mA scale respectively

a **Determine** the voltage and current from the meters and include the "half-scale" uncertainty, $\delta\bar{x}$. (4 marks)

b **Calculate** the experimental value for resistance including percentage and absolute uncertainty. (4 marks)

c **Identify** whether this is within the stated uncertainty (tolerance) range of ±5% for the resistor. (1 mark)

d **Calculate** the absolute and percentage errors (E_a, E%) (2 s.f.). (4 marks)

Worked example 7.6C

Interpreting an *I–V* graph

The current through a device was measured as the voltage across it was changed. The data is shown in the graph in Figure 7. The voltage was recorded to 1 d.p.

a **Determine** the resistance of the device using the graph (2 s.f.). (4 marks)

b **Assess** whether the conductor is ohmic. (2 marks)

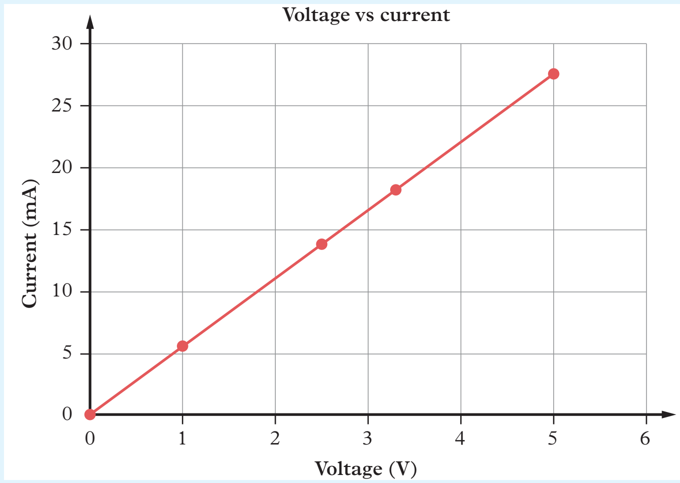


FIGURE 7 Graph of experimental data (I vs V)

Think	Do
Step 1: For part **a**, look at the cognitive verb and mark allocation to determine what the question is asking.	"Determine" means to conclude after a calculation, so we must identify the appropriate formula, use it to calculate a value and draw a conclusion.
Step 2: Identify the appropriate formula and gather any data that you require. This is an Ohm's law question.	**a** Gradient $= \frac{I}{V} = \frac{1}{R}$ The coordinates of widely separated points that are on the line are the ordered pairs (5, 27.5) and (0, 0).
Step 3: Rearrange the formula so that you can calculate the unknown value. Here, we need to make R (resistance) the subject.	$R = \frac{1}{\text{gradient}}$ (1 mark)
Step 4: Substitute the known values into the formula. Find the unknown.	Gradient $= \frac{(27.5 \times 10^{-3}) - 0}{(5 \times 10^{-3})} = 5.5 \times 10^{-3}$ (1 mark) $R = \frac{1}{\text{gradient}} = \frac{1}{5.5 \times 10^{-3}}$ $= 181.8$ (1 mark)
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance is expressed in ohms (Ω). You must express your answer to 2 s.f.	$R = 180\,\Omega$ (1 mark)
Step 6: For part **b**, look at the cognitive verb and mark allocation to determine what the question is asking.	"Assess" means to make a judgment about the outcomes, so we must think about the data we have been provided and use it to judge whether the device is ohmic.
Step 7: Identify the trend in the line.	**b** The trendline is linear and directly proportional as it is straight and goes through the origin. (1 mark)
Step 8: Make a judgment and state the justification.	The I–V characteristics are linear and directly proportional, so the device is ohmic. (1 mark)

Your turn

The current through a wire was measured as the voltage across it was changed. The data is shown in the graph in Figure 8.

a **Determine** the resistance of the wire using the graph (2 s. f.). (4 marks)

b **Assess** whether the wire is ohmic. (2 marks)

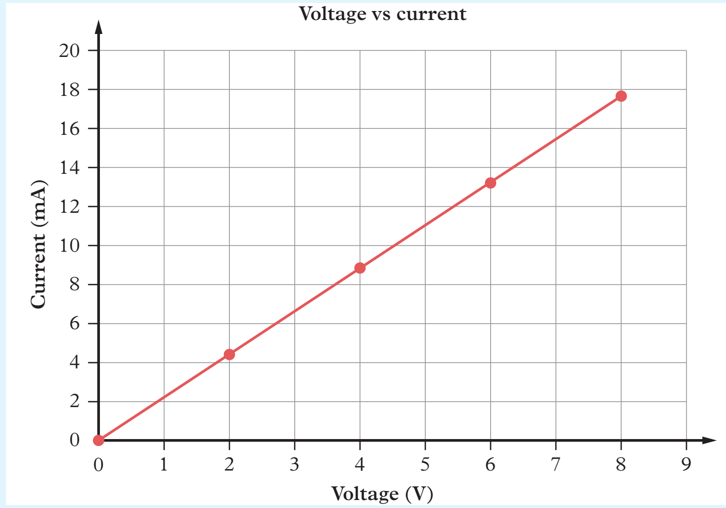


FIGURE 8 Graph of experimental data (I vs V)

Non-ohmic devices

As we have learnt, the many substances for which Ohm's law holds are called "ohmic". These include good conductors such as copper (Figure 9), aluminium and nichrome, and even a non-conductor such as silicon. They all obey Ohm's law over a certain range of voltages. But if the voltage gets high enough, there will be departures from Ohm's law in **all** cases. They become **non-ohmic**.

non-ohmic
not following Ohm's law

Effect of temperature

The essence of Ohm's law is that the I–V graph is linear, but it is not a fair test of the law if the object heats up as well. The temperature and physical factors must remain constant to be able to apply Ohm's law. The resistance will change if the object heats up (like it does in a light bulb), but this is not a fair test of Ohm's law.

If the temperature of a wire gets too high, ohmic devices can become non-ohmic. A light bulb is considered a non-ohmic device for this reason. It obeys Ohm's law for low voltages when it is cool, but at higher voltages it gets hotter and so the resistance gets greater. As the voltage increases, the electrons carry more energy. When they collide with metal atoms in the conductor, they transfer more energy. This makes the atoms vibrate a lot more and increases the resistance. Hence, the current–voltage graph does not follow a straight line.

This effect can be seen on the graphs in Figure 10 for an actual experiment measuring the current–voltage characteristics of a light bulb. As the light bulb heats, the resistance increases and the graph is no longer linear but curved. For this reason, the light bulb is called non-ohmic. If you could stop the light bulb from heating up (using ice perhaps), its resistance would remain constant and the graph would be linear and directly proportional, and thus ohmic.

FIGURE 9 Copper is an example of an ohmic substance.

There is no single resistance of a light bulb, as shown in the graphs. Its resistance changes at higher voltages and currents. However, you can calculate its instantaneous resistance at any given voltage. For example, the instantaneous resistance at 4.0 V, where the current is 0.15 A, is:

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{4.0}{0.15} \\ &= 27\,\Omega \end{aligned}$$

At 8.0 V where the current is 0.225 A, the resistance is:

$$\begin{aligned} R &= \frac{V}{I} \\ &= \frac{8.0}{0.225} \\ &= 36\,\Omega \end{aligned}$$

Note that doubling the voltage from 4.0 V to 8.0 V did not double the current, so it is non-ohmic, as shown by the different resistances at different voltages.

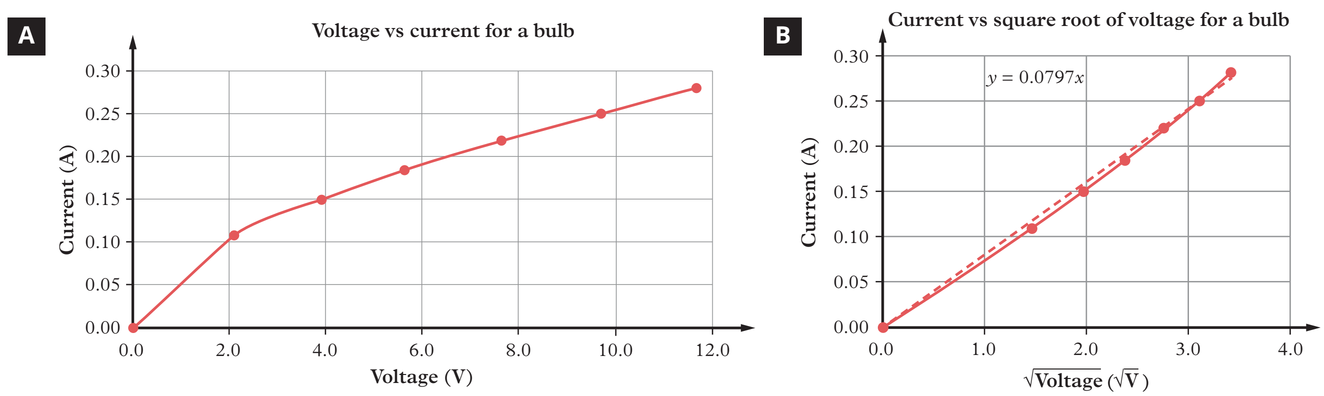


FIGURE 10 Graphs showing the current vs voltage curves using student data for a 12 V light bulb. (A) The relationship appears to be $y \propto \sqrt{x}$ and (B) a linearised graph supports this. A plot of I^2 vs V would also give a linear relationship (y^2 "proportional to symbol" x).

True non-ohmic devices

The best examples of true non-ohmic conductors are modern semiconductor devices such as transistors, diodes and thermistors, which usually rely on special properties of modified silicon for conduction. They are designed to be non-ohmic.

Study tip

Non-ohmic devices rarely have a straightforward mathematical relationship between V and I. However, in the case of the light bulb we discussed, the proposed relationship $y \propto \sqrt{x}$ can be confirmed by the linearised graph in which y (current) is plotted against the $\sqrt{x}$ (square root of voltage). As shown in Figure 10B, a linear relationship is found.

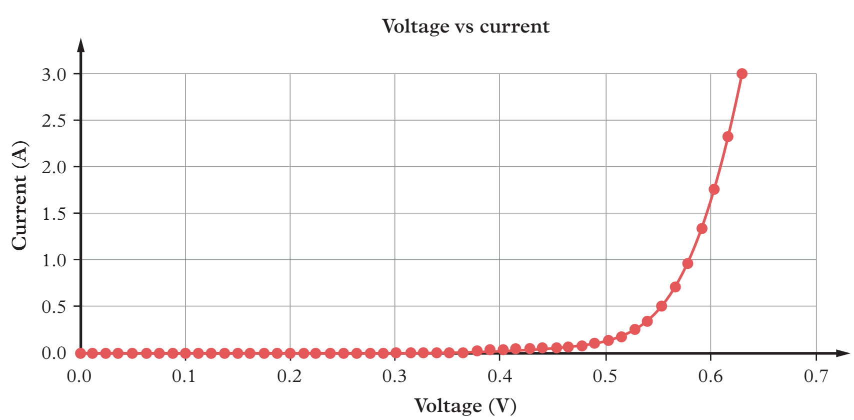


FIGURE 11 The characteristic I–V curve for a silicon semiconductor diode. At about 0.55 V, the current increases dramatically without the diode heating up. It is as if a voltage-controlled switch turns on at 0.55 V.

We can calculate the resistance of the diode at any voltage we choose. For example, at 0.55 V, its resistance is $R = \frac{V}{I} = \frac{0.55}{0.50} = 1.1$ W. At 0.60 V, its resistance is $\frac{0.60}{1.6} = 0.38$ W. This is noticeably different and confirms its non-ohmic nature.

Real-world physics

Hertha Ayrton and negative resistance

Hertha Ayrton (1854–1923) is renowned for her work on electrical conduction. She completed her course at Cambridge University in 1880 but as they didn't award degrees to women, she went to the University of London and was awarded a Bachelor of Science degree the following year.

Ayrton became interested in arc lighting, which was common around London at the time. Arcs are created when pointed carbon rods are brought close and a high voltage applied to them. They glow with a brilliant white light as the carbon combines with oxygen. The strange thing about them was their resistance.

FIGURE 12 Portrait of Hertha Ayrton, University of Cambridge

In the 1800s and 1900s scientists and engineers knew about the resistance of metals and non-metals, but they had never experienced a strange phenomenon called negative resistance. We know that ohmic and non-ohmic materials will allow more current to pass through them as the voltage is increased. However, Ayrton found a strange phenomenon in the mist surrounding a carbon arc. At some points, as the voltage is increased, the current actually decreases. This is shown as a negative gradient for the I vs V curve in that region. This didn't seem to make sense, but she noted that this didn't happen across the whole range of voltages. This was lucky, as the arc would have self-destructed from a run-away current.

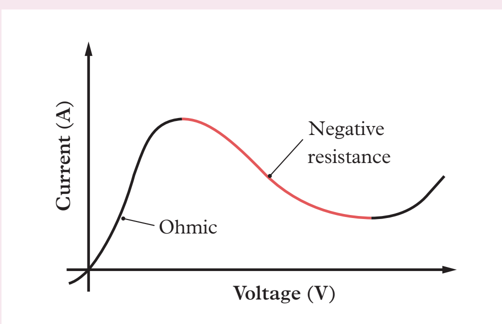


FIGURE 13 The graph shows the variation of current as a function of voltage in a device. The first (black) section shows positive resistance and is generally ohmic but the red section shows negative resistance before turning positive again.

Hertha Ayrton had four papers published by the Royal Society of London in their journal. She was forbidden to present her papers to an audience at the meetings and they had to be read out by a man she knew. Nevertheless, she was awarded a medal by the Royal Society for her contributions to physics. Normally, such a person would be invited to become a Fellow of the Society, but this was denied Ayrton because she was married. Luckily, the Institute of Electrical Engineers were less narrow-minded, and she was inducted into their ranks. She was the first woman to be inducted, and this opened new roles for women in physics and engineering.

Apply your understanding

1 **Explain** whether a device that exhibits negative differential resistance has current going in the opposite direction to one with positive differential resistance. (2 marks).
2 **Explain** why a device cannot exhibit negative resistance over all voltages. (1 mark)

Check your learning 7.6

Check your learning 7.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** Ohm's law as it applies to a fixed resistor. (2 marks)

2 **Describe** the difference between an ohmic and a non-ohmic device. (2 marks)

3 **Calculate** the current flowing through the bulb of a 4.5 V torch when its resistance is 4.60 Ω (2 s.f.). (2 marks)

4 **Calculate** the resistance of a mobile phone that has a 1.35 V battery and through which 0.150 mA flows (3 s.f.). (2 marks)

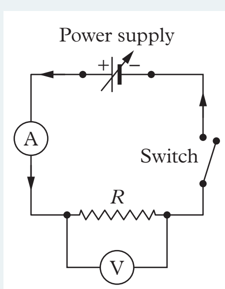
Analytical processes

5 **Determine** the resistance of a portable amplifier when 1.50 A flows through it as the battery applies 12.0 V to the circuit (3 s.f.). (2 marks)

6 **Determine** the voltage needed to operate a laser pointer that has a resistance of 140 Ω, given that 20.0 mA passes through it (2 s.f.). (2 marks)

7 **Deduce** the voltage drop in a headphone cord having 1.2 kΩ resistance and through which 10 mA is flowing (2 s.f.). (2 marks)

8 A student set up the experimental apparatus as shown and found the results listed in the table.



Voltage (V)	0.0	2.0	4.0	6.0	8.0	10.0	12.0
Current (A)	0.0	0.013	0.025	0.04	0.05	0.06	0.08

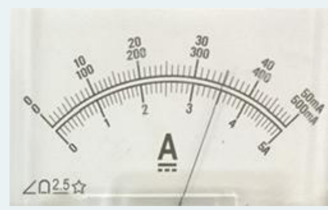
a **Determine** the value of the resistance at all points using $R = \frac{V}{I}$ (2 s.f.). (7 marks)

b **Sketch** a graph of voltage (horizontal axis) versus current (vertical axis) and **calculate** the gradient. **Deduce** a conclusion about the nature of the resistance of the device. (4 marks)

c **Explain** if the resistor is "ohmic" in its characteristics. (2 marks)

Knowledge utilisation

9 Students connected a resistor to a laboratory power supply and measured the voltage across the resistor and the current passing through it. The meter readings are shown. Note that the voltmeter is on the 30 V scale, and the ammeter is on the 50 mA scale.



a **Determine** the "best estimate" readings on the meters and estimate scale reading uncertainties. (4 marks)

b **Calculate** the experimental value of the resistance, including absolute and percentage uncertainty (2 s.f.). (4 marks)

c **Calculate** the absolute and percentage error in the experimental value of resistance if the accepted value of the resistance is 220 Ω (1 s.f.). (4 marks)

d **Propose** whether the resistor is within the tolerance range of ±10%. (2 marks)

e **Modify** the following conclusion to make it more acceptable: "Because $V = IR$, the resistor must be ohmic". (2 marks)

10 The table shows experimental data from a light bulb.

Power supply (V)	Current (A)		Voltage (V)	
	Trial 1	Trial 2	Trial 1	Trial 2
0	0.0	0.0	0.0	0.0
2	0.11	0.11	2.14	2.13
4	0.15	0.15	3.87	3.88
6	0.19	0.18	5.63	5.60
8	0.22	0.22	7.69	7.56
10	0.25	0.25	9.67	9.69

a **Construct** (plot) an appropriate graph. Place voltage on the horizontal axis. (2 marks)

b This data is non-linear.

i **Propose** a relationship and generate a linearised graph. (2 marks)

ii **Sketch** a line of best fit (trendline) and express the relationship in the form of an equation. (2 marks)

iii **Generate** and display the R^2 value (optional). (1 mark)

iv **Evaluate** the precision of the data by referring to the R^2 value. (2 marks)

c **Comment**, with reference to the data, on whether the light bulb is ohmic or non-ohmic. (2 marks)

Practical

Lesson 7.7

Finding resistance using current and voltage across an ohmic resistor

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Practical

Lesson 7.8

Ohmic and non-ohmic resistors

oxforddigital

This This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

MODULE 7

Lesson 7.9
Review: Current, potential difference and energy flow

Summary

7.1
- Charge is classified as positive and negative.
- Conductors are substances that allow free movement of charge through them.
- Insulators are substances that do not allow free movement of charge through them.

7.2
- Electric current is the rate of movement of electric charge carriers from one part of a conductor to another.
- Electron flow is the flow of electrons in a circuit and is opposite to electric current.

7.3
- Electrical potential is the amount of work needed to move a unit of charge from one point to another.
- Electrical potential energy is the energy stored in a charge and circuit system.

7.4
- Power is a measure of the rate at which work is done or the rate at which energy is transferred or transformed.

7.5
- Resistance is the opposition to the flow of electric current through a conductor and is measured in units called ohms.
- Resistance is dependent on length, area and material.

7.6
- Ohm’s law states the relationship between voltage, current and resistance.
- Problems involving voltage, current and resistance can be solved using Ohm’s law.
- Ohmic and non-ohmic resistors have different voltage/current characteristics.
- The resistance across an ohmic resistor can be interpreted using experimental data.

7.7
- Practical: Finding resistance using current and voltage across an ohmic resistor

7.8
- Practical: Ohmic and non-ohmic resistors

Key formulas

Electrical potential	$W = \frac{V}{q}$
Elementary charge	$n = \frac{Q}{q_e}$
Electric current	$I = \frac{q}{t}$
Power	$\text{Power} = \frac{\text{energy}}{\text{time}} = \text{voltage} \times \text{current}$ $P = \frac{W}{t} = VI$
Resistance	$R = \frac{V}{I}$
Ohm’s law	$I = \frac{V}{R}$

Review questions 7.9A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 The free electrons of a metal
  A do not collide with each other.
  B are free to escape through the surface.
  C are free to fall into the nuclei.
  D are free to move anywhere in the metal.

2 When there is an electric current passing through a wire, the particles that are moving are
  A electrons.
  B protons.
  C atoms.
  D ions.

3 The current flowing through a conductor when 2×10^7 electrons pass in 1 μs will be
  A 1.6×10^{-6} A
  B 3.2×10^{-6} A
  C 4.2×10^{-6} A
  D 6×10^{-6} A

4 The amount of charge flowing through a cross-sectional area of a wire per unit of time is called
  A voltage.
  B power.
  C resistance.
  D current.

5 Select one of the following as a valid statement about current in a conductor.
  A Current exists when there are more positive than negative charges present.
  B Current represents the motion of positive charge in a circuit.
  C Current is the motion of protons, and electron flow is the motion of electrons.
  D Charge carriers move at the speed of light in a circuit.

6 The resistance of a torch bulb drawing a 2.0 A current at 12.0 V is
  A 1.7 Ω.
  B 6 Ω.
  C 14 Ω.
  D 24 Ω.

7 The current in a wire
  A depends only on the potential difference applied.
  B depends only on the resistance of the wire.
  C depends on both resistance and potential difference.
  D does not depend on resistance or potential difference.

8 Ohm's law relates potential difference to which of the following?
  A Power
  B Energy
  C Current
  D Time

9 Which one of the following is an ohmic resistor?
  A Light-emitting diode
  B Silicon diode
  C Nichrome wire
  D Diamond

10 The resistance of a wire is proportional to
  A the inverse of length.
  B length squared.
  C the inverse of cross-sectional area.
  D the square of the inverse of cross-sectional area.

11 Deduce the effect on the current through a wire if the resistance is halved but the voltage remains the same.
  A Quartered
  B Halved
  C Doubled
  D Quadrupled

12 Calculate the current flowing through a 20 Ω resistor when it is connected to an 8 V power pack.
  A 0.25 A
  B 0.4 A
  C 2.5 A
  D 4.0 A

13 Determine what happens to the resistance of ohmic wire as the voltage across the wire increases.

A It increases.
B It decreases.
C It stays the same.
D It doubles.

14 A current of 12 A flows through a 230 V electric heater. The resistance of the heater is closest to

A 0.05 Ω.
B 2 Ω.
C 20 Ω.
D 2,880 Ω.

Review questions 7.9B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

15 **Describe** the law of conservation of charge in the context of electrifying a plastic rod with fur. (2 marks)

16 **Describe** electric current, electrical potential, EMF and power as they apply to a simple electrical circuit. (4 marks)

17 **Calculate** the electric current in the following cases.

a 20 C of charge passes through an ammeter in 1 min 30 s. (2 marks)

b 5 μC of charge passes through an ammeter in 3.0 s. (2 marks)

c A 200 C lightning bolt travels to the ground in 0.5 s. (2 marks)

18 **Calculate** the increase in electrical potential (potential difference) produced by a cell if every 2.6 C of charge passing through the cell is supplied with 3.9 J of energy. (2 marks)

19 **Calculate** how many electrons pass out every second from a 12.0 V car battery that runs a single 30.0 W headlight. (4 marks)

20 Two points in space are at electrical potentials of +18 V and −6 V respectively.

a **Calculate** the potential difference between these points. (1 mark)

b **Calculate** the work done in moving a charge of 5.5 μC from one point to the other. (2 marks)

21 In one particular lightning flash, the potential difference between the two ends of the lightning bolt was 10^9 V and the quantity of charge transferred was 10 C. **Calculate** how much energy was released. (2 marks)

22 In moving an electron from point X to point Y along a uniform field, a total of 2×10^{-20} J of work is done. **Calculate** the potential difference between X and Y. (2 marks)

23 **Calculate** the resistance of a 50 m length of silver wire of cross-sectional area 0.50 mm^2 at 20°C given that a 25 m length of the wire with area 1.0 mm^2 has a resistance of 2.6 Ω. (2 marks)

24 A piece of metal wire of length 20.0 m has a diameter of 0.58 mm and a resistance of 1.13 Ω at 20°C. **Calculate** the resistance of an identical wire that is twice as long and its cross-sectional area is triple that of the first. (2 marks)

25 You have a 100.0 m length of resistance wire of uniform cross-sectional area 0.1 mm^2 and a resistance of 500 Ω. The wire is now drawn out (stretched) to three times its original length.

Calculate the new resistance of the wire. (4 marks)

26 An electric current of 3.5 A passes through a salt solution for a period of 5 minutes. **Determine** how many coulombs of charge pass into the solution. (2 marks)

Analytical processes

27 **Infer** whether there is any difference between the internal energy of a battery that is flat and when it is fully charged. (3 marks)

28 A device uses 25 W of power from eight AA 1.5 V batteries connected in series. After 10 hours, the batteries are "flat" and no more power is produced. **Determine** how many joules of energy are produced by each battery before going flat. (3 marks)

29 Conducting metal A has a resistance of 0.36 Ω at 25°C. **Determine** the resistance of conducting metal B compared to conducting metal A under the following conditions.

- **a** B is three times longer than A (2 s.f.). (1 mark)
- **b** B is only half the cross-sectional area of A (2 s.f.). (1 mark)
- **c** B has just been heated to 350°C (only a non-quantitative answer is required; no calculations necessary). (1 mark)

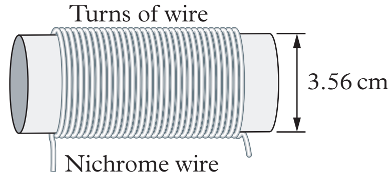
30 General tungsten wire has 5.6% of the resistance of nichrome wire. **Calculate** the length of tungsten wire that has the same resistance as 1.5 m of nichrome wire. Ignore any temperature differences. (2 marks)

31 The data in the table was collected from an Ohm's law experiment in which the voltage across a circuit device was changed and the current passing through it measured. Temperature was kept constant.

Voltage, *V* (V)	0.0	1.5	3.0	4.5	6.0	7.5
Current, *I* (A)	0.0	0.10	0.20	0.30	0.40	0.50

- **a** **Construct** a suitable graph with the independent variable on the *x*-axis. (2 marks)
- **b** Using your graph
  - **i** **describe** whether the device is ohmic (2 marks)
  - **ii** **calculate** the resistance by graphical means (2 s.f.) (2 marks)
  - **iii** **deduce** the voltage at 0.60 A by extrapolation (2 s.f.) (1 mark)
  - **iv** **deduce** the current at 2.0 V by interpolation (2 s.f.). (1 mark)

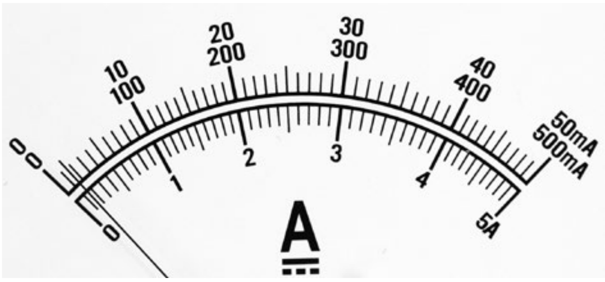
32 Nichrome wire of diameter 0.315 mm has a resistance of 13.77 ohms per metre. A student doing an experiment wants to make a coil of the wire by wrapping it around a cylindrical tube of diameter 3.56 cm. **Calculate** the number of turns of wire required if the coil is to have a resistance of 100.0 Ω. The set-up is shown. (5 marks)



33 Two 1.0 m lengths of stainless steel wire, each of diameter 0.80 mm and resistance 1.37 Ω are placed side by side (in parallel) and their combined resistance measured. Based on the increased cross-sectional area, **calculate** their total resistance (2 s.f.). (3 marks)

Knowledge utilisation

34 A meter that is part of a circuit is shown.



- **a** **Determine** the reading on the meter (on the 5 A scale) to the nearest half-scale division (including its uncertainty). Give your answer to 2 decimal places. (2 marks)
- **b** **Discuss** whether you could get a more accurate reading by changing to one of the other scales. (2 marks)
- **c** A student claimed that this was a multimeter because it had multiple scales. **Evaluate** whether this is an ammeter or a multimeter. (2 marks)

35 A 100 Ω ± 10% fixed resistor was used in an Ohm's law experiment in which pairs of I vs V data were collected. The data is displayed in the table.

Voltage, V (V)	Current, I (A)
0.0	0.000
1.8	0.022
3.4	0.038
4.9	0.062
6.7	0.082
8.7	0.100
10.5	0.125
11.5	0.132

a **Construct** a graph of the data, with V on the horizontal axis. (2 marks)

b **Assess** whether the resistor is ohmic. (2 marks)

c **Construct** a trendline. (2 marks)

d **Determine** the relationship between V and I. (1 mark)

e **Determine** the experimental value of the resistance. (1 mark)

f **Determine** the absolute and percentage errors (2 s.f.). **Assess** whether the experimental value is within the ±10% tolerance range allowed by the manufacturer. (5 marks)

36 A student set up a circuit to collect V vs I data for an experiment to assess a device as ohmic or non-ohmic. The results are displayed in the table.

Voltage, V (V)	Current, I (A)
2.0	0.013
4.0	0.025
6.0	0.040
8.0	0.050
10.0	0.060
12.0	0.080

a **Determine** the value of the resistance at 2 V and at 12 V. (2 marks)

b **Construct** a graph of voltage (horizontal axis) versus current (vertical axis). (3 marks)

c **Evaluate**, with justification, whether the resistor is ohmic or non-ohmic. (2 marks)

Data drill

Investigating resistors

A student set up the apparatus shown by the circuit diagram in Figure 1 to investigate the current passing through a fixed resistor as a function of voltage. The student varied the voltage across the resistor and measured the current on an ammeter. The data was processed and plotted in Figure 2.

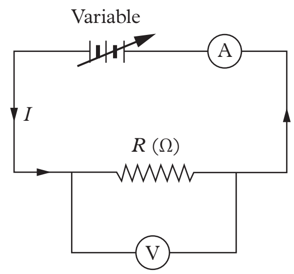


FIGURE 1 Circuit diagram for the experiment

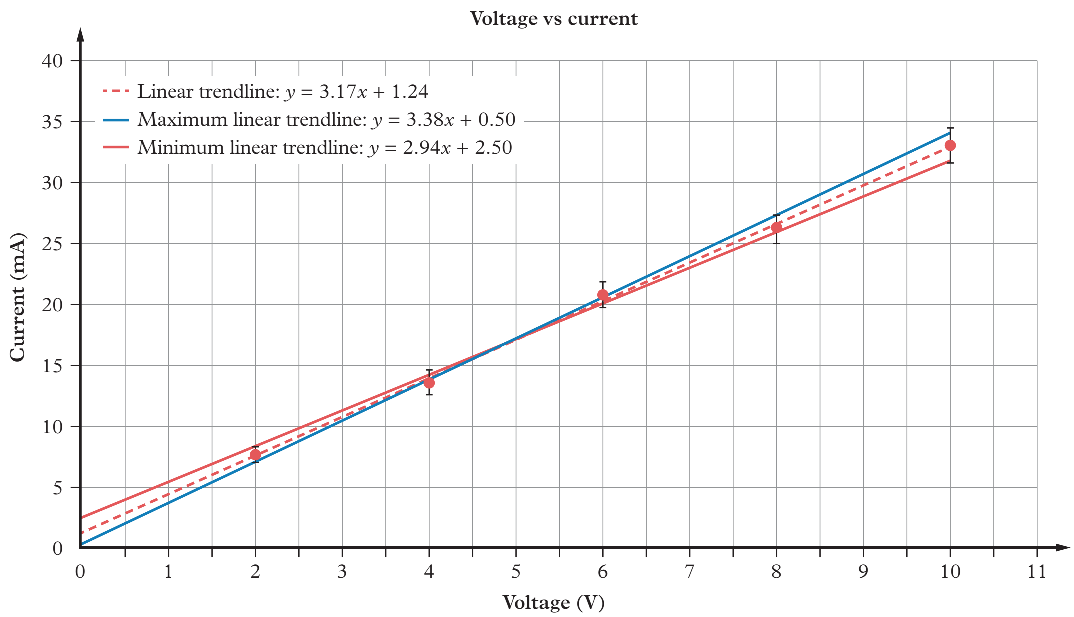


FIGURE 2 A graph of current versus voltage for the experiment

Apply understanding

1 **Estimate** the current at a voltage of 9.0 V. (1 mark)

2 **Calculate** the resistance at 6.0 V (2 s.f.). (2 marks)

Analyse data

3 **Identify** a mathematical relationship between the voltage, V, across the resistor and the current, I, passing through it, including the uncertainty of the gradient and y-intercept. (3 marks)

Interpret evidence

4 **Draw a conclusion** that quantifies the magnitude of the resistance of the fixed resistor, including the absolute or percentage uncertainty in the value you determine. Show your reasoning. (4 marks)

Module 7 checklist: Current, potential difference and energy flow

Quizlet: Revise key terms online to test your understanding

MODULE 8

Circuit analysis and design

Introduction

Why is it that some birds can sit on 11,000 V overhead wires without a problem, but bigger animals such as bats get electrocuted? If a larger animal touches more than one wire, the charge will pass through its body. Birds perched on a single wire are at a potential of 11,000 V, but the charge has nowhere to go. The ground (0 V) is many metres below them. A circuit must be completed before charge flows.

Prior knowledge

Prior knowledge quiz

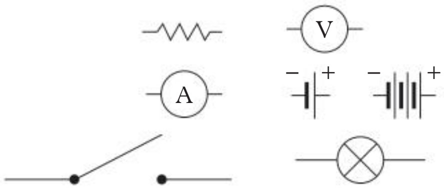
Check your understanding of electrical circuits before you start.

Subject matter

Science understanding

→ Describe the concept of power dissipation over resistors in a circuit.

→ Construct electrical circuit diagrams using the following symbols



→ Solve problems involving electrical potential difference, electric current, resistance and power.

→ Describe series and parallel connections of components in electrical circuits.

- → Solve problems involving finding equivalent resistance, electrical potential difference and electric currents in series and parallel circuits using $P = VI$, $P = I^2 R$, $V_t = V_1 + V_2 + \dots V_n$, $R_t = R_1 + R_2 + \dots R_n$, $I_t = I_1 + I_2 + \dots I_n$, $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_n}$.
- → Describe simple series, parallel and series/parallel circuits.

Science inquiry

- → Investigate series and parallel circuits.
- → Investigate simple circuits for specific ‘real-life’ purposes.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 8.3 Investigating series and parallel circuits
Lesson 8.5 Circuits for real-life purposes – using a fuse for protection

Lesson 8.1

Circuit design – resistors in series and parallel

Key ideas

- → Resistors can be used to control current and divide voltage.
- → Resistors can be arranged in series and parallel configurations for different purposes.

Learning intentions and success criteria

Can resistors be combined?

You were introduced to resistors in Module 7. Remember that resistors are simple devices used to control the flow of charge in a circuit. If you look inside an electronic device, you'll see dozens of resistors in all sorts of odd combinations. Most circuits have more than one resistor. The simplest combinations of resistors are the series and parallel connections illustrated in Figures 1 and 2. The total resistance of a combination of resistors depends on both their individual values and how they are connected.

How do resistors in series work?

Figure 1 shows three resistors connected in series so that any charge flowing from A to B must pass through each in turn. This effect simply adds the individual resistances to create a total of all three. We call it an "equivalent" resistance. It is the same as increasing the effective length of a single resistor.

Therefore:

$$R_t = R_1 + R_2 + \ldots + R_n$$

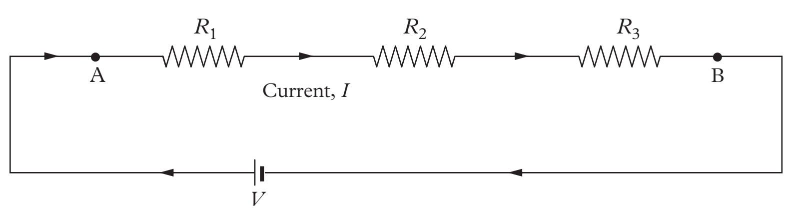


FIGURE 1 Resistors in series

As the charge passes through each resistor, the charge loses some of its energy to heat. If the three resistances are all the same value, the potential difference across each resistor is the same. (Remember from Module 7 that potential difference is the difference in electrical potentials between two points in an electric field, including a conducting wire connected to a battery.) The total voltage is divided up between the series resistors.

Summary

This list summarises resistors in series:

1. Series resistances add to form an "equivalent" resistance: $R_t = R_1 + R_2 + \ldots + R_n$.
2. The same current flows through each resistor in series.

3 Individual resistors in series do not each have the full voltage drop across them, but instead the voltage is divided between them. The potential difference for each resistor will be the product of the current through it and the resistance; that is, $\Delta V_1 = I \times R_1$. The current is the same for each resistor, so we can also say $\Delta V_2 = I \times R_2$ and $\Delta V_3 = I \times R_3$. We will look at this in more detail in Lesson 8.2.

Worked example 8.1A

Calculating equivalent resistance for resistors in series

Calculate the total (equivalent) resistance of three resistors ($10\,\Omega$, $33\,\Omega$ and $100\,\Omega$) connected in series. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$R_t = R_1 + R_2 + R_3$ (1 mark) $R_1 = 10\,\Omega$, $R_2 = 33\,\Omega$, $R_3 = 100\,\Omega$
Step 3: Substitute the known values into the formula. Find the unknown.	$R_t = 10 + 33 + 100 = 143$ (1 mark)
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. In this case, the answer is expressed to the nearest whole number (no decimal places). The convention is that when adding you should express the answer to the least number of decimal places in the numbers being added.	$R_t = 143\,\Omega$ (1 mark)

Your turn

Calculate the total (equivalent) resistance of three resistors ($3.3\,k\Omega$, $1.2\,k\Omega$ and $470\,\Omega$) connected in series. Hint: convert the values in $k\Omega$ to Ω so they can be added. (3 marks)

Worked example 8.1B

Calculating potential difference for resistors in series

Three resistors $2.0\,\Omega$, $4.0\,\Omega$ and $6.0\,\Omega$ are connected in series across a $24\,V$ battery. **Calculate** (2 s.f.) the

a equivalent resistance of the combination (2 marks)

b potential difference across the combination (1 mark)

c current passing through the resistors (1 mark)

d potential difference across each resistor. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer. Each question part has a different mark allocation. This is a clue about the number of steps required to find an answer.

Think	Do
Step 2: For part **a**, identify the appropriate formula and gather any data that you require.	**a** $R_t = R_1 + R_2 + R_3$ $R_1 = 2.0\,\Omega$, $R_2 = 4.0\,\Omega$, $R_3 = 6.0\,\Omega$
Step 3: Substitute the known values into the formula. Find the unknown.	$R_t = 2.0 + 4.0 + 6.0$ (1 mark) $= 12$
Step 4: Finalise your answer and make sure you have included the correct units. Resistance (R) is expressed in ohms (Ω).	$R_t = 12\,\Omega$ (1 mark)
Step 5: For part **b**, identify the appropriate formula and gather any data that you require. In this case no formula is needed. The potential difference across the combination will be the same as the potential difference of the source (battery), as the combination is connected by wires to the battery. We assume there is no potential drop in a connecting wire. No further steps required.	**b** $V = 24\,\text{V}$ (1 mark)
Step 6: For part **c**, identify the appropriate formula and gather any data that you require. This is an Ohm's law calculation. $R = 12\,\Omega$ as we are working with total resistance.	**c** $V = IR$ $V = 24\,\text{V}$, $R = 12\,\Omega$
Step 7: Rearrange the formula so that you can calculate the unknown value. Here, make I the subject.	$I = \frac{V}{R}$
Step 8: Substitute the known values into the formula. Find the unknown.	$I = \frac{24}{12}$ $= 2.0$
Step 9: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Current (I) is expressed in ampere (A). Express your answer to 2 s.f. because the least precise value in the question has 2 s.f.	$I = 2.0\,\text{A}$ (1 mark)
Step 10: For part **d**, identify the appropriate formula and gather any data that you require.	**d** $\Delta V_1 = I \times R_1$ $\Delta V_2 = I \times R_2$ $\Delta V_3 = I \times R_3$ $I = 2.0\,\text{A}$, $R_1 = 2.0\,\Omega$, $R_2 = 4.0\,\Omega$, $R_3 = 6.0\,\Omega$
Step 11: Substitute the known values into the formulas. Find the unknowns. In this case, apply Ohm's law to each resistor. Check that the sum of the potential difference values adds to the total potential difference as they are in series.	$\Delta V_1 = 2.0 \times 2 = 4$ $\Delta V_2 = 2.0 \times 4 = 8$ $\Delta V_3 = 2.0 \times 6 = 12$ $V = 24$ $4 + 8 + 12 = 24$
Step 12: Substitute the known values into the formulas. Find the unknowns. In this case, apply Ohm's law to each resistor. Check that the sum of the potential difference values adds to the total potential difference as they are in series.	$\Delta V_1 = 2.0 \times 2 = 4$ $\Delta V_2 = 2.0 \times 4 = 8$ $\Delta V_3 = 2.0 \times 6 = 12$ $V = 24$ $4 + 8 + 12 = 24$
Step 13: Finalise your answer and make sure you have included the correct units. Voltage (V) is expressed in volts (V).	$\Delta V_1 = 4\,\text{V}$ $\Delta V_2 = 8\,\text{V}$ $\Delta V_3 = 12\,\text{V}$ (1 mark each)

Your turn

Three resistors (3.3 kΩ, 1.2 kΩ and 500 Ω) are connected in series across a 50 V power source. **Calculate** the following values. Hint: convert the values in kΩ to Ω so they can be added.

a The equivalent resistance of the combination (2 marks)

b The potential difference across the combination (1 mark)

c The current passing through the resistors (1 mark)

d The potential difference across each resistor (3 marks)

How do resistors in parallel work?

Figure 2 shows three resistors connected in parallel, much like the rungs of a ladder. Current flowing from A to B in this situation has three paths it could take. In a sense, the total cross-sectional area of the conductor for current (I) is being increased, and thus the total resistance is reduced.

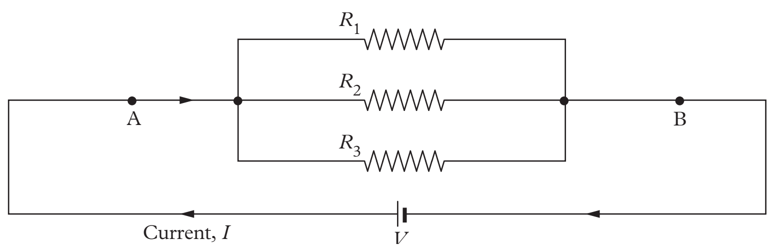


FIGURE 2 Resistors in parallel

If the three resistances are equal, then one-third of the current goes through each. However, the potential difference between A and B (ΔV_{AB}) is the same for all three ($\Delta VR_1 = \Delta VR_2 = \Delta VR_3$). Even if the three resistances are different, the potential difference (voltage) across each one is still the same.

To work out the overall resistance, we must add the reciprocals of each resistance. This goes back to the idea that resistance is proportional to the reciprocal of the cross-sectional area, $R \propto \frac{1}{A}$ or $A \propto \frac{1}{R}$. So, the total area is proportional to the sum of the reciprocals of the resistances. To get the equivalent resistance we then just take the reciprocal of the result. This gives us a relationship expressed as:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}.$$

Summary

Parallel resistance can be summarised in the following way:

1 Parallel resistance is found by calculating $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$ and it is smaller than any individual resistance in the combination.

2 Each resistor in parallel has the same full voltage of the source applied to it.

3 Parallel resistors do not each receive the total current. Instead, a fraction of the total current goes through each.

Worked example 8.1C

Calculating potential difference for resistors in parallel

Three resistors, 10 Ω, 33 Ω and 100 Ω, are connected in parallel. **Calculate** the equivalent resistance of the combination (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	“Calculate” means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: Identify the appropriate formula and gather any data that you require.	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$ (1 mark) $R_1 = 10\,\Omega$, $R_2 = 33\,\Omega$, $R_3 = 100\,\Omega$

Think	Do
Step 3: Substitute the known values into the formula. Find the unknown.	$\frac{1}{R_t} = \frac{1}{10} + \frac{1}{33} + \frac{1}{100}$ $= 0.140$
Step 4: Calculate the reciprocal to finalise your answer. Make sure you have included the correct units and expressed your answer to the correct number of significant figures. Resistance (R) is measured in ohms (Ω) and the question requests a response correct to two significant figures.	$R_t = \frac{1}{0.140}$ $= 7.1\,\Omega$ (2 marks)

Your turn

Three resistors are connected in parallel. The equivalent resistance of the combination is $2.86\,\Omega$. Two of the resistors are known to be $5\,\Omega$ and $10\,\Omega$. **Calculate** the resistance of the third resistor (2 s.f.). (3 marks)

Worked example 8.1D

Calculating potential difference for resistors in parallel

Three resistors of $2\,\Omega$, $4\,\Omega$ and $6\,\Omega$ are connected in parallel across a 24 V battery similar to the circuit in Figure 2. **Calculate** the

a equivalent resistance of the combination (2 marks)

b potential difference across the combination (1 mark)

c total current in the circuit leaving the battery (2 marks)

d potential difference across each resistor (1 mark)

e current passing through each resistor. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer. Each question part has a different mark allocation. This is a clue about the number of steps required to find an answer.
Step 2: For part **a**, identify the appropriate formula and gather any data that you require.	**a** $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$ (1 mark) $R_1 = 2\,\Omega$, $R_2 = 4\,\Omega$, $R_3 = 6\,\Omega$
Step 3: Substitute the known values into the formula. Find the unknown.	$\frac{1}{R_t} = \frac{1}{2} + \frac{1}{4} + \frac{1}{6}$ $= \frac{6+3+2}{12}$ $= \frac{11}{12}$
Step 4: Calculate the reciprocal to finalise your answer. Make sure you have included the correct units. Resistance is measured in ohms. Don't leave it as a fraction.	$R_t = \frac{12}{11}$ $= 1.09\,\Omega$ (1 mark)
Step 5: For part **b**, identify the appropriate formula and gather any data that you require. In this case no formula is needed. The potential difference across the combination will be the same as the potential difference of the source (battery), as the combination is connected by wires to the battery. We assume there is no potential drop in a connecting wire. No further steps required.	**b** $V = 24\,\text{V}$ (1 mark)

Think	Do
Step 6: For part **c**, identify the appropriate formula and gather any data that you require. This is an Ohm's law calculation. $R = 1.09\,\Omega$ as we are working with total resistance.	**c** $V = IR$ (1 mark) $V = 24$, $R_t = 1.09\,\Omega$
Step 7: Rearrange the formula so that you can calculate the unknown value. Make I the subject. Substitute the known values into the formula. Find the unknown.	$I = \frac{V}{R}$ $= \frac{24}{1.09}$ $= 22.0$
Step 8: Finalise your answer and make sure you have included the correct units. Current (I) is measured in ampere (A).	$I = 22.0\,\text{A}$ (1 mark)
Step 9: For part **d**, identify the appropriate formula and gather any data that you require. In this case no formula is needed. The potential difference across each resistor will be the same, as they are connected at their ends (in parallel).	**d** $V = 24\,\text{V}$ (1 mark)
Step 10: For part **e**, identify the appropriate formula and gather any data that you require. This is an Ohm's law question.	**e** $I = \frac{V}{R}$ $V = 24\,\text{V}$, $R_1 = 2\,\Omega$, $R_2 = 4\,\Omega$, $R_3 = 6\,\Omega$
Step 11: Substitute the known values into the formula. Find the unknown. Check that the sum of currents adds to the total current as they are in parallel.	$I_1 = \frac{V}{R_1} = \frac{24}{2} = 12$ $I_2 = \frac{V}{R_2} = \frac{24}{4} = 6$ $I_3 = \frac{V}{R_3} = \frac{24}{6} = 4$ $12 + 6 + 4 = 22$
Step 12: Finalise your answer and make sure you have included the correct units. Current (I) is measured in ampere (A).	$I_1 = 12\,\text{A}$ $I_2 = 6\,\text{A}$ $I_3 = 4\,\text{A}$ (1 mark each)

Your turn

Three resistors of $11\,\Omega$, $22\,\Omega$ and $33\,\Omega$ are connected in parallel across a 60V battery similar to the circuit in Figure 2. **Calculate** the

- **a** equivalent resistance of the combination (2 marks)
- **b** potential difference across the combination (1 mark)
- **c** total current in the circuit leaving the battery (2 marks)
- **d** potential difference across each resistor (1 mark)
- **e** current passing through each resistor. (3 marks)

So far we have only looked at circuits containing resistors either in series or in parallel – but not together. This is not that much more complicated if you follow several rules formulated by Kirchhoff in the late 1800s, which we'll visit in the next lesson.

Check your learning 8.1

Check your learning 8.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** whether resistors in series can ever have a combined resistance smaller than that of any one of the resistors in the combination. (3 marks)

2 Three resistors of $2\,\Omega$, $4\,\Omega$ and $6\,\Omega$ are connected as part of a circuit. **Calculate** the equivalent resistance (to the nearest whole number) if they are connected in

- **a** series (1 mark)
- **b** parallel. (2 marks)

3 Three resistors of 3 Ω, 6 Ω and 9 Ω are connected in series across a 12 V battery. **Calculate** the
   a equivalent resistance of the combination (1 mark)
   b current passing through the resistors (1 mark)
   c potential difference across each resistor. (3 marks)

4 Three resistors of 20 Ω, 40 Ω and 50 Ω are connected in parallel across a 12 V battery. **Calculate** (2 s.f.) the
   a equivalent resistance of the combination (2 marks)
   b current passing through each resistor. (3 marks)

Analytical processes

5 Two equal resistors are connected in parallel and give a combined resistance of 5 Ω. **Determine** the resistance of each of the two resistors (2 s.f.). (2 marks)

6 A 100 Ω resistor is connected in parallel with an unknown resistor to give a combined resistance of 66.7 Ω. **Determine** the value of the unknown resistor (2 s.f.). (3 marks)

Knowledge utilisation

7 **Propose** whether the combined resistance of two resistors in parallel can ever be greater than that of either of the two resistors. **Justify** your reasoning. (3 marks)

Lesson 8.2
Kirchhoff's circuit laws

Key ideas

→ Kirchhoff's current law expresses the idea of conservation of charge at a node in a circuit.

→ Kirchhoff's voltage law expresses the idea of conservation of energy in a circuit loop.

→ The electrical potentials and currents in a circuit can be predicted using a combination of Kirchhoff's laws and Ohm's law.

Learning intentions and success criteria

How do circuits work?

Charge leaving a battery is the same as the charge returning to it. If there is nothing else hooked up to the battery, then the charge just goes around the circuit. Also, the current leaving a battery is the same as the current returning – otherwise the charges would pile up somewhere or there would be gaps if some of the charges raced ahead.

Ohm's law ($I \propto V$) is one of the most important laws in physics. In Lesson 8.1, we saw that Ohm's law allowed us to see how voltage and current were related in

FIGURE 1 German physicist Gustav Robert Kirchhoff

a resistor. However, this law didn't cover complicated situations such as series and parallel combinations.

The next two circuit laws were formulated by German physicist Gustav Robert Kirchhoff (1824–1887) while studying electrical networks.

What is Kirchhoff's current law?

The first of these laws is based on the law of conservation of electric charge and applies to junction points in a circuit – points where a wire is joined to two other wires to form a junction of three wires. These points are sometimes called "nodes" (Latin for "knot"). The law is usually referred to as **Kirchhoff's current law** (KCL) and is represented in Figure 2.

Kirchhoff's current law
electric charge is conserved at all points in an electrical circuit; e.g. at any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node

If you apply the convention that currents coming in to a junction are positive and those leaving a junction are negative, the sum will cancel and equal zero.

For example, in the circuit in Figure 3, if we let I_1 (in) be positive, then I_2 and I_3 will be negative. This can be written in the following way, with the Greek letter sigma (Σ), for sum, meaning to add up all that follows: $\Sigma I = +I_1 + (-I_2) + (-I_3) = 0$. This can be summarised as $\Sigma I = 0$. This can also be written in terms of magnitudes: $I_{in} = I_{out}$.

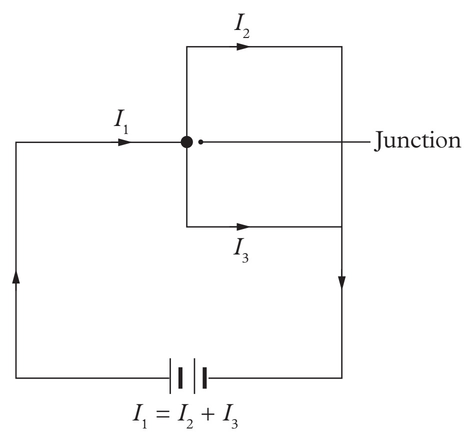


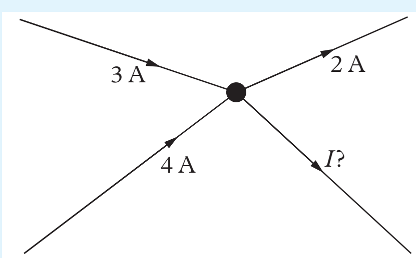
FIGURE 2 Kirchhoff's current law

Worked example 8.2A

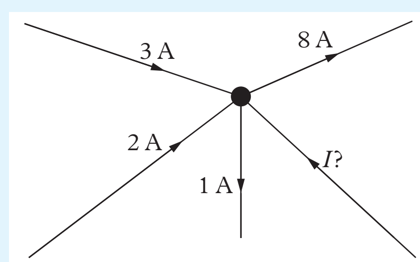
Calculating current using Kirchhoff's current law

Calculate the value of I for the following circuits containing junctions. (2 marks each)

a



b



Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: For part **a**, identify the appropriate formula and gather any data that you require. This is a Kirchhoff's current law question.	**a** $I_t = I_1 + I_2 + \ldots + I_n$ $I_{in} = I_{out}$ $I_{in} = 3 + 4$ $I_{out} = 2 + I$ (1 mark)

Think	Do
Step 3: Substitute the known values into the formula and solve the equation.	$I_{in} = 3 + 4 = 7$ $I_{out} = 2 + I$ By KCL: $I_{in} = I_{out}$ $7 = 2 + I_{out}$ $I_{out} = 7 - 2 = 5$
Step 4: Finalise your answer and make sure you have included the correct units. Current (I) is expressed in ampere (A).	$I_{out} = 5\,\text{A}$ (out) (1 mark)
Step 5: For part **b**, identify the appropriate formula and gather any data that you require. This is a Kirchhoff's current law question.	**b** $I_t = I_1 + I_2 + \ldots + I_n$ $I_{in} = I_{out}$ $I_{in} = 3 + 2 + I$ $I_{out} = 8 + 1$ (1 mark)
Step 6: Substitute the known values into the formula and solve the equation.	$I_{in} = 3 + 2 + I$ $I_{out} = 8 + 1 = 9$ By KCL: $I_{in} = I_{out}$ $5 + I_{in} = 9$ $I_{in} = 9 - 5 = 4$
Step 7: Finalise your answer and make sure you have included the correct units. Current (I) is expressed in ampere (A).	$I_{in} = 4\,\text{A}$ (in) (1 mark)

Your turn

A current of 10.0 A enters a parallel combination of three resistors. The currents in two of the branches are 2.5 A and 3.5 A respectively. Use KCL to **calculate** the current in the third branch. (3 marks)

What is Kirchhoff's voltage law?

The second law is called Kirchhoff's voltage law (KVL), which can be applied to complete closed-circuit paths or loops.

Consider the circuits in Figure 3. Figure 3A shows a simple circuit with a battery as the source of potential, V_t, and three resistors R_1, R_2 and R_3 with corresponding potential differences V_1, V_2 and V_3. Figure 3B gives specific values for voltage losses through each resistor.

You will notice that the voltage gain, V_t (gain), at the battery is equal in magnitude to the sum of voltage losses, V_t (loss), around the circuit through the three resistors R_1, R_2 and R_3. That is, the total voltage gain from the battery, V_t (gain), is 12 V, and the total voltage loss, V_t (loss), in the resistors is $V_1 + V_2 + V_3$ or $2 + 4 + 6 = 12\,\text{V}$.

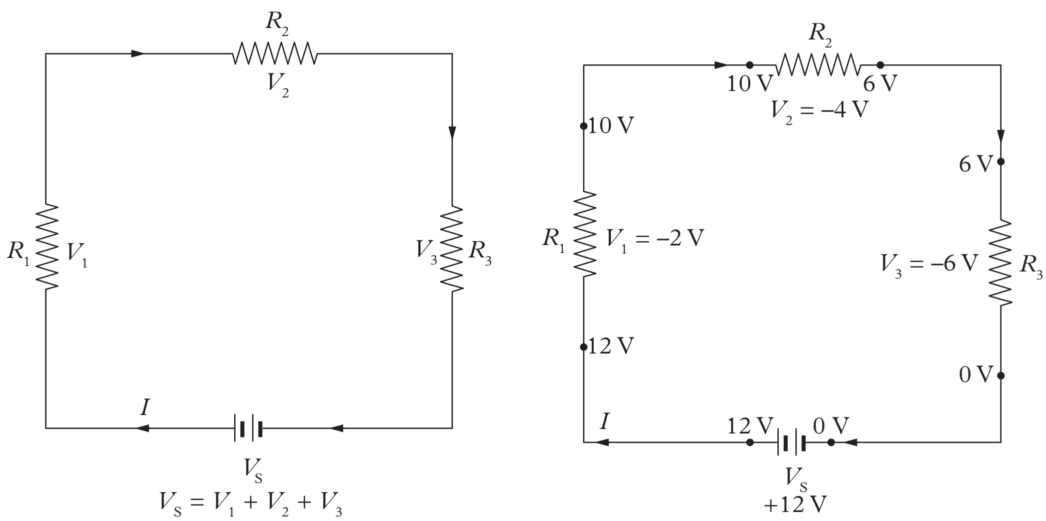


FIGURE 3 Kirchhoff's voltage law

Kirchhoff's voltage law (KVL) states that the energy inputs in a circuit equal the sum of energy outputs from loads in the circuit such that the directed sum of the electrical potential differences around any closed network is zero.

This is really a statement about conservation of energy. It says that for a complete circuit (or loop) the total voltage gain of the source, V_t (gain), will equal the total voltage loss, V_t (loss). We have a convention that voltage gain is positive, so V_t (gain) is positive, and the total potential losses, V_t (loss), is negative.

- Total voltage gain from cell or battery: V_t (gain) is positive.
- Total voltage loss due to resistors, bulbs, etc.: V_t (loss) is negative.
- As gains and losses are equal in magnitude and opposite in sign:

$$V_t\text{(gain)} + V_t\text{(loss)} = 0$$
$$V_t\text{(gain)} + (V_1 + V_2 + V_3)\text{(loss)} = 0$$
$$+12 + (-2) + (-4) + (-6) = 0$$
$$\Sigma V = 0$$

This, then, is Kirchhoff's voltage law in equation form.

Kirchhoff's voltage law
the energy inputs in a circuit equal the sum of energy outputs from loads in the circuit such that the directed sum of the electrical potential differences around any closed network is zero; $\Sigma V = 0$

Worked example 8.2B

Applying Kirchhoff's laws to a complex circuit

For the circuit in Figure 4, **calculate**

a V_A and V_B (2 marks)
b total resistance, R_t (1 mark)
c circuit current, I (1 mark)
d $\Delta V_{3\,\Omega}$ and $\Delta V_{1\,\Omega}$ (2 marks)
e V_C. (1 mark)

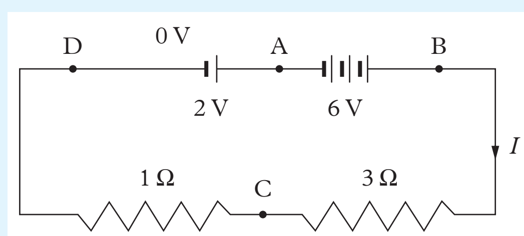


FIGURE 4 Diagram for a complex circuit

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.

Think	Do
Step 2: Identify the appropriate formula. This is a complex circuit requiring KVL.	$V_t = V_1 + V_2 + \ldots + V_n$
Step 3: For part **a**, substitute the values and calculate the total gains at point A, and then the total gains at point B.	**a** $V_A = 0 + 2$ $= 2\,V$ (1 mark) $V_B = 2 + 6$ $= 8\,V$ (1 mark) (This is the total potential difference or voltage of the two cells: V_t.)
Step 4: For part **b**, calculate total resistance for resistors in series.	**b** R_t (in series) $= 1 + 3 = 4\,\Omega$ (1 mark)
Step 5: For part **c**, the full circuit current passes through both resistors one after the other, so we use the total (equivalent) resistance in Ohm's law.	**c** $I = \frac{V_t}{R_t}$ $= \frac{8}{4}$ $= 2\,A$ (1 mark)
Step 6: For part **d**, we apply Ohm's law to each of the resistors in series ($3\,\Omega$ and $1\,\Omega$).	**d** $\Delta V_{3\Omega} = I \times 3$ $= 2 \times 3$ $= 6\,V$ (1 mark) $\Delta V_{1\Omega} = I \times 1$ $= 2 \times 1$ $= 2\,V$ (1 mark)
Step 7: For part **e**, the potential at C is equal to the potential at B, minus the potential difference (p.d.) across the $3\,\Omega$ resistor.	**e** $V_C = V_t - \Delta V_{3\Omega}$ $= 8 - 6$ $= 2\,V$ (1 mark)
Step 8: Cross-check to see if the potential difference across the $1\,\Omega$ resistor takes the voltage back to $0\,V$ (which is what it should be back at the negative terminal of the cell; that is, at point D). Note: the voltage gain across the two cells ($2 + 6 = 8\,V$) equals the voltage loss (drop) across the two resistors ($6 + 2 = 8\,V$). This is Kirchhoff's voltage law in action again.	$V_C - 2 = 2 - 2 = 0\,V$

Your turn

The circuit in Figure 5 was set up using two resistors, a $2\,V$ cell and a $6\,V$ battery.

Calculate (2 s.f.)

a V_X and V_Y (2 marks)

b total resistance, R_t (1 mark)

c circuit current, I (1 mark)

d $\Delta V_{9\Omega}$ and $\Delta V_{6\Omega}$ (2 marks)

e V_Z. (1 mark)

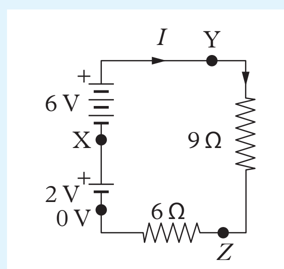


FIGURE 5 Circuit diagram for a complex circuit

Study tip

Potential differences are assigned + (for gains, such as the battery) and − for losses such as the resistors. When the + and − signs are included, the algebraic sum is zero.

How do you use the circuit laws in combination?

In the analysis of most DC circuits, the three laws – Ohm's law, KCL and KVL – are used in combination.

Worked example 8.2C

Combining KCL and KVL calculations

Figure 6 shows a circuit.

Use circuit laws to **calculate** the readings on

a ammeter A_1 (3 marks)

b ammeter A_2 (2 marks)

c voltmeter V. (1 mark)

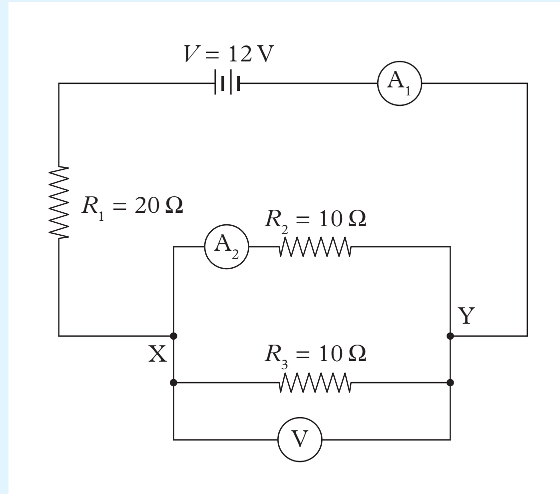
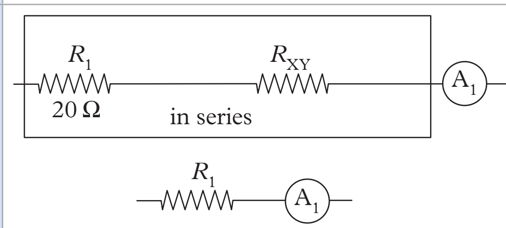


FIGURE 6 Circuit diagram for a complex circuit

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: For part **a**, look at the circuit – if we can work out the total resistance, we can work out the total current. To work out the total resistance, we must find: • the equivalent resistance of the parallel pair of resistors between X and Y; call this R_{XY} • the total equivalent resistance (R_t) in the circuit • the total current flowing from the battery, A_1.	
Step 3**:** Substitute values for the parallel pair R_2 and R_3.	**a** $\frac{1}{R_{XY}} = \frac{1}{R_2} + \frac{1}{R_3}$ $\frac{1}{R_{XY}} = \frac{1}{10} + \frac{1}{10}$ $R_{XY} = 5\,\Omega$ (1 mark)
Step 4: Calculate total resistance. Note: the circuit could now be redrawn with only this single equivalent resistor.	$R_t = R_1 + R_{XY}$ $= 20 + 5$ $= 25\,\Omega$ (1 mark)
Step 5. Calculate total current flowing from battery.	$I_t = \frac{V}{R_t}$ $= \frac{12}{25}$ $= 0.48$ A $= 480$ mA (1 mark) This is the reading on ammeter A_1.
Step 6: For part **b**, to calculate the current in meter A_2, we need to know: • the voltage drop across the equivalent resistance XY, V_{XY} • the current flowing through resistor R_2 measured by meter A_2.	

Think	Do
Step 7: Use Kirchhoff's voltage law to calculate V_{XY}.	**b** $V = V_{XY} + I_t \times R_1$ $V_{XY} = V - (I_t \times R_1)$ $= 12 - (480 \times 10^{-3} \times 20)$ $= 12 - 9.6$ $= 2.4\,V$ (1 mark) Notice that the sum of voltages around the circuit is 2.4 V + 9.6 V, and 12 V across R_1.
Step 8: Calculate the current flowing through the resistor R_2.	$V_{XY} = I_2 \times R_2$ $2.4 = I_2 \times 10$ $I_2 = 0.24\,A$ $= 240\,mA$ (1 mark) This is the reading on ammeter A_2.
Step 9: For part **c**, we have already calculated the voltage on the meter V, in part **b**.	**c** The voltage on V is 2.4 V. (1 mark)

Your turn

Figure 7 shows a circuit containing a simple network of three resistors connected to a DC battery of 6 V.

Use circuit laws to **calculate** the currents I_1, I_2, and I_3. (6 marks)

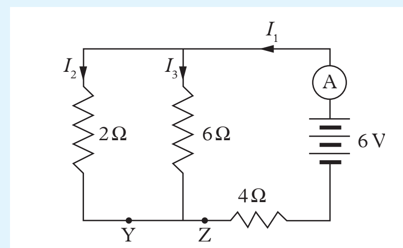


FIGURE 7 Circuit diagram

Check your learning 8.2

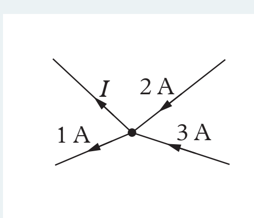
Check your learning 8.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Recall** Kirchhoff's current law and Kirchhoff's voltage law. (2 marks)

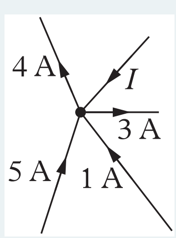
2 **Calculate** the current I in each circuit.

a



(2 marks)

b



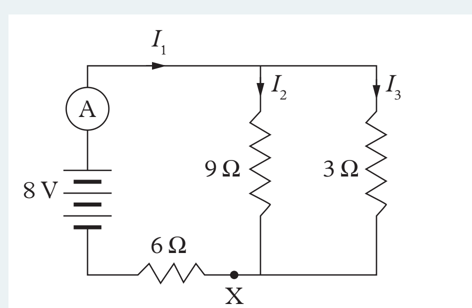
(2 marks)

3 For the circuit shown, **calculate** (2 s.f.)

a the total resistance for the whole circuit (3 marks)

b currents I_1, I_2 and I_3 (6 marks)

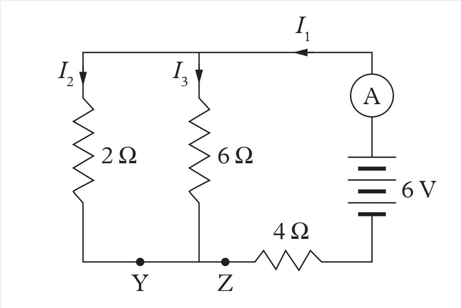
c the voltage at point X. (2 marks)



4 For the circuit shown, **calculate**

a currents I_1, I_2 and I_3 (6 marks)

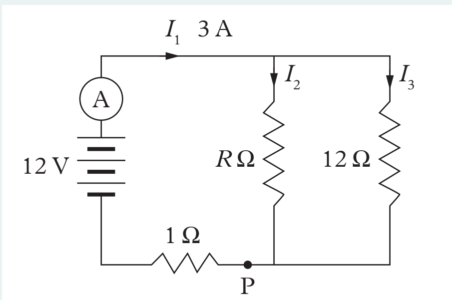
b V_Y and V_Z. (2 marks)



5 For the circuit shown, **calculate** (1 s.f.) the

a value of resistor R (4 marks)

b voltage at point P. (2 marks)



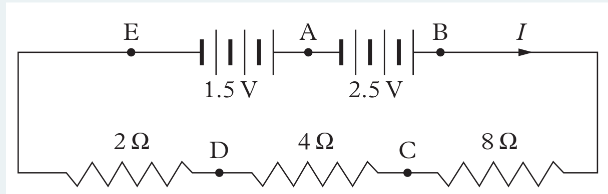
6 The circuit shown has three resistors in series. **Calculate**

A V_A and V_B (2 marks)

b the current, I (3 marks)

c V_C and V_D (6 marks)

d the potential difference across the 2 Ω resistor. (2 marks)



Practical

Lesson 8.3

Investigating series and parallel circuits

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Lesson 8.4
Circuit analysis

Key ideas

→ Circuit diagrams can be expressed by using symbols for resistor, voltmeter, ammeter, cell, battery, switch and bulb.

→ Problems involving electrical potential difference, electric current, resistance in series and parallel circuits can be solved by using Kirchhoff's laws and Ohm's law.

→ Power dissipation in a circuit can be calculated by use of several interrelated formulas.

Learning intentions and success criteria

What are circuit diagram symbols?

We have already used several common electrical circuit symbols. Electrical circuit diagrams are the standard method of representing actual circuits in practice. Some standard symbols used for electrical circuits are shown in Figure 1. Note that a rectangular style is used when drawing electrical circuit diagrams for ease of reading the connections between various components.

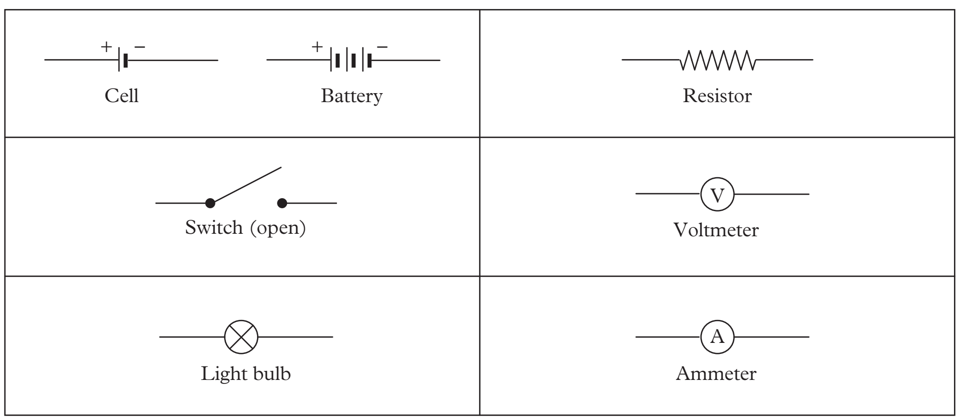


FIGURE 1 Circuit diagram symbols

How do you perform circuit analysis?

This lesson will analyse a more complex electrical circuit, making use of all the circuit laws, electric meters and methods of connection discussed so far. You must be able to read unfamiliar electrical circuits and carry out the necessary calculations to solve for unknown or required circuit component values. You must also be able to use the laws of circuit behaviour to predict voltages and currents at any point in a circuit.

Worked example 8.4A illustrates the general steps that might be followed, but remember there is usually more than one way to the solution.

Worked example 8.4A

Calculations using Kirchhoff's laws on a complex circuit

Consider the circuit in Figure 2.
The battery consists of three cells, each of 1.5 V.

Calculate (2 s.f.) the

a circuit current, I_c, flowing from the battery (3 marks)

b voltage reading on V_1 and V_2 (2 marks)

c current reading on ammeters A_1 and A_2 (2 marks)

d battery EMF. (1 mark)

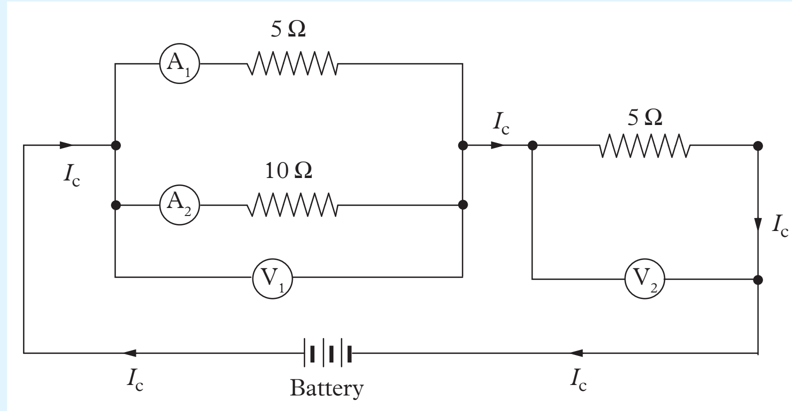
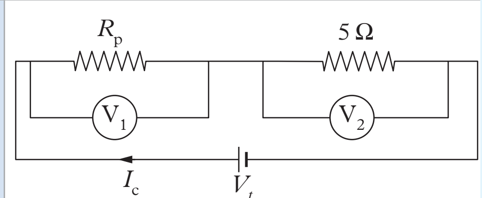
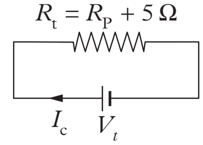


FIGURE 2 Circuit diagram

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. Each question part has a different mark allocation. This is a clue about the number of steps required to find an answer.
Step 2: Identify this as a complex circuit needing both KCL and KVL. Keep in mind the following: • The battery has three cells, each of 1.5 V, therefore EMF or V_t = 4.5 V. • The 10 Ω and 5 Ω resistors are in parallel, and this combination is in series with the 5 Ω resistor. • The current readings for $A_1 + A_2$ will equal I_c (Kirchhoff's current law). • The voltages across the 5 Ω and 10 Ω resistors will both be equal to voltage V_1. • The sum of voltages $V_1 + V_2$ will equal the EMF, 4.5 V (Kirchhoff's voltage law).	
Step 3: For part **a**, calculate equivalent resistance of parallel combination, R_p.	**a** $\frac{1}{R_p} = \frac{1}{5} + \frac{1}{10}$ $= \frac{3}{10}$ $= 3.3\,\Omega$ (1 mark)
Step 4: Calculate equivalent circuit total resistance in series with battery, R_t.	$R_t = R_p + 5$ $= 3.3 + 5$ $= 8.3\,\Omega$ $R_t = R_p + 5\,\Omega$  (1 mark)
Step 5: Calculate total current flow, I_c, using Ohm's law. Show the result to 2 s.f.	$I_c = \frac{V}{R_t}$ $= \frac{3.5}{8.3}$ $= 0.54$ A (1 mark)

Think	Do
Step 6: For part **b**, consider only the 5 Ω resistor. Apply Ohm's law to find the voltage V_2.	**b** $V_2 = I_c \times R$ $= 0.54 \times 5$ $= 2.7$ V (1 mark)
Step 7: Calculate the voltage V_1, using the KVL (loop) law. Show result to 2 s.f.	$V_1 + V_2 = V_t$ $V_1 + 2.7 = 4.5$ $V_1 = 1.8$ volts Thus, voltage $V_1 = 1.8$ V. (1 mark)
Step 8: For part **c**, voltage $V_1 = 1.8$ V is the voltage drop across each resistor of 5 Ω and 10 Ω in the parallel arm. Hence, calculate currents I_1 (in meter A_1) and I_2 (in meter A_2). Notice that the sum of the currents I_1 and I_2 equals the circuit current $I_c = 0.54$ A, as required by Kirchhoff's current law. It is also possible to redraw equivalent but simplified circuit diagrams at each step to further aid understanding of the analysis.	**c** $V_1 = I_1 \times 5$ $1.8 = I_1 \times 5$ $I_1 = 0.36$ A (1 mark) $V_1 = I_2 \times 10$ $1.8 = I_2 \times 10$ $I_2 = 0.18$ A (1 mark)
Step 9: For part **d**, state the answer from earlier calculations. Express the answer to 2 s.f.	**d** $V_t = 4.5$ V (as calculated earlier) (1 mark)

Your turn

Figure 3 shows a complex circuit with the resistances shown. **Calculate**

a the voltage across R_2 (3 marks)

b the current through it. (2 marks)

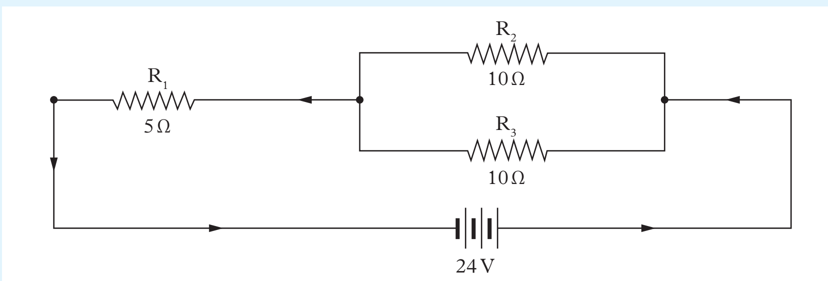


FIGURE 3 Circuit diagram

How is electrical energy distributed?

In modern society, electrical energy can be easily converted into a whole range of other energy forms, such as heat, light, mechanical energy and electromagnetic energy (radio and television).

Electrical energy is generated in several ways – from the simple DC level with devices such as cells and batteries, through to AC generators of different types. Domestic and industrial AC electricity supply is often generated by coal-, oil- or gas-burning power stations, but increasingly thermal, wind power and hydroelectric power stations are being used. Australia is also seeing a dramatic increase in electricity production by roof-mounted photovoltaic (PV) panels.

Once the electrical energy is produced, AC transformers can change the voltage so it may be efficiently distributed via conducting cables around the country to factories and homes.

Real-world physics

Electricity distribution in a national network

We need a reliable supply of electricity for our society to function in this digital age. Computers, smartphones and the internet may have changed the world, but none would be possible without a reliable supply of electricity.

In Australia, household electricity consumption varies over the year, with peaks in June and January. On top of this, population growth and increasing use of electricity per head of population means demand for electricity is increasing every year despite the increased contribution of electricity generated by solar panels.

Electricity suppliers must be able to meet peak demands, such as in the summer holidays when air-conditioner use adds to the demand. Electricity suppliers all have reserve capacity and can share electricity around the country through a national network. This helps them to manage power requirements for unusually hot or cold days in one part of the country.

Why use AC for power distribution?

All large power-distribution systems in Australia (and in most of the world) are alternating current (AC). Moreover, the power is transmitted at much higher voltages than the 240 V AC we use in homes and industry. Economies of scale make it cheaper to build a few very large electric power generation plants than to build numerous small ones. As a result, electricity must be transmitted over long distances and we want to ensure not too much energy is wasted on the way.

A power station produces electricity at 275 kV or 330 kV. This is sent along wires on huge steel towers until it is 'stepped down' at substations to 110 kV and then to 33 kV. It's sent at high voltage because that means low current, and as the loss of power by heating is given by $P(\text{loss}) = I^2R$, the lower the current, the better. At suburban substations, this is stepped down further to 11 kV and sent around the streets in wires on power poles or underground. For safety reasons, the voltage is then reduced from 11 kV to 415 V by small transformers attached to the poles in your street. The 415 V is distributed in the lower four wires outside your home. Electricity suppliers connect houses to two of these wires to give 230 V to your home.

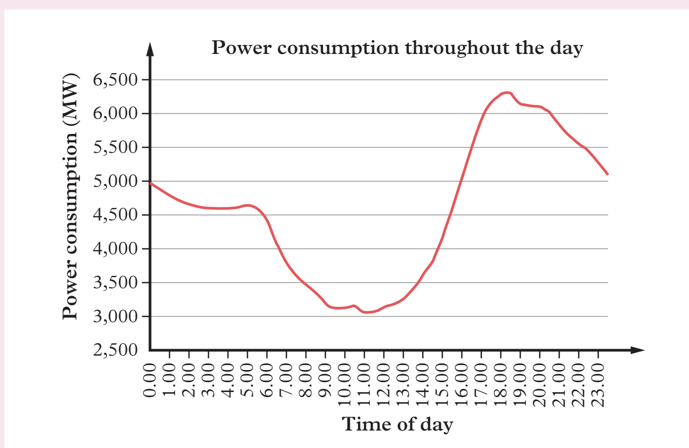


FIGURE 4 Energy uses in homes and businesses during the day

Apply your understanding

1 **Calculate** the current needed to transmit 100 MW of power at 275 kV (2 s.f.). (2 marks)

2 **Calculate** the power dissipated (lost) by the transmission lines if they have a resistance of 1.00 Ω (2 s.f.). The formula for power losses is $P_{\text{lost}} = I^2R$. (2 marks)

3 **Express** the power losses as a percentage of input power (100 MW) (2 s.f.). (2 marks)

Skill drill

Developing a research question

Science inquiry skills: Planning investigations (Lesson 1.4)

Consider the following claim:

"With the prices of grid-supplied electricity escalating, the only sensible solution for domestic electricity supply is rooftop solar panels."

Practise your skills

1 **Identify** and **define** four key terms in this claim. (4 marks)

2 **Create** a research question for this claim. (1 mark)

What is power dissipation?

When electric charge flows through a resistor, thermal heat is produced (Lesson 7.5). Electrical energy is being converted to thermal energy within the resistor, and this forms the basis of any electrical appliance designed to produce heat, such as radiators, electric stove elements, hot water systems, electric blankets and electric kettles. In incandescent light bulbs, this resistive heating of a filament wire produced light energy. (Incandescent light bulbs are no longer common in Australia.)

Electrical energy is often converted into mechanical energy – for example, in any appliance that contains an electric motor. We refer to this loss of electrical energy as **power dissipation**.

power dissipation
a measure of the rate at which energy is lost from an electrical system

Many domestic and industrial electric appliances state the power dissipation rating on their compliance plates. For example, a television rated 110 W will consume electrical energy at the rate of 110 joules per second. It is this energy usage that consumers must pay for as it is supplied by the electricity authority.

The common unit for electrical energy usage in domestic and industrial situations is the kilowatt hour (kW h). The electricity authority commonly refers to the kW h as a "unit" of electricity – it represents the amount of electrical energy used by a device rated at 1 kilowatt over a period of 1 hour.

Worked example 8.4B

Calculating power consumption of domestic appliances

a **Calculate** the power used by an electric drill operating from the normal 230 V AC supply and drawing an operating current of 1.60 A (2 s.f.). (2 marks)

b **Calculate** the monthly (30 day) energy by a television with a power rating of 110 W that is operating daily for 6.5 hours (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to find a numerical answer using mathematical processes and showing working. We must identify the appropriate formula and use it to find an answer.
Step 2: For part **a**, identify the appropriate formula and gather any data that you require. These questions are about power and energy.	**a** $P = VI$ $V = 230\,\text{V}$, $I = 1.60\,\text{A}$ (1 mark)
Step 3: Substitute the known values into the formula. Find the unknown.	$P = VI$ $= 230 \times 1.60$ $= 368$

Think	Do
Step 4: Finalise your answer and make sure you have included the correct units. The unit for electrical power is the watt (W).	$P = 370\,\text{W}$ (2 s.f.) (1 mark)
Step 5: For part **b**, identify the appropriate formula and gather any data that you require. These questions are about power and energy.	**b** $W = P \times t$ $P = 110\,\text{W}$, $t = 6.5\,\text{h}$
Step 6: Substitute the known values into the formula. Find the unknown. Convert hours per day to seconds to get daily usage in joules, based on the relationship $1\,\text{W} = 1\,\text{J}\,\text{s}^{-1}$.	$W = P \times t$ $= 110 \times 6.5 \times 60 \times 60$ (1 mark) $= 2.57 \times 10^6\,\text{J}$ in 1 day (1 mark)
Step 7: Finalise your answer and make sure you have included the correct units. The unit for energy is the joule (J). You are required to calculate the monthly energy used, so multiply your answer for 1 day by 30 for days in a month.	$W = 2.57 \times 10^6 \times 30$ $= 7.7 \times 10^7\,\text{J}$ in one month (1 mark)

Your turn

An electric kettle has a power consumption of 2 kW. It takes 2 minutes to boil 500 mL of water. **Calculate** the total energy consumption per day if the kettle is used to boil 500 mL of water 8 times in the day (2 s.f.). (1 mark)

Skill drill

Circuit analysis

Science inquiry skills: Processing and analysing data (Lesson 1.7)

A circuit was set up as shown in Figure 5. Measurements of the current at B and C were taken for a number of different input voltages. The results are shown in Table 1.

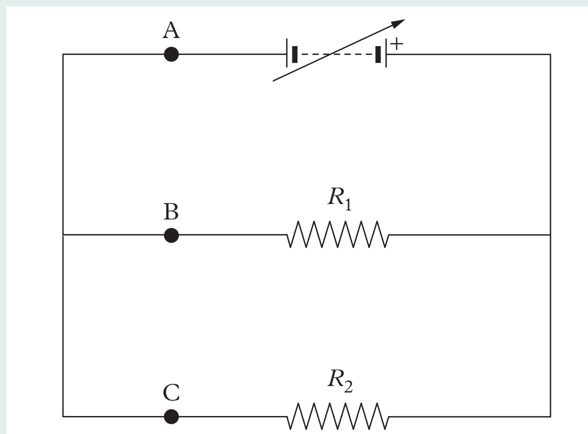


FIGURE 5 A simple circuit diagram

TABLE 1 Current readings for varied voltages

Voltage (±0.05 V)	Current at B (±0.1 A)			Current at C (±0.01 A)		
	Trial 1	**Trial 2**	**Trial 3**	**Trial 1**	**Trial 2**	**Trial 3**
2.0	0.97	1.01	1.02	0.48	0.49	0.52
4.0	1.99	2.03	2.01	0.94	0.98	1.00
6.0	3.02	2.99	2.99	1.47	1.50	1.41
8.0	3.97	3.99	4.02	2.0	1.96	1.92
10.0	5.03	5.01	4.99	2.60	2.45	2.55

Practise your skills

1 **Identify** whether the data presented in Table 1 is quantitative or qualitative. **Justify** your response. (2 marks)
2 **Identify** which column or row is the independent variable. **Justify** your response. (2 marks)
3 **Determine** whether the relationship between current at B and the voltage is linear. **Justify** your response. (2 marks)
4 **Calculate** the current reading expected at A when the input voltage is 6.0 V (2 s.f.). **Explain** how you have determined your answers and **justify** your solution. (3 marks)

Check your learning 8.4

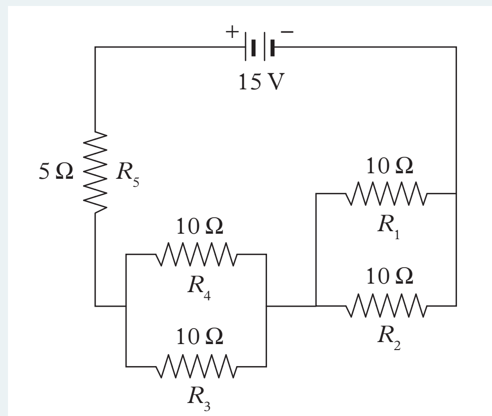
Check your learning 8.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Sketch** circuit diagram symbols for resistor, voltmeter, ammeter, cell, battery, switch and light bulb. (7 marks)
2 **Construct** circuit diagrams for
   a a 10 Ω resistor in series with a switch and a 1.5 V cell (2 marks)
   b 10 Ω and 20 Ω resistors in parallel with a 12 V cell. (2 marks)
3 You have three 10 Ω resistors and a 6 V battery.
   a **Sketch** all possible circuits in which current flows in all 3 resistors. (3 marks)
   b **Calculate** the total current out of the battery in each case. (6 marks)
4 **Calculate** the power (dissipation) rating of a light bulb operating at 230 V and 0.60 A (2 s.f.). (2 marks)
5 **Calculate** the resistance at normal operating conditions of the following appliances run from the 230 V AC mains (2 s.f.).
   a 50 W television (2 marks)
   b 1.0 kW hair dryer (2 marks)
   c 100 W light bulb (2 marks)

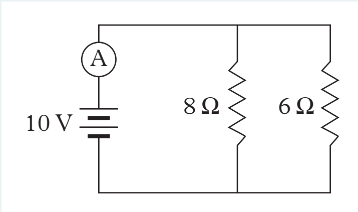
Analytical processes

6 **Consider** this electrical circuit.



Calculate the current flowing through each resistor and the voltage drop across each resistor using the laws of circuit analysis (2 s.f.). Fully describe your steps and redraw the appropriate equivalent circuits at each step. (8 marks)

7 A cell of voltage 10.0 V is connected with two resistors in parallel, as shown in the diagram. The position of the two resistors is now swapped. **Consider** what effect this will have on power consumption. Show your working. (3 marks)



8 **Determine** how many seconds it would take a kettle with a power rating of 1,800 W to produce 36,000 J (2 s.f.). (2 marks)

9 You want to use 200,000 J of electrical energy in a microwave oven of 900 W power rating.

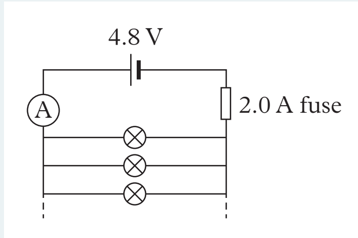
a **Determine** how many seconds (to the nearest whole number) the microwave oven should be turned on for. (2 marks)

b **Calculate** the current drawn from a 230 V supply (2 s.f.). (2 marks)

Knowledge utilisation

10 **Propose** the main way power is "dissipated" in an electric toaster. (1 mark)

11 In modelling a household lighting set-up, students set up the following circuit. The bulbs were all 10 Ω when operating.



a **Predict** the maximum number of bulbs that could be used in parallel before the fuse will blow (when current exceeds 2 A). (3 marks)

b If the bulbs were replaced with 20 Ω types, **calculate** how many could now be used before the fuse blows. (3 marks)

Practical

Lesson 8.5

Circuits for real-life purposes – using a fuse for protection

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

MODULE 8

Lesson 8.6
Review: Circuit analysis and design

Summary

8.1
- Resistors can be used to control current and divide voltage.
- Resistors can be arranged in series and parallel configurations for different purposes.

8.2
- Kirchhoff's current law expresses the idea of conservation of charge at a node in a circuit.
- Kirchhoff's voltage law expresses the idea of conservation of energy in a circuit loop.
- The electrical potentials and currents in a circuit can be predicted using a combination of Kirchhoff's laws and Ohm's law.

8.3
- Practical: Investigating series and parallel circuits

8.4
- Circuit diagrams can be expressed by using symbols for resistor, voltmeter, ammeter, cell, battery, switch and bulb.
- Problems involving electrical potential difference, electric current, resistance in series and parallel circuits can be solved by using Kirchhoff's laws and Ohm's law.
- Power dissipation in a circuit can be calculated by use of several interrelated formulas.

8.5
- Practical: Circuits for real-life purposes – using a fuse for protection

Key formulas

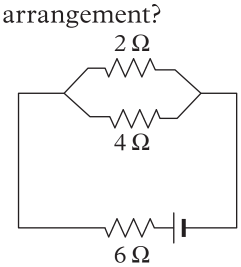
Kirchhoff's voltage law	$V_t = V_1 + V_2 + \ldots + V_n$
Kirchhoff's current law	$I_t = I_1 + I_2 + \ldots + I_n$
Overall resistance (resistors in series)	$R_t = R_1 + R_2 + \ldots + R_n$
Overall resistance (resistors in parallel)	$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$

Review questions 8.6A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 For the circuit shown, which statement best describes the arrangement?



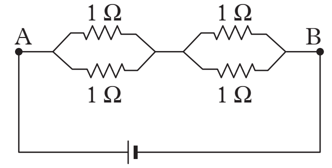
A The 2 Ω , 4 Ω and 6 Ω resistors are in series.

B The 2 Ω and 4 Ω resistors are in parallel and the combination is in parallel with the 6 Ω resistor.

C The 2 Ω , 4 Ω and 6 Ω resistors are in parallel.

D The 2 Ω and 4 Ω resistors are in parallel and 6 Ω resistor is in series with them.

2 Consider the circuit.



The resistance across AB in this circuit is

A 1 Ω. **B** 2 Ω.
C 4 Ω. **D** 5 Ω.

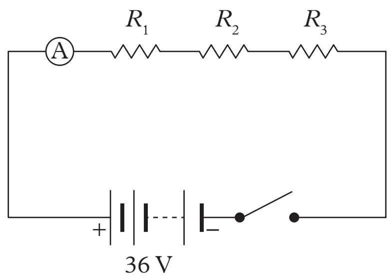
3 Identify the correct description of Kirchhoff's current law.

A At any node in a circuit, the sum of the currents flowing into that node is equal to the sum of the currents flowing out of that node.
B At any node in a circuit, the currents flowing into that node are equally divided among the currents flowing out of that node.
C The energy inputs in a circuit equal the sum of energy outputs from loads in the circuit.
D The current flowing in a circuit is proportional to the voltage.

4 When current I flows through resistance R for time t, the electrical energy transferred is given by

A IRt. **B** I^2Rt.
C IR^2. **D** $\frac{I^2R}{t}$.

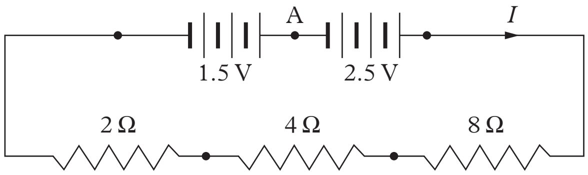
5 Three resistors ($R_1 = 3\,\Omega$, $R_2 = 6\,\Omega$, and $R_3 = 9\,\Omega$) are connected in series to each other and to a 36 V battery, as shown.



The ammeter reading after the switch is closed is

A 6 A. **B** 5 A.
C 4 A. **D** 2 A.

6 Consider the circuit shown. Identify the correct statement.



A The total resistance is 1.1 Ω.
B The total current is 0.29 A.
C The voltage drop across the 8 Ω resistor is 4.0 V.
D The current flowing at A is 0.18 A.

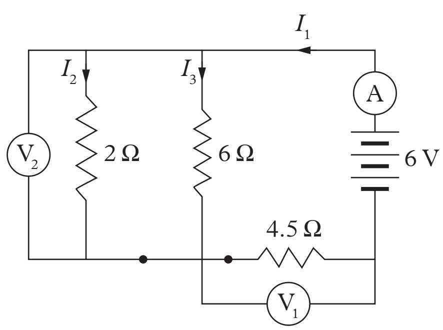
7 A decorative light fitting in a home has five small light bulbs. The bulbs are rated at 230 V, 25 W. If the light operates for 4 hours per night, the daily energy consumption is

A 0.500 kJ. **B** 260 kJ.
C 1,800 kJ. **D** 16,560 kJ.

8 The homeowner replaces the light bulbs described in question **7** with lower wattage bulbs that are rated at 230 V, 5.5 W. How much energy will this conversion save in a month (30 days)?

A 538 kJ
B 1,404 kJ
C 11,800 kJ
D 42,120 kJ

9 Which of the following is a correct analysis of the circuit shown?



A $R_t = 12.5\,\Omega$, voltage at $V_1 = 4.5\,V$, $I_1 = 0.48\,A$, $I_2 = I_3 = 0.24\,A$
B $R_t = 4.57\,\Omega$, voltage at V_1 and at $V_2 = 6\,V$, $I_1 = 1.31\,A$, $I_2 = 0.33\,A$
C $R_t = 6\,\Omega$, $I_1 = 1\,A$, $I_2 = 0.75\,A$, voltage at $V_2 = 1.5\,V$
D $R_t = 1.125\,\Omega$, $I_1 = 5.33\,A$, $I_2 = 4\,A$, voltage at $V_2 = 4\,V$

Review questions 8.6B Short response

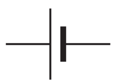
Review questions: Complete these questions online or in your workbook.

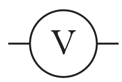
Retrieval and comprehension

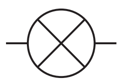
10 **Identify** these circuit symbols. (6 marks)

a 

b 

c 

d 

e 

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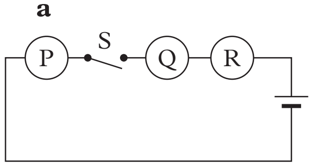
11 **Identify** the characteristic that enables you to differentiate between a series circuit and a parallel circuit. (1 mark)

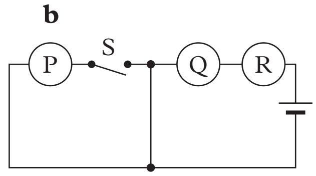
12 **Describe** total battery voltage and power dissipation as it applies to a circuit with two cells in series and two resistors in series. (3 marks)

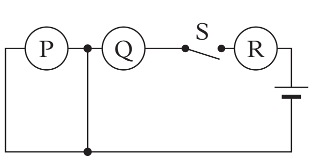
13 **Explain** why birds can safely touch overhead power cables but humans standing on the ground cannot. (2 marks)

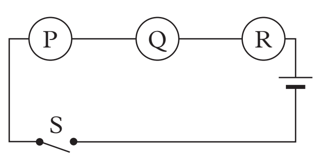
14 **Describe** Kirchhoff's current law and Kirchhoff's voltage law without using a formula. (2 marks)

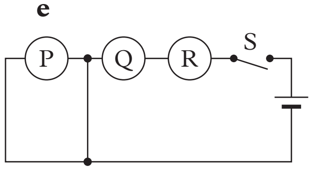
15 **Identify** which of the circuits shown, with the switch open, would light lamps Q and R but not lamp P, and **explain** your reasoning. (3 marks)

a 

b 

c 

d 

e 

16 An electric jug is marked 240 V, 1.6 kW. **Calculate** the current drawn by the heating element when the kettle is in normal use. (2 marks)

17 **Calculate** the energy gained by a charge of 18 C when it passes through a cell of 12 V. (2 marks)

18 A 10 Ω and a 20 Ω resistor are connected in parallel. **Explain** whether the following are the same in each resistor.

a Current (2 marks)

b Resistance (2 marks)

c Potential difference (2 marks)

d Power (2 marks)

19 Two 10 Ω resistors are connected in series. **Explain** whether the following are the same in each resistor.

a Current (2 marks)

b Resistance (2 marks)

c Potential difference (2 marks)

d Power dissipated (2 marks)

20 A10 Ω and a 20 Ω resistor are connected in series. **Explain** whether the following are the same in each resistor.

a Current (2 marks)

b Resistance (2 marks)

c Potential difference (2 marks)

d Power dissipated (2 marks)

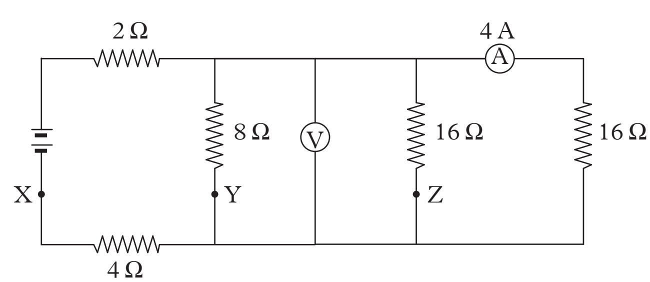
21 **Calculate** the largest number of 100 W lamps (whole number) connected in parallel that can safely be run from a 230 V supply without exceeding a current of 5 A. (3 marks)

22 An automatic washing machine is labelled 30 V, 960 W. **Calculate** the

a operating current during normal use (2 marks)

b operating resistance. (2 marks)

23 Consider the circuit.



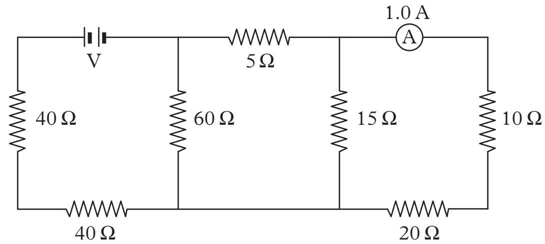
Calculate the

a battery voltage (to the nearest whole number) (7 marks)

b circuit current at the points labelled X, Y and Z (3 marks)

c reading on the voltmeter, V. (1 mark)

24 Consider the complex circuit in the diagram.



Calculate, to the nearest whole number, the

a total circuit resistance (3 marks)

b voltage drop across the 60 Ω resistor. (3 marks)

Analytical processes

25 **Calculate** how much energy would be produced by a 12 V heater that drew a current of 4 A for 2 minutes (to the nearest whole number). (2 marks)

26 A car battery has a voltage of 12 V. The car lights at the sides and rear require 12 V each to operate and the two interior lights require 6 V each. **Determine** whether the lights are connected in series or in parallel. (3 marks)

27 The headlights on a car operate typically at 60 W and the parking lights operate typically at 5 W. Assume that a particular car has two main headlights and four parking lights, and that the car's battery can supply a total of 216,000 J before it goes 'flat'. **Determine** the length of time in minutes it will take to discharge the battery if the lights are left on (2 s.f.). (3 marks)

28 A particular household circuit is designed to take a safe maximum current of 8 A. **Determine** whether the following devices can run safely on the circuit (separately) if the power supply is 230 V.

a 100 W television (2 marks)

b 800 W electric iron (2 marks)

c 2.2 kW kettle (2 marks)

Knowledge utilisation

29 You are conducting a circuit analysis. **Decide** which of Kirchhoff's laws would be applied if there were two resistors

a in series (1 mark)

b in parallel. (1 mark)

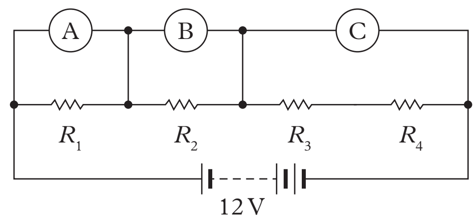
30 Assume you have only five 12 Ω resistors.

a **Devise** a circuit that would let you connect some or all of the resistors to produce an effective total resistance of 4 Ω. (3 marks)

b **Decide** the maximum and minimum resistance you could have using any or all of the resistors. (2 marks)

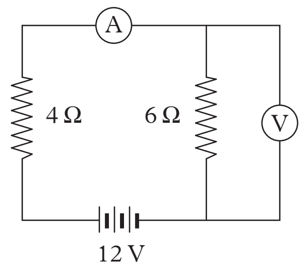
31 **Devise** and **sketch** a circuit diagram that shows how you might measure the operating resistance of a single light bulb using a battery, ammeter and/or voltmeter. (4 marks)

32 The four resistors in the circuit are all equal in value. Assume the connecting wires in the circuit have negligible resistance. **Predict** what you would expect voltmeters A, B and C to read. (4 marks)

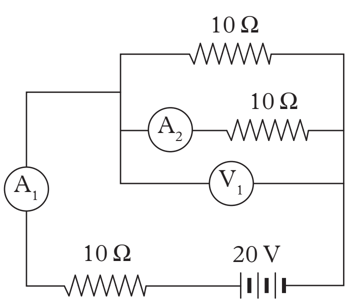


33 For each circuit, **determine** the readings on all voltmeters and ammeters as well as the total equivalent resistance of the circuit.

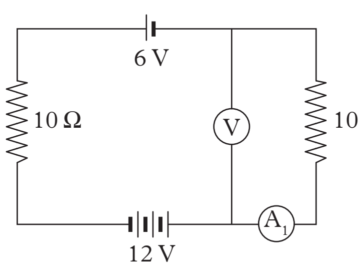
a (4 marks)



b (7 marks)



c (6 marks)



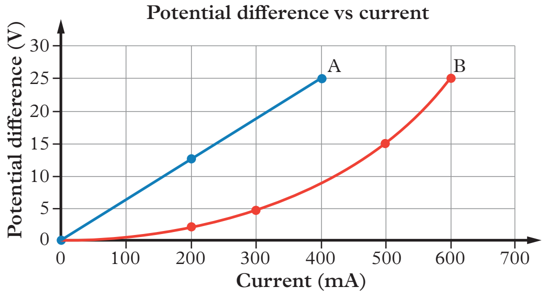
34 The graph of potential difference versus current for two different electrical devices, A and B, is shown.

a **Assess** and explain whether either device is an ohmic resistor. (4 marks)

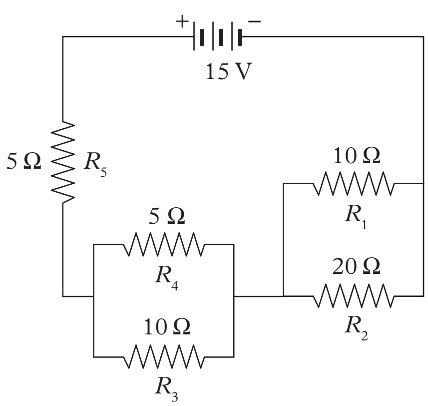
b **Determine** the total potential difference across A and B, if A and B are connected in series and a current of 200 mA passes through them (2 s.f.). (2 marks)

c If A and B are connected in parallel, **determine** what potential difference across them would produce a current in A that is half the current in B (2 s.f.). (2 marks)

d **Calculate** the resistance of device A and compare this to the resistance of B with a voltage of 15 V applied (2 s.f.). (5 marks)



Use the following image to answer questions 35 and 36.



35 **Calculate** the total resistance of the circuit to the nearest whole number. (3 marks)

36 **Determine** the voltage drop across R_1 and R_2. Show your working and give your answer to the nearest whole number. (3 marks)

37 Power boards are rated at 230 V, 8 A. A student has the following appliances plugged into a power board that has four outlets.

- A laptop charger, 100 W
- A phone charger, 100 W
- A desk lamp, 60 W

She has one outlet left. **Determine** whether it is safe to plug in a 1,200 W fan heater. Show your working. (3 marks)

38 An electric kettle is marked as 230 V, 2.2 kW. One litre of water requires 334.4 kJ of energy to come to the boil from 20°C. **Determine** how long the kettle will take to bring 2.0 L of water at 20°C to the boil, assuming all of the energy is converted to thermal energy in the water. Express your answer in minutes to one decimal place. (4 marks)

39 An AA battery operates at 1.5 V and has a capacity of at least 2,000 mA h. One amp-hour (A h) means that the battery can deliver a current of 1 A for 1 hour at the designated voltage, or equivalent (e.g. 2 A for 0.5 hour, or 0.5 A for 2 hours, or 0.1 A for 10 hours).

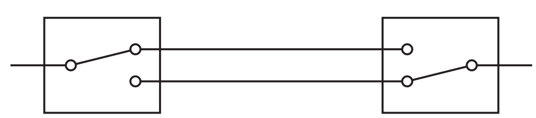
When several batteries are used in an appliance, they are usually connected in series, in which case the voltages add, and the capacity remains the same. Thus 2 × AA batteries will produce 2 × 1.5 V, or 3.0 V, with a capacity of 2,000 mA h.

A hiker's head torch operates on three AA batteries connected in series. The light bulb is rated at 1 W. The hiker is planning to hike through the night. They fit fresh batteries to the head torch at 6 p.m., just as it is getting dark.

Determine the current drawn by the light bulb, and hence **determine** if or when the hiker will need to replace the batteries. (Assume it is dark for 12 hours.) (5 marks)

40 Light bulbs have a life proportional to $\frac{1}{V^{14}}$ seconds, where V is the applied voltage. It is said that if you run a 240 V light bulb at 80% of its rated voltage, you will increase its lifetime by a factor of 23 times. **Determine** whether this is correct. Show your working. (4 marks)

41 **Design** and **draw** the diagram for a two-way model circuit that will operate a lamp from two different locations in a house – say, from upstairs and downstairs. The switches for the circuit are shown. (3 marks)



Data drill

Identifying ohmic resistance

A circuit was set up as shown in Figure 1. Measurements of the current at B and C were taken for a number of different input voltages. The results are shown in the table.

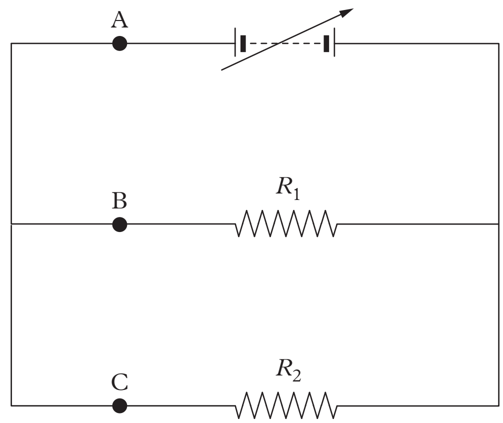


FIGURE 1 Circuit used to compare resistors

TABLE 1 Results from the experiment

Voltage (±0.05 V)	Current at B (±0.01 A)			Current at C (±0.01 A)		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
2.0	0.97	1.01	1.02	0.48	0.49	0.52
4.0	1.99	2.03	2.01	0.47	0.49	0.50
6.0	3.02	2.99	2.99	0.49	0.50	0.47
8.0	3.97	3.99	4.02	0.50	0.48	0.48
10.0	5.03	5.01	4.99	0.52	0.49	0.51

Apply understanding

1 **Identify** which resistor, R_1 or R_2, has the higher resistance at 10.0 V. (1 mark)

2 **Calculate** the average current reading (3 s.f.) and percentage uncertainty (2 s.f.) for each resistor when the input voltage is 10.0 V. (2 marks)

Analyse data

3 **Identify** whether each resistor is ohmic. **Explain** your reasoning. (2 marks)

4 **Compare** the resistance of R_1 and R_2. (1 mark)

Interpret evidence

5 **Draw a conclusion** about the effective resistance of the circuit in terms of the resistances of R_1 and R_2. Justify your conclusion. (4 marks)

Module 8 checklist: Circuit analysis and design

Quizlet: Revise key terms online to test your understanding

UNIT 1

Topic 3 review

Multiple choice

(1 mark each)

1 An ammeter displays a current of 2 A passing through a resistor in a circuit. The charge passing through it in a time of 2 minutes is

A 3.8×10^{-19} C.
B 1.0×10^{0} C.
C 4.0×10^{0} C.
D 2.4×10^{2} C.

2 A battery is supplying electric charge carriers at the rate of $15\,\mathrm{C\,s^{-1}}$. This value is equivalent to

A 15 J.
B 15 A.
C 15 V.
D 15 W.

3 As electrical charges move through a circuit, the energy available to them is measured in terms of the

A potential difference.
B resistance.
C velocity.
D current.

4 A bulb uses 60 J of energy for every 15 C of charge that passes through it. The voltage across the bulb is

A 0.25 V.
B 4 V.
C 15 V.
D 60 V.

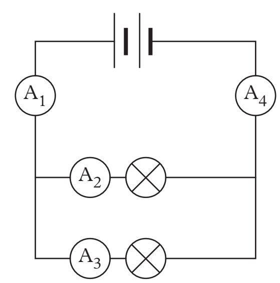
5 A 30 cm length of nichrome wire in a circuit is replaced with a similar nichrome wire that has twice the length and also twice the diameter. Which relationship describes how the new resistance (R_{new}) compares to the old resistance (R_{old})?

A $R_{new} = \frac{1}{2} \times R_{old}$
B $R_{new} = 1 \times R_{old}$
C $R_{new} = 2 \times R_{old}$
D $R_{new} = 4 \times R_{old}$

6 Select one of the following for which Ohm's law does not apply.

A DC circuits
B High currents
C Small resistors
D Semiconductors

7 An electrical circuit consists of two bulbs, each with a resistance of 4 Ω, placed as shown across a 24 V cell. The reading on meters A_1 to A_4 in ampere, in order, is



A 6, 3, 3, 6.
B 12, 6, 6, 12.
C 3, 1.5, 1.5, 3.
D 48, 24, 24, 48.

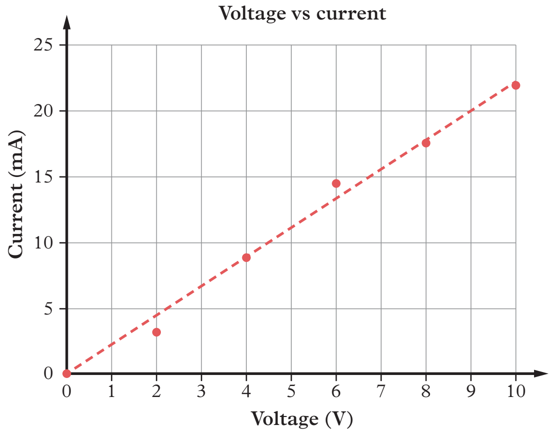
8 How many electrons are required to produce a charge of 10 μC?

A 3.2×10^{19}
B 6.2×10^{13}
C 6.2×10^{16}
D 6.2×10^{19}

9 A current of 2.0 mA flows through a fine piece of resistance wire when the potential difference across it is 8.0 V. The resistance of the wire is

A 0.0004 Ω.
B 0.016 Ω.
C 4000 Ω.
D 4 Ω.

10 Students conducted an experiment to investigate how current through a device changes as the voltage across it is increased. The graph shows their findings.



The device's resistance is

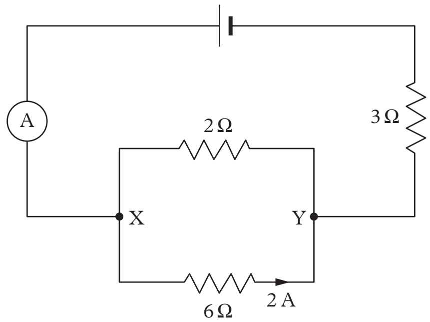
A $2.2 \times 10^{-3}\,\Omega$.

B $4.5 \times 10^{-1}\,\Omega$.

C $2.2 \times 10^{0}\,\Omega$.

D $4.5 \times 10^{2}\,\Omega$.

11 A circuit contains three resistors as shown. The current through the $6\,\Omega$ resistor is $2\,A$. Calculate the voltage of the cell.



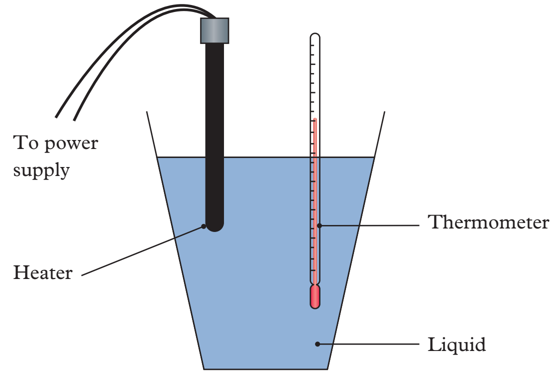
A 11 V

B 18 V

C 30 V

D 36 V

12 A water heater consists of a $40\,\Omega$ resistance coil connected to an 8.0 V electricity supply as shown in the diagram. What is the power output of the coil, and the energy delivered in 6.0 minutes?



A 0.2 W, 72 J

B 0.2 W, 1.2 J

C 1.6 W, 9.6 J

D 1.6 W, 576 J

13 The current in a resistor is measured on a digital scale as 2.00 A. Which of the following correctly identifies the absolute uncertainty and the percentage uncertainty in the current?

	Absolute uncertainty	Percentage uncertainty
A	±0.005 A	±0.25%
B	±0.01 A	±0.01%
C	±0.01 A	±0.5%
D	±0.02 A	±1%

14 The ratio of the work done per quantity of charge that flows through a circuit is the definition of

A power.

B charge.

C resistance.

D potential difference.

15 An 8.0 V battery is used to power a circuit with $2.4\,\Omega$ and $3.6\,\Omega$ resistors placed in series. Calculate the total power of the circuit.

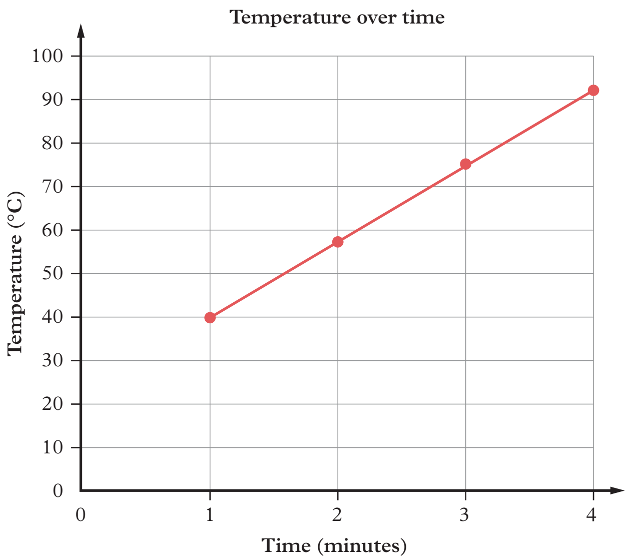
A 1.3 W

B 11 W

C 44 W

D 48 W

16 The graph shows the temperature of 500 g of water in an electric kettle being heated at a constant rate by the element in the bottom.



The kettle runs off a 240 V power supply. The current drawn by the kettle is

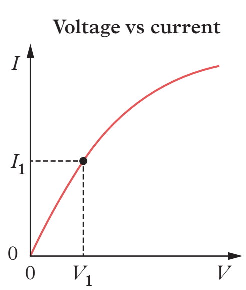
A 1.9 A.

B 2.5 A.

C 113 A.

D 150 A.

17 An Ohm's law experiment was conducted, and the results were plotted on a graph.



Which of the following shows the resistance of the component used in the experiment when the current $I = I_1$?

A The slope of the line from (0, 0) to the point (V_1, I_1)

B The slope of the line at the point V_1, I_1

C $\frac{V_1}{I_1}$

D $\frac{I_1}{V_1}$

18 Two wires P and Q are the same length, have the same circular cross-section and are made of the same metal. The diameter of P is twice the diameter of Q.

What is the ratio of R_Q to R_P?

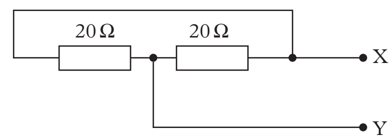
A 0.25

B 0.50

C 2.0

D 4.0

19 Two 20 Ω resistors are connected as shown in the figure.



What is the resistance between points X and Y?

A 0 Ω

B 10 Ω

C 20 Ω

D 40 Ω

20 A radioactive nuclide undergoing beta negative decay emits a burst of 2 μC of the particles. They pass through an electric field where they experience a potential difference of 2500 V. How much work is done on them by the field?

A 1.25×10^9 J

B 4×10^{-10} J

C 5×10^{-3} J

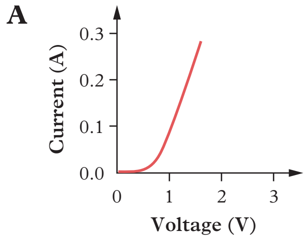
D 5×10^3 J

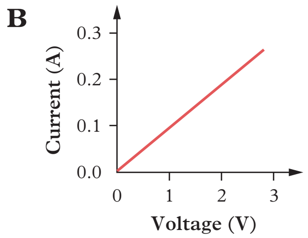
Short response

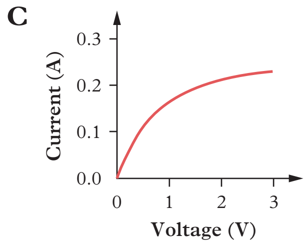
21 A direct current of 6.0 A is flowing through a circuit and passes into a branch that has two similar resistors in parallel. **Calculate** the number of electrons (in coulomb, C) that flow in each resistor in 10.0 seconds (2 s.f.). (2 marks)

22 **Explain** why charge separation produces an electrical potential difference, using a 1.5 V cell as an example. (3 marks)

23 Three circuit devices are being tested to see how the current through them varies with the voltage across them. The results are graphed.







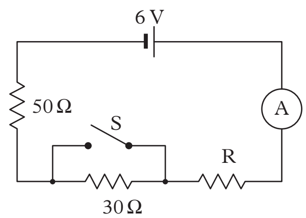
Propose, with reasons, which figure (A, B, or C) represents

a a lightbulb (1 mark)

b a semiconductor diode (1 mark)

c a length of nichrome wire. (1 mark)

24 A student set up the electrical circuit shown in the figure.



a The ammeter displays a reading of 0.0333 A. **Determine** the potential difference across the 30 Ω resistor (2 s.f.). (2 marks)

b **Calculate** the resistance of the resistor R (2 s.f.). (3 marks)

c **Determine** the total resistance and current of the circuit when switch S is closed (2 s.f.). (3 marks)

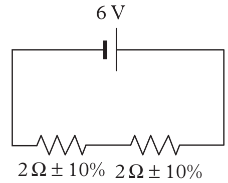
25 a **Recall** Ohm's law, using a 10 Ω resistor as an example. (1 mark)

b **Explain** whether Ohm's law can be tested with just one pair of voltage and current measurements of a resistor. (2 marks)

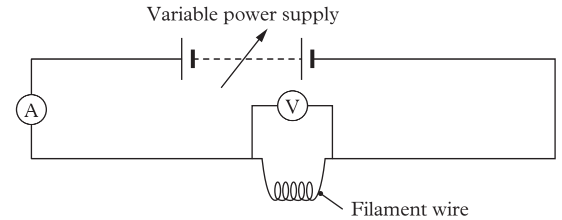
c A light bulb is being tested to see if it is ohmic or non-ohmic. The bulb heats up during the experiment. **Explain** whether this is a fair test to confirm if a device is ohmic or non-ohmic. (2 marks)

26 **Determine** the largest number of 100W lamps connected in parallel that can safely be run from a 230V supply with a 5A fuse. Note: the fuse will "blow" and disconnect the circuit if a current of 5A is exceeded. (Express your answer as a whole number). (3 marks)

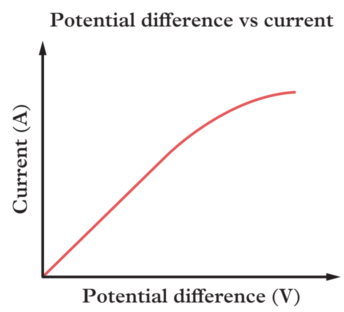
27 Two resistors, each with a resistance of 2 Ω ± 10%, are placed in series in a circuit across a battery with a voltage of 6.0 V, as shown. **Determine** the maximum and minimum power that could be dissipated in the circuit. (6 marks)



28 A bulb heats up when an electric current passes through the filament wire. The current was measured when different voltages were applied across the filament wire shown in the diagram.

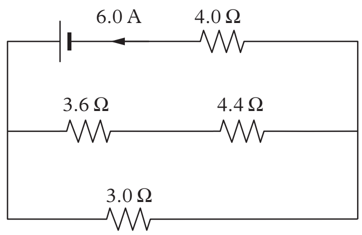


a The graph shows how the current through the filament wire changed as the potential difference across it changed. **Describe** the effect of increasing the potential difference on the current flowing through the filament wire. (1 mark)



b **Explain** the shape of this graph in terms of the resistance of the filament wire. (2 marks)

29 A student is investigating series and parallel resistance in a laboratory experiment. They set up the circuit shown in the figure and adjust the power supply until a current of 6.0 A is produced.

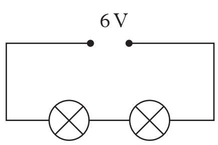


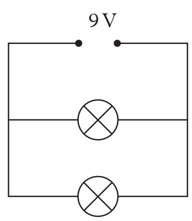
a **Calculate** the effective resistance of the circuit. (2 marks)

b **Calculate** the potential difference across the 3.0 Ω resistor. (2 marks)

30 **Construct** a circuit diagram, using the correct symbols, consisting of a battery of two 1.5 V cells in series, with the positive terminal connected to a 10 Ω resistor and a 15 Ω resistor in series. Include an ammeter and a voltmeter to measure the current and voltage associated with the 15 Ω resistor. (4 marks)

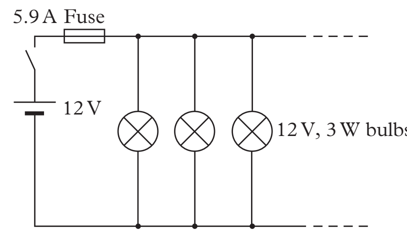
31 Two identical light bulbs may be connected across a battery in two ways, as shown in the figures.





A student said that the series circuit would be the brighter as the 6 V goes through the first bulb and then through the second, so each light bulb gets the 6 V, whereas the parallel circuit has to split the 9 V in two to give each light bulb just 4.5 V. **Evaluate** this claim and **determine** which circuit would have the brighter light bulbs. (4 marks)

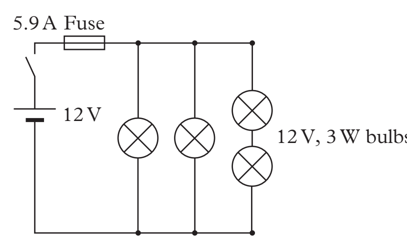
32 Christmas-tree lights are connected in parallel across a power supply, as shown in the following diagram. The circuit allows for extra lights to be added as needed. The fuse in the circuit is rated as 5.9 A, so it will "blow" if the current exceeds this value and prevent a fire. The lights are rated as "12 V, 3 W" which means they will dissipate 3 W when connected to a 12 V supply.



a **Determine** the maximum number of lights that can be added to this circuit without blowing the fuse. Express your answer as a whole number. (3 marks)

b **Determine** the resistance of a light when in normal operation. (2 marks)

33 As an experiment, four lights were connected in a circuit as shown in the diagram. As in question **32**, the lights are rated as "12 V, 3 W", which means they will dissipate 3 W when connected to a 12 V supply.



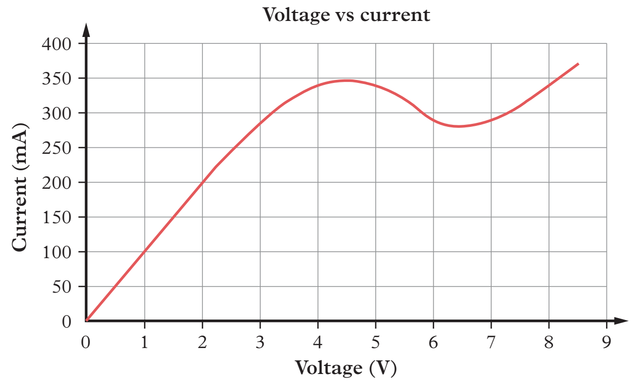
Determine the total resistance of the four lights, and the total current passing through the fuse. (4 marks)

34 A 300 W electrical heater is placed in a beaker containing 0.25 kg of water at a temperature of 18°C. The heater is switched on for 120 seconds, after which time the temperature of the water is 45°C. The beaker absorbs negligible heat.

a **Determine** the efficiency of the transformation of electrical energy to thermal energy (2 s.f.). (3 marks)

b **Evaluate** the experiment to propose the source of any losses or gains of energy. (2 marks)

35 A student applied a varying voltage across a non-ohmic device connected in series with an ammeter. The current passing through the device was recorded and plotted in the graph.



a **Identify** a point on the graph at which the device exhibits minimum instantaneous resistance. **Explain** your reasoning. (3 marks)

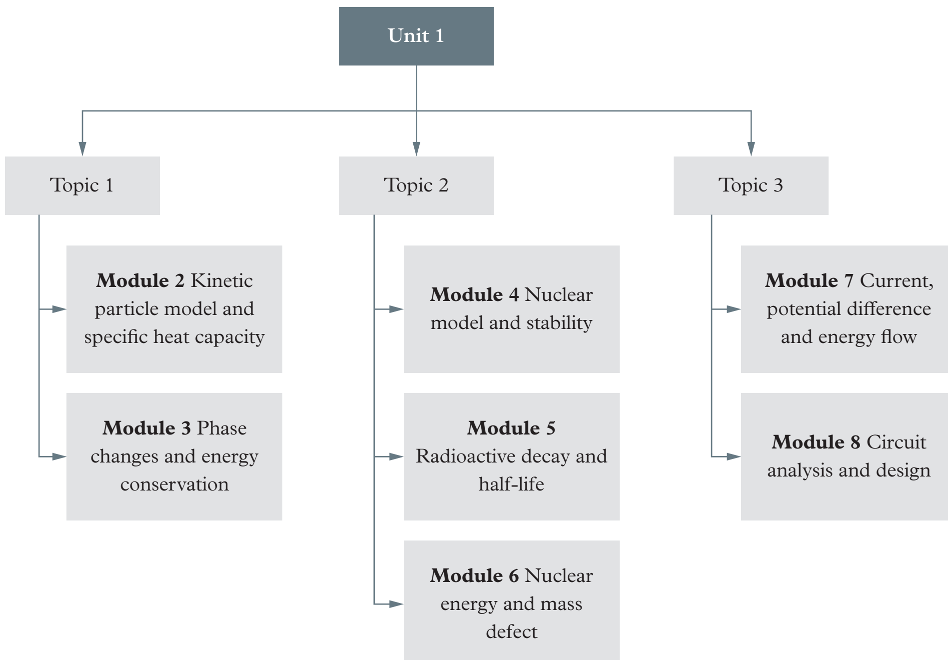
b **Deduce** and **explain** whether the current is reversing direction over this range of voltages. (2 marks)

TOTAL MARKS
/84

UNIT 1 Review

Part A – Revisit and revise

Part A of the Unit review asks you to reflect on your learning and identify areas in which you need more work.



Part B – Exam essentials

Now that you have completed your revision for Unit 1, it is time to learn and practise some of the skills you'll need to answer exam questions like a pro! Our expert authors have created the following advice and tips to help you maximise your results on the end-of-year examination.

Exam tip 1: Watch out for the familiarity trap.

Don't assume questions are like the ones you've done before. When you are under time pressure in exams, any way to save time is great. The simplest way is to answer questions in the same way you have used in practice. It is a shortcut we all use.

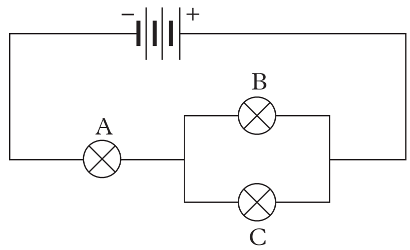
But don't rush into a solution without reading the question properly! You might fall into the trap of familiarity and miss something.

See it in action

Read the following real exam question and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 7 (6 marks)

A circuit consists of a battery with three identical cells and three identical lightbulbs, connected as shown.



b) Draw a conclusion about the relative brightness of lightbulb A compared to lightbulbs B and C. Explain your reasoning. [*4 marks*]

Source: *QCAA Alternative sequence, 2022, Paper 2* © State of Queensland (QCAA)

Complete response

Indicates an understanding of the scenario in relation to power in an electrical circuit [1 mark]

Brightness of the lightbulb is related to the rate of energy transformed to light, i.e. power, $P = I^2R$. Since current is conserved at a junction and all lightbulbs have equal resistance, the current will split evenly across lightbulbs B and C, and each will receive half the current that lightbulb A receives, so A will be brighter than B or C.

Provides appropriate reasoning to determine the relative brightness of the brightest lightbulb [1 mark]

$P_B = P_C = I_B{}^2R$

$P_A = (2I_B)^2R = 4I_B{}^2R$

Concludes that lightbulb A will be brighter than lightbulbs B and C [1 mark]

Therefore, lightbulb A will be four times brighter than lightbulbs B and C.

Determines the relative brightness of the lightbulbs [1 mark]

Incomplete response

Indicates an understanding of the scenario in relation to power in an electrical circuit [1 mark]

Has provided appropriate reasoning to determine the relative currents but has not related that to the brightness of the lightbulbs [0 marks]

Brightness of the lightbulbs is related to the relative energy dissipation of the bulbs. Since all lightbulbs have equal resistance, the current will divide equally between lightbulbs B and C, and lightbulb A will get twice as much current as B or C. So, A will be brighter than B or C. Lightbulb A gets twice the current as lightbulbs B and C, so it will be twice as bright.

Has determined the relative brightness of the lightbulbs based on current but not on power, which is related to current squared so no mark [0 marks]

Has concluded that lightbulb A will be brighter than lightbulbs B and C, which deserves a mark [1 mark]

Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the following marking guide to mark the response.

QUESTION 21 (3 marks)

Explain how the capture of a neutron by a nucleus may lead to nuclear fission.

Nuclear fission is the splitting of a nucleus into two or more parts. The capture of a neutron by a nucleus gives it too many neutrons to be stable, so it converts one of them to a proton. This splits off a beta particle and an electron antineutrino, which carry a lot of energy with them. This fission process makes the nucleus more stable.

Source: *QCAA Alternative sequence 2021, Paper 1* © State of Queensland (QCAA)

Marking guide

Question 1a	• identifies that absorption of the neutron causes the nucleus to become unstable [1 mark] • identifies the daughter nuclei [1 mark] • identifies that energy is released from the nucleus [1 mark]

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Exam tip 2: Use widely separated data points when determining the gradient of a graph.

Determining the gradient of a graph can cause two problems for students. One is understanding what the gradient means, and that is a conceptual issue. Often, it will be something unexpected. The other is a mechanical one. Here are two tips:

- When determining the gradient, you need to choose two points as widely separated as possible. This reduces the uncertainty of the result.
- When you do this, if the graph goes through the origin, make sure you specify (0, 0) as one of the points and do not assume the assessor knows you have done this.

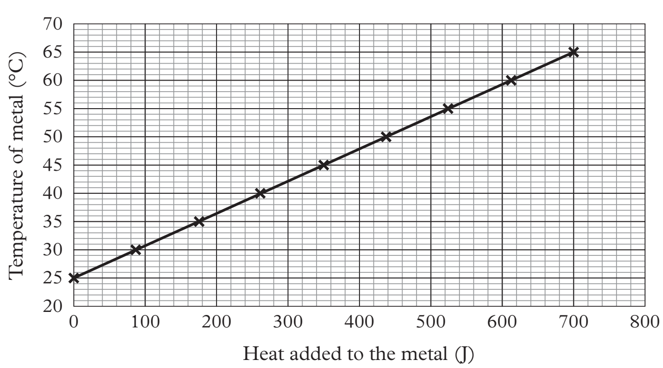
See it in action

Read the real exam question and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 25 (4 marks)

A 0.050 kg metal block was heated from 25°C to 65°C.

This graph shows the amount of heat added to the metal and its temperature.



Deduce the specific heat capacity of the metal.

Source: *QCAA Alternative sequence 2020, Paper 1* © State of Queensland (QCAA)

Complete response

Specific heat capacity formula is $Q = mc\Delta T$. This can be rearranged to $c = \frac{Q}{m\Delta T}$.

Gradient is $\frac{\Delta T}{Q}$, which means $c = \frac{1}{m \times \text{gradient}}$ — Indicates an understanding of the physical scenario in relation to specific heat capacity and energy [1 mark]

$\text{gradient} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{65 - 25}{700 - 0} = 0.0571$ — Identifies relevant points on the graph to determine the gradient of the graph [1 mark]

$c = \frac{1}{0.050 \times 0.0571}$ — Provides pertinent mathematical operation(s) correctly performed [1 mark]

$c = 350\ \text{J kg}^{-1}\ \text{K}^{-1}$ — Arrives at a consequentially correct answer [1 mark]

Incomplete response

Specific heat capacity formula is $Q = mc\Delta T$. This can be rearranged to $c = \frac{Q}{m\Delta T}$.

Gradient is $\frac{\Delta T}{Q}$, which means $c = \frac{1}{m \times \text{gradient}}$. — Indicates an understanding of the physical scenario in relation to specific heat capacity and energy [1 mark]

$\text{gradient} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{65 - 60}{700 - 610} = 0.055$ — Identifies points on the graph to determine the gradient of the graph, but they are not that "relevant"; should have used points as widely spaced as possible [0 marks]

$c = \frac{1}{0.050 \times 0.055}$ — Provides pertinent mathematical operation(s) correctly performed [1 mark]

$c = 364\ \text{J kg}^{-1}\ \text{K}^{-1}$ — Arrives at a consequentially correct answer; allow follow-through error (FTE) for mistake in determining the gradient [1 mark]

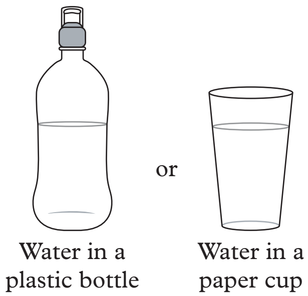
Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the marking guide to mark the response.

QUESTION 22 (4 marks)

The following diagram shows the same amount of hot water in both a clear plastic bottle with a lid, and a white paper cup in a cold room.



Predict which of the containers will keep the water hot for the longest time. Justify your answer in terms of radiation, conduction and convection concepts.

The plastic bottle has a cap so this will stop heat escaping to the surroundings. The cap stops convection. The containers are both made of materials that are not good conductors so there is no difference in conduction. There is no difference in losses from radiation as radiation can't get through solid walls of the container. Therefore, the plastic bottle will keep the water hotter for longer.

Source: *QCAA Mock Paper 1, 2020* © State of Queensland (QCAA)

Marking guide

Question 1	• indicates an understanding of the physical scenario in relation to the concept of conduction between the bottle and cup [1 mark] • indicates an understanding of the physical scenario in relation to the concept of convection between the bottle and cup [1 mark] • indicates an understanding of the physical scenario in relation to the concept of radiation between the bottle and cup [1 mark] • gives correct conclusion [1 mark]

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Exam tip 3: Watch out for the quantities and units on graphs.

Sometimes, graphs will be presented to you in exams with unexpected quantities and units.

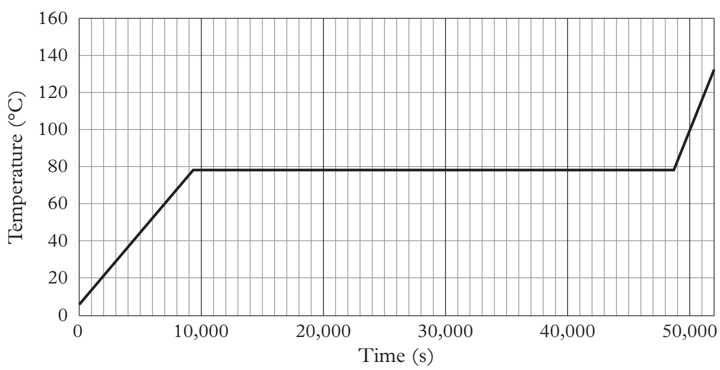
- For example, you may have practised Ohm's law questions with graphs of current on the y-axis and voltage on the x-axis, but find in an exam that the axes are swapped and that current is in mA, not A. So, not only are the axes different, but there is also a different prefix (milli, m).
- For half-life graphs, the amount of substance on the y-axis could be in nanograms (ng) and you may not have expected that.
- In question 26 below, the x-axis is shown as time in seconds (s), whereas you may be more familiar with energy profiles presented with energy in joules (J) on the x-axis.

See it in action

Read the real exam question below and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 26 (5 marks)

A 7.5 W immersion heater is submerged in liquid ethanol, which has a density of 789 kg m^{-3} and a latent heat of vaporisation of 851 kJ kg^{-1}. The data is presented in the following graph.



Determine the volume of ethanol used in this experiment in cm^3 (to 2 significant figures.)

Source: *QCAA Alternative sequence Mock Exam, 2020, Paper 1* © State of Queensland (QCAA)

Complete response

Indicates an understanding of the physical scenario in relation to specific latent heat and power [1 mark]

Heat gain = electrical work done = $P \times t$

$Q = 7.5 \times (48{,}900 - 9{,}200) = 297{,}750\ J$

Indicates an understanding of how the graph can be used to determine latent heat of vaporisation by identifying the relevant points on the graph [1 mark]

$Q = mL_v$

$m = \dfrac{Q}{L_v} = \dfrac{297{,}750}{851 \times 10^3} = 0.3499\ kg$

Provides pertinent mathematical operation(s) correctly performed for mass [1 mark]

$D = \dfrac{m}{V}$ or $V = \dfrac{m}{D}$

$V = \dfrac{0.3499}{789} = 4.43 \times 10^{-4}\ m^3$

Provides pertinent mathematical operation(s) correctly performed for volume [1 mark]

$V(cm^3) = V(m^3) \times (10^2)^3$

$= 4.43 \times 10^{-4} \times 10^6$

$= 443\ cm^3 = 440\ cm^3\ (2\ s.f.)$

Arrives at a consequentially correct value and answer; answers between 440 cm^3 (or mL) and 445 cm^3 (or mL), inclusive, are accepted [1 mark]

Incomplete response

Indicates an understanding of the physical scenario in relation to specific latent heat and work, but not power [0 marks]

Heat gain = electrical work done, $Q = W$

$Q = 49{,}000 - 9{,}500 = 39{,}500\ J$

Does not indicate an understanding of how the graph can be used to determine latent heat of vaporisation by identifying the relevant points on the graph; assumes that *x*-axis shows heat, not time [0 marks]

$Q = mL_v$

$m = \dfrac{Q}{L_v} = \dfrac{39{,}500}{851 \times 10^3} = 0.0464\ kg$

Provides pertinent mathematical operation(s) correctly performed for mass; allow a follow-through error (FTE) for mistake in calculating Q [1 mark]

$D = \dfrac{m}{V}$ or $V = \dfrac{m}{D}$

$V = \dfrac{0.0464}{789} = 5.88 \times 10^{-5}\ m^3$

Provides pertinent mathematical operation(s) correctly performed for volume; allow a FTE for mistake in calculating Q [1 mark]

$V(cm^3) = V(m^3) \times (10^2)^3$

$= 5.88 \times 10^{-5} \times 10^6$

$= 58.8\ cm^3 = 59\ cm^3\ (2\ s.f.)$

Fails to arrive at a consequentially correct value and answer; allow a FTE [1 mark]

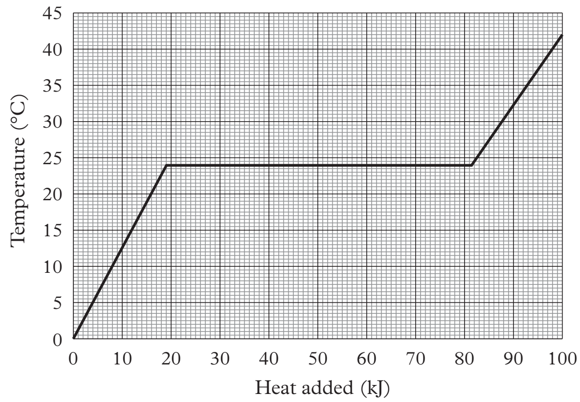
Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the marking guide below to mark the response.

QUESTION 21 (3 marks)

A constant supply of heat was added to a 250 g sample of solid coconut oil. The graph shows the temperature of the coconut oil with respect to the amount of heat added.



Determine the latent heat of fusion of coconut oil in kJ kg^{-1} (to 3 significant figures).

$Q = 81.5 - 19.0 = 62.5\ J$

$Q = mL_f$

$L_f = \frac{Q}{m} = \frac{62.5}{0.250} = 250\ J\ kg^{-1}$

Source: *QCAA 2020 Alternative sequence Mock Paper 1* © State of Queensland (QCAA)

Marking guide

Question 21	• indicates an understanding of the physical scenario in relation to specific latent heat and how it is represented on a graph of temperature vs heat [1 mark] • provides pertinent mathematical operation(s) correctly performed [1 mark] • arrives at a consequentially correct value [1 mark] Accept any other value if it is the product of acceptable variations to rounding; differences in values read off a graph or chosen from a table; or expressed to a greater precision than done so in the sample response. Accept answers between 246 kJ kg^{-1} and 258 kJ kg^{-1} inclusive.

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Part C – Exam practice

Now it is time to put the tips and advice you've learnt into practice while you complete these exam-style questions! During your examination, you will most likely be asked multiple choice questions, short response questions, and more complex, multi-part short response questions. The questions here, in Part C, give you practice at these types of questions.

Multiple choice

(1 mark each)

1 When measured in °C, what temperature is 300 K?

A −27°C

B 27°C

C 29°C

D 573°C

2 An infrared heater was used to change the temperature of liquid water. Which of the following is the main way the water temperature changed?

A Infrared radiation was reflected off surfaces and into the water.

B Heat was conducted along the floor and into the water.

C The heater caused convection currents in the air and this added to the kinetic energy of the water particles.

D Radiant electromagnetic energy from the heater travelled through the air and was transformed to kinetic energy of the water particles.

3 Radiation is described as heat transfer

A by vibrating electrons.

B directly through a vacuum.

C through a fluid under the influence of gravity.

D by electromagnetic waves.

4 A student conducted an experiment to determine the specific heat capacity of an unknown solid. An electric heater transferred 550 J of energy to 31.6 g of the solid and it was found that the temperature rose from 25.5°C to 67.0°C. What is the specific heat capacity of the solid?

A $2.38 \times 10^{-3}\,\mathrm{J\,kg^{-1}\,K^{-1}}$

B $4.19 \times 10^{-1}\,\mathrm{J\,kg^{-1}\,K^{-1}}$

C $2.38 \times 10^{0}\,\mathrm{J\,kg^{-1}\,K^{-1}}$

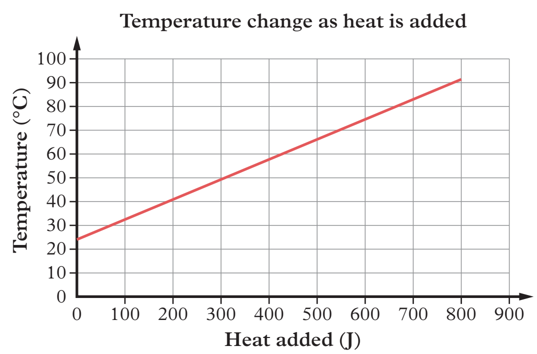
D $4.19 \times 10^{2}\,\mathrm{J\,kg^{-1}\,K^{-1}}$

5 The specific heat capacity of a metal is $3.80 \times 10^{2}\,\mathrm{J\,kg^{-1}\,K^{-1}}$. For a 250 g sample of the metal, how much heat is required to raise its temperature from 25°C to 90°C?

A $6.18 \times 10^{3}\,\mathrm{J}$ **B** $7.13 \times 10^{3}\,\mathrm{J}$

C $6.18 \times 10^{4}\,\mathrm{J}$ **D** $6.18 \times 10^{6}\,\mathrm{J}$

6 A 0.030 kg block of metal was heated on a hotplate. A graph of its temperature as a function of heat added is shown in the graph. What is the specific heat capacity of the metal?



A $2.8\,\mathrm{J\,kg^{-1}\,K^{-1}}$ **B** $329\,\mathrm{J\,kg^{-1}\,K^{-1}}$

C $404\,\mathrm{J\,kg^{-1}\,K^{-1}}$ **D** $897\,\mathrm{J\,kg^{-1}\,K^{-1}}$

7 A motor does 18,000 J of useful work and produces 42,000 J of heat energy. What is the efficiency of the motor?

A 30% **B** 43%

C 57% **D** 70%

8 Which is the main force holding nucleons together in an atom?

A Electromagnetic force

B Strong nuclear force

C Electromotive force

D Gravitational force

9 Beta positive radiation is defined as

A an electron emitted from the nucleus.

B a positron emitted from the nucleus.

C an electron emitted from an atom.

D a positron emitted from an atom.

10 What is the name of the composite particle consisting of two protons and two neutrons tightly bounded together?

A Tritium **B** Deuterium

C Helium atom **D** Alpha particle

11 Which one of the following lists, in order, the type of radiation with the greatest penetrating power and the type of radiation with the greatest ionisation power?

A Alpha, alpha **B** Gamma, alpha

C Alpha, gamma **D** Gamma, gamma

12 The decay of U-239 produces a beta negative particle and

A Np-239, electron antineutrino.
B Pa-239, electron antineutrino.
C Np-239, electron neutrino.
D Pa-239, electron neutrino.

13 Which of the following is a correctly balanced nuclear equation?

A ${}^{23}_{11}\text{Na} + {}^{1}_{1}\text{H} \rightarrow {}^{20}_{10}\text{Na} + {}^{4}_{2}\text{He}$
B ${}^{11}_{5}\text{B} + {}^{1}_{0}\text{n} \rightarrow {}^{12}_{5}\text{B} + \beta^{-} + {}^{1}_{0}\text{n}$
C ${}^{9}_{4}\text{B} + {}^{4}_{2}\text{He} \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$
D ${}^{14}_{7}\text{N} + {}^{1}_{1}\text{H} \rightarrow {}^{15}_{8}\text{O} + \beta^{+}$

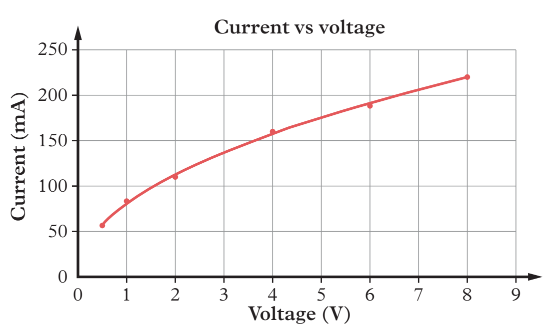
14 Hg-204 is a stable isotope that is unlikely to experience spontaneous nuclear decay, while Hg-209 will likely decay into Ti-209. The reason for this is

A Hg-209 has too many neutrons compared to Hg-204 and a neutron decays into a proton to increase stability.
B Hg-209 has too many protons compared to Hg-204 and a proton decays into a neutron to increase stability.
C Hg-209 has too many neutrons compared to Hg-204, so it emits 5 neutrons to increase stability.
D Hg-209 has too much mass compared to Hg-204 and emits an alpha particle to increase stability.

15 The radioactive decay of a 2 mg sample of N-13 was recorded over time. How many half-lives would pass before 0.125 mg of N-14 remained?

A 4 **B** 7 **C** 8 **D** 9

16 An experiment was conducted to determine the resistance of a torch bulb. The graph shows the current in the bulb as the voltage across it was changed.



What is the resistance at a voltage of 3.0 V?

A 22 Ω **B** 45 Ω **C** 60 Ω **D** 135 Ω

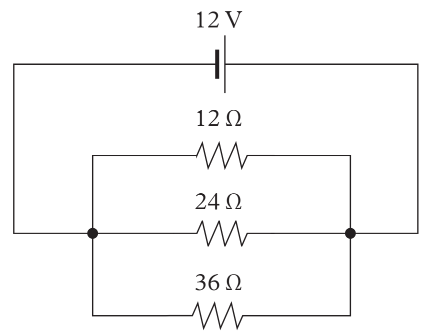
17 Two identical resistors are connected in parallel and the total resistance is 10 Ω. If another identical resistor is connected to them in parallel, what is the total resistance now?

A $3\frac{1}{3}$ Ω **B** $6\frac{2}{3}$ Ω **C** 14 Ω **D** 20 Ω

18 Three resistors, 11 Ω, 22 Ω and 33 Ω, are placed in parallel across a 12 V battery. Calculate the power dissipated in the circuit.

A 0.46 W **B** 2.0 W
C 2.2 W **D** 24 W

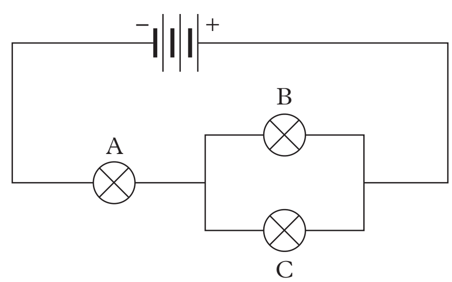
19 A circuit was constructed as shown in the figure.



What is the current through the 24 Ω resistor?

A 0.17 A **B** 0.50 A
C 1.8 A **D** 2.0 A

20 A circuit consists of a battery of three identical cells and three identical lightbulbs connected as shown. The battery supplies 4.0 J of energy for every 0.60 C of charge passing through it.



The potential difference of each cell is

A 0.80 V. **B** 2.2 V.
C 2.4 V. **D** 6.7 V.

Short response

21 When you rub your hands together, they begin to warm up. **Predict** how the temperature of your hands will keep rising so long as you continue rubbing. **Justify** your conclusion in terms of heat transfer processes. (3 marks)

22 A person adds 350 g of ice cubes at 0°C to an insulated bucket containing 2.30 kg of water at 26°C. **Calculate** the final temperature of the total amount of water once thermal equilibrium is reached. (5 marks)

23 **Describe** thermal equilibrium in terms of temperature and kinetic energy. (2 marks)

24 **Construct** a balanced equation for a beta positive decay in which the daughter nuclide is neon-21. (3 marks)

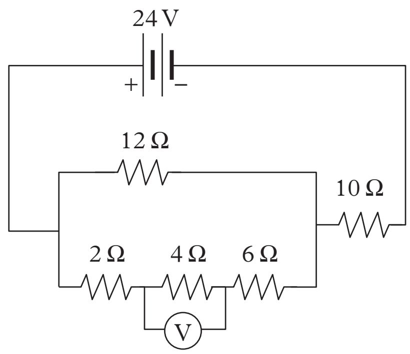
25 Alpha radiation and beta-positive radiation have different penetrating powers. **Explain** this in terms of their composition. (5 marks)

26 The isotope for phosphorus-32 has a nuclear mass (excluding electrons) of 4.975033×10^{-26} kg. **Calculate** the binding energy of the nucleus in MeV (2 s.f.). (4 marks)

27 A direct current of 220 mA is flowing through a resistor in an electrical circuit. **Calculate** the number of electrons that flow through the resistor in 1 minute (2 s.f.). (4 marks)

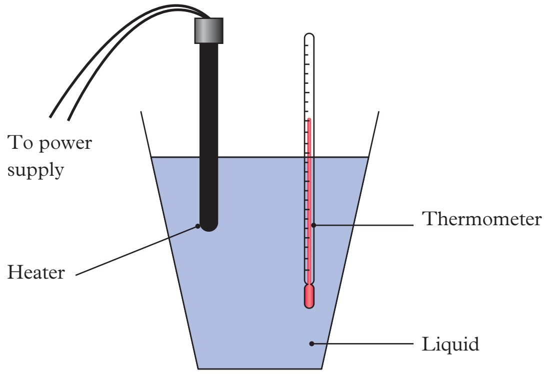
28 A voltmeter was connected across a heating coil with a resistance of 27.8 Ω. The voltage measured was 230 V. The power output of the appliance was measured as 1600 J s^{-1}. **Calculate** the efficiency of the appliance to the nearest whole number. (4 marks)

29 A circuit is constructed with five resistors and a 24 V battery as shown.



Calculate the voltage as measured on the voltmeter. (7 marks)

30 A water heater consists of a 10 Ω resistance coil connected to a 12 V electricity supply, as shown in the diagram. The cup contains 180 g of water at 23°C.

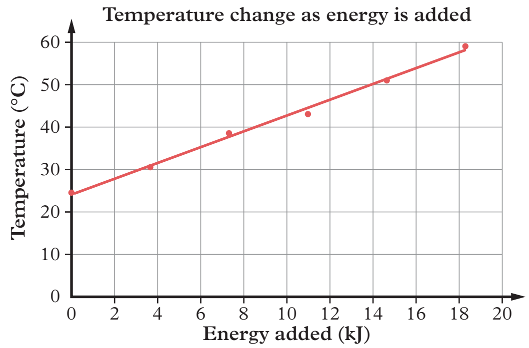


a **Calculate** the power output of the coil. (2 marks)

b **Calculate** the energy delivered in 3 minutes. (2 marks)

c **Determine** the temperature of the water after 3 minutes. (3 marks)

31 A 0.125 kg sample of water was heated on a hotplate and the temperature recorded as a function of the energy added. The graph is shown.



Calculate the specific heat capacity of water from this graph (3 s.f.). (2 marks)

32 **Explain** how a deficiency of protons in a nucleus relative to the number of neutrons causes the emission of beta negative radiation. (3 marks)

33 Gold has a particular radioactive isotope $^{196}_{79}$Au, which is a positron emitter with a half-life of 6 days. A medical treatment involves injecting 100 µg of the isotope into the bloodstream and then measuring it some weeks later.

a **Determine** the amount of Au–196 present in the blood after 30 days have elapsed. (2 marks)

b **Determine** the daughter nuclide of the Au-196 by writing a balanced decay equation. (2 marks)

34 Nuclear fission power reactors use the energy produced by the reaction to heat water and make steam to drive turbines. **Calculate** (2 s.f.) the mass of water that can be heated from a liquid at 20°C to steam at 150°C from the energy released by the fission of 1 kg of U-235 according to this reaction:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{94}_{38}\text{Sr} + ^{139}_{54}\text{Xe} + 3\,^{1}_{0}\text{n}$$

The mass of each nuclide can be found in Appendix 1. (5 marks)

35 **Evaluate** the statement: 1 g of $^{2}_{1}$H undergoing fusion according to the reaction $2\,^{2}_{1}\text{H} \rightarrow ^{4}_{2}\text{He}$ releases as much energy as needed to run a 3 kW motor continuously for 1 year (3 s.f.). The mass of each nuclide can be found in Appendix 1. (7 marks)

TOTAL MARKS /85

UNIT 2

Linear motion and waves

Unit 2 overview

An understanding of linear motion – whether it is cars driving along roads or particles moving up and down in waves – underpins modern society's transportation and communication. Newton's laws relating displacement, velocity, acceleration and time allow calculation of the linear motion of objects ranging from nuclear particles to spaceships. The role of gravity in providing an accelerating force on objects enables calculations about the motion of objects that are dropped or thrown – such as time of flight, maximum height and impact speeds. The laws of conservation of energy and momentum enable us to further predict the motion of objects, whether they are a nucleus exploding or two cars colliding.

The motion of waves helps explain mechanical waves on Slinkys and strings, and sound waves in open and closed pipes and in musical instruments. This is in contrast to electromagnetic waves – waves that require no medium for their transmission and are as familiar as visible light with its rainbow colours, microwaves for cooking and X-rays in medicine. Light waves enable experiments with lenses and mirrors to confirm laws of reflection and refraction. Experiments with thin slits help to explain the processes of diffraction and interference. Together with polarisation, these show the power of the wave model for light.

This unit will show that physics can explain natural phenomena and be used to predict the behaviour of matter and waves in a broad range of scenarios.

Unit objectives

1. Describe ideas and findings about linear motion and force, and waves.
2. Apply understanding of linear motion and force, and waves.
3. Analyse data about linear motion and force, and waves.
4. Interpret evidence about linear motion and force, and waves.
5. Evaluate processes, claims and conclusions about linear motion and force, and waves.
6. Investigate phenomena associated with linear motion and force, and waves.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Unit 2 Topics

Topic	Module	
Topic 1 Linear motion and force	**Module 9**	Linear motion
	Module 10	Classical mechanics
	Module 11	Energy
Topic 2 Waves	**Module 12**	Waves
	Module 13	Sound
	Module 14	Light

MODULE

9 Linear motion

Introduction

People have been watching things move and recording their motion for thousands of years. The motions of the heavens are some of the oldest recorded observations we have. More recently, a need to measure the speed of advancing armies or athletes or ships required better ways of measuring distance and time. Over the centuries, measurements have become more accurate and now form the basis of physics. We can now measure distances and times with incredible accuracy. In this module we will consider linear motion; that is, straight line motion or an idealisation of approximately straight line motion when an object moves from one place to another.

Prior knowledge

Prior knowledge quiz

Check your understanding of distance, speed and acceleration before you start.

Subject matter

Science understanding

→ Contrast vectors and scalars, and use these terms to categorise physical quantities, e.g. velocity and speed.

→ Symbolise vectors graphically and algebraically, e.g. $\mathbf{F}$, $\tilde{\mathrm{F}}$ and $\vec{\mathrm{F}}$.

→ Calculate resultant vectors through the addition and subtraction of two vectors in one dimension.

→ Describe the concepts of displacement, velocity and acceleration.

→ Compare instantaneous and average velocity.

→ Interpret linear motion graphs to describe the motion of an object, referring to the

  → intercepts, gradients and uncertainties (using minimum and maximum lines of best fit) of displacement–time and velocity–time graphs

  → areas under velocity–time and acceleration–time graphs using simple geometry.

→ Solve problems relating to uniformly accelerated motion in one dimension using $v = u + at$, $s = ut + \frac{1}{2}at^2$ and $v^2 = u^2 + 2as$

→ Interpret experimental data to determine the value of acceleration due to gravity on the Earth's surface.

Science inquiry skills

- → Investigate situations that involve displacement–time and velocity–time graphs.
- → Linearise a dataset that suggests a non-linear relationship (e.g. t^2 versus s) and calculate the equation of the linear trend line.

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Practicals

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Lesson 9.6 Displacement–time and velocity–time graphs for a ball on an incline

Lesson 9.9 Acceleration due to gravity by linearising time–displacement graphs

Lesson 9.1
Vectors and scalars

Key ideas

→ A vector quantity needs both magnitude and spatial direction to specify it fully.
→ Horizontal and vertical coordinates are used to represent direction.
→ Vector quantities can be represented pictorially and symbolically.
→ Scalar quantities have magnitude but no spatial direction.

Learning intentions and success criteria

What are vector and scalar quantities?

If you walk 100 m on your school oval you may get from one end to the other. You're probably thinking, "What if I walk 50 m one way and then 50 m another way, then I won't." True! To completely specify a physical quantity, you cannot just state its magnitude. To fully describe the motion of an object, you need to state its distance away from the start and the direction in which it is heading, or its speed and the direction in which it is heading. When magnitude and direction are both known, they combine to form an example of a **vector quantity**.

vector quantity
a quantity that has both magnitude and spatial direction

The word "vector" comes from the Latin "vectus", a form of the verb meaning "to carry" (such as to carry extra information, data or disease). In biology, a vector is an organism that carries disease from one place to another (e.g. a mosquito is the vector for malaria). In physics we think about it differently. A vector means a quantity that carries information about both **magnitude** and **spatial direction**. Displacement, velocity, acceleration and force are examples of vector quantities.

magnitude
a quantitative measure of the size or amount of a physical quantity

spatial direction
a direction in space

scalar quantity
a quantity that has a magnitude but no spatial direction

Quantities that have magnitude but do not include a spatial direction are called **scalar quantities**. Distance, speed, mass and time are all scalar quantities. Scalar quantities require no statement about direction. For example, time = 3.5 s, mass = 25.5 kg and current = 2.0 A are scalar quantity measurements – no direction has to be specified. The word "scalar" comes from the Latin "scalaris" meaning "pertaining to a ladder". This refers to the change in the size of something without any reference to direction. Examples of scalar and vector quantities are shown in Table 1.

TABLE 1 Scalar and vector quantities

Scalar	Vector
Length	Displacement
Speed	Velocity
Time	Acceleration
Volume	Force
Mass	Weight
Energy	Momentum
Frequency	Torque
Pressure	Moment
Power	Electric current
Temperature	Electric field
Charge	Magnetic flux density

Students often ask, "Is temperature a vector quantity, because you can have negative and positive temperatures?" and for time they say, "You can have negative values for time as well as positive values." For example, liquid nitrogen boils at −198°C, and a rocket being launched may begin its countdown at minus 10 seconds. The answer is no, temperature and time are not vector quantities even though they can be positive (+) or negative (–). The sign is not a "spatial" direction (i.e. a direction in space); it is simply a point on a number line.

What coordinate systems represent direction?

The simplest coordinate system we can use to indicate direction in one dimension is shown in Figure 1.

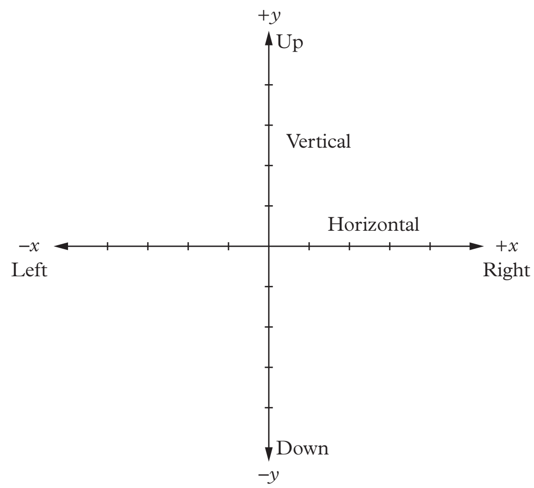


FIGURE 1 Coordinate system to indicate direction in one dimension

Horizontal plane

In the horizontal plane, we represent left and right on the horizontal axis (x-axis). The coordinate system is a number line with forwards motion to the east (E) or to the right being called positive (+). Backwards motion is depicted being to the west (W) or to the left and is called negative (–). We can use a number line as shown in Figure 2.

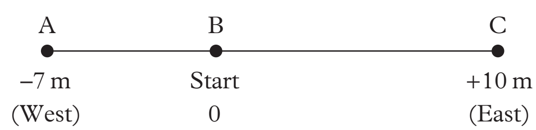


FIGURE 2 A number line can be used to depict left/right horizontal motion.

If we consider the position of B to be the zero (0) point, then the position of C is 10 m E or simply +10 m. Similarly, the position of A is 7 m W or −7 m. Motion to the north or south can also be thought of as directions in the horizontal plane, and is discussed below.

Vertical plane

In the vertical plane, we represent up and down on the vertical axis (y-axis). A ball dropped off a cliff can be said to be heading in the negative direction (downwards). Figure 3 shows a ball at the top of a cliff being thrown vertically upwards. It starts at 0 m and reaches a height of +30 m, so it has travelled a distance of 30 m in the positive (+) direction, which is upwards.

Figure 3 also shows a ball being dropped from the top of a cliff (at 0 m) and landing at the base below at a position marked as −50 m. It has travelled 50 m in the negative (–) direction.

Once you have chosen a coordinate system for a question, you should not change it. We will not be using the vertical coordinate system until later in this module.

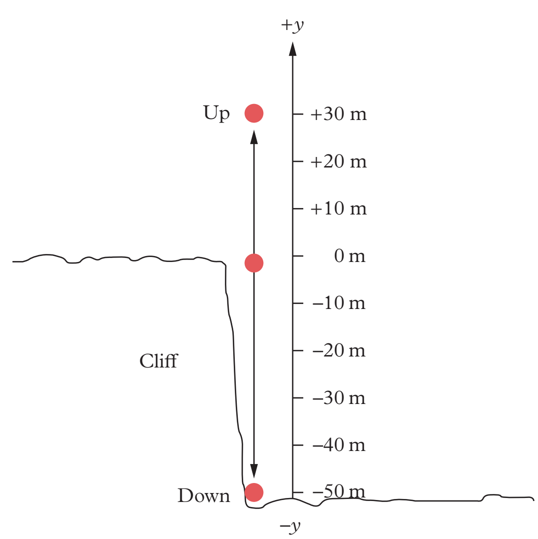


FIGURE 3 Vertical motion is represented as up/down on the vertical axis.

How do you represent vector quantities?

A vector quantity can be represented in two ways:

- pictorially
- symbolically.

Pictorially

When representing a vector pictorially, the length of the arrow represents the magnitude of the vector and the arrowhead points in its direction. It is called a **directed line segment**.

directed line segment
an arrow representing a vector in which the arrowhead represents the spatial direction of the vector, and the length represents the magnitude

For example, the three vectors in Figure 4 represent a person who has walked 30 m east, 60 m west and 10 m north respectively.

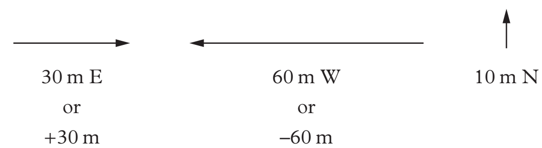


FIGURE 4 Vectors represented by directed line segments

When vectors do not lie along the compass points (N, E, S, W), angles need to be specified. Figure 5 shows how the direction is indicated.

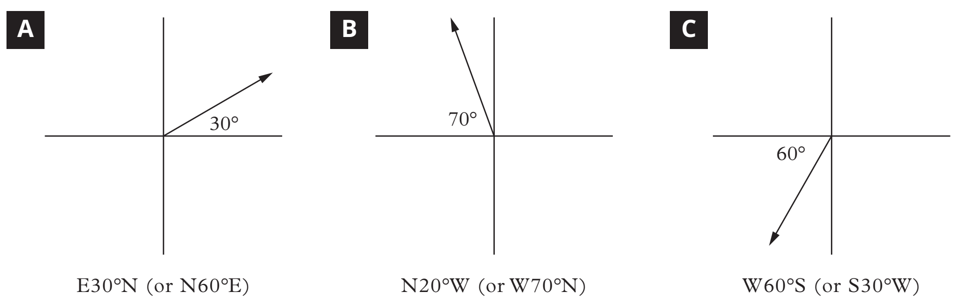


FIGURE 5 Angles must be specified when vectors do not lie along the compass points.

Students often find it hard to work out the directions. Think of Figure 5A as saying: the vector was pointing east but was rotated 30° to the north. You could also say it was pointing north but rotated 60° to the east (N60°E). They mean the same thing.

It is possible that you may need to specify a direction at some angle in the upwards or downwards direction. Say for instance you climbed a ladder that makes an angle of 60° to the ground. Then you would say your displacement is at 60° to the horizontal. This is covered in detail in Unit 3.

Study tip
You must be able to use both vector conventions (symbolic and pictorial). Remember to define the positive and negative directions.

Symbolically

The other way to represent a vector is by using a letter with an overhead arrow. Imagine an object travelling at 15 metres per second ($15\,m\,s^{-1}$) in the west (W) direction. We would write: $\vec{v} = 15\,m\,s^{-1}$ W or $\vec{v} = -15\,m\,s^{-1}$. You can also represent a vector by using a bold font, for example, $\boldsymbol{v} = -15\,m\,s^{-1}$, but this harder for you to do reliably, so it won't be used here.

Challenge

Displacement of a cat

You are required to consider vector quantities in one dimension only; that is, in a straight line. However, in Unit 3 you will need to consider vectors in two dimensions, and then in advanced (university) physics, in three dimensions. Here's a taste of 1-D, 2-D and 3-D vector addition.

A cat goes for a walk. It starts at point A and goes 10 m north to the base of a tree (point B). It climbs 5 m vertically up the tree and then heads east along a branch for a distance of 5 m and stops at point D.

Determine the displacement of the cat at

a point B (2 marks)

b point C (3 marks)

c point D. (3 marks)

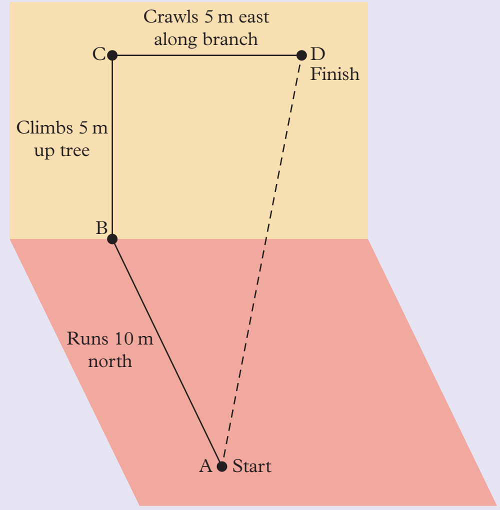


FIGURE 6 The path a cat takes on its walk

Check your learning 9.1

Check your learning 9.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** a vector quantity and scalar quantity in the context of someone walking on the oval. (4 marks)

2 **Identify** an example of a vector quantity and a scalar quantity related to change of position. (2 marks)

3 **Explain** if the time of day, and time elapsed, are vector or scalar quantities. (4 marks)

4 **Explain** how you would represent the velocity of a person who was at rest. (1 mark)

5 **Sketch** the following vector quantities on a directed number line using the same scale.

- **a** 30 m E (2 marks)
- **b** 100 m W (2 marks)

6 **Sketch** the following vector quantities using directed arrows.

- **a** 60 m W (2 marks)
- **b** 30 m N (2 marks)
- **c** 60 m N30°E (2 marks)
- **d** 30 m S60°E (2 marks)

Analytical processes

7 A person's position is represented by the vector 40 m E. **Identify** the magnitude and direction of the quantity. (2 marks)

Knowledge utilisation

8 **Assess** whether it would be possible to depict the downwards direction as positive. (2 marks)

9 You can run around an oval at constant speed, but your direction keeps changing. **Decide**, with justification, whether speed is a scalar or vector quantity. (2 marks)

Lesson 9.2
Distance and displacement

Key ideas

- → Distance describes the total length of the pathway taken between the origin and the destination point; a scalar quantity.
- → Displacement describes change in position in a given direction and is a vector quantity.
- → Two or more vector quantities can be added to produce a single resultant vector.
- → Vector quantities can also be subtracted. Change in a vector measurement means subtraction.
- → Multiplication of a vector (magnitude + direction) by a scalar (magnitude) will change the magnitude of the vector but will leave its direction unchanged.

Learning intentions and success criteria

Why do we measure distances, angles and time?

You probably know many road rules, such as not having your headlights on high beam if another vehicle is closer to you than 200 m, and judging whether street lights are less than 100 m apart. That's all very well in theory, and you may pass a written driving test, but what if you can't estimate these things in practice?

Being able to measure distances, angles and time is important, and has been since ancient times. Often it was done for religious reasons (e.g. for worshipping Sun gods), and at other times it was an attempt to plot the motion of the stars (a primitive astronomy). However, sometimes it had a more practical purpose. For example, measuring distance was important in the construction of houses, building canals and cultivating fields. Today, measuring distance can help you avoid traffic fines!

What is distance?

distance
the total length of the pathway taken between the origin and the destination point; symbol *d*

displacement (linear motion)
a vector quantity representing a change in position irrespective of the path actually taken between two points (symbol: *s*; SI unit: metre; symbol: m); displacement (change in position) = final position – initial position

While length is a measure of the length or width of an object, we use the term **distance** to describe how far an object has moved. A person travelling from one city to another might have moved a distance of 1,200 km.

In physics, we need to be able to state not only distance but also the direction of movement. For example, we may want to say that a person has moved 1,200 km north. We are now describing a person's displacement – a vector quantity that combines magnitude and direction.

What is displacement?

Displacement is the change in position of an object in a given direction. It is a vector quantity because it has both magnitude and spatial direction. Think of it as the position measured relative to the origin. In simple terms, displacement is a change in position in a stated direction. It is given the symbol *s* for the Latin word "spatium", meaning distance or space.

Consider Figure 1. If you started at point X and walked 8 m east to point Z and then turned around and walked 5 m west to point Y, you would have covered a distance of 13 m; however, you would only have a change of position (displacement) of 3 m east. That is, your position would only have changed by 3 m to the east. In symbols, this could be written as $\vec{s}$ = 3 m E. Note that the "*s*" has an arrow overhead to indicate it is the symbol for a vector quantity.

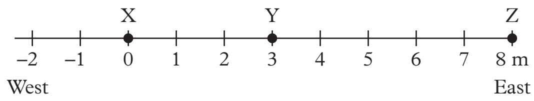


FIGURE 1 If you started at X and ended at Y, your displacement could be written as $\vec{s}$ = 3 m E.

We can show this by the equation:

Displacement (change in position) = final position – initial position = +3 m – 0 = +3 m

There is no SI symbol for position, so we just use the words.

How do you add vectors?

There are many situations in which more than one vector quantity is involved. When this is the case, we need rules to perform some form of arithmetic. We apply normal rules to scalar quantities – the rules for addition, subtraction, multiplication and division. In vector arithmetic, these rules must also take into account the direction of the vector quantities. If you walk 3 m north and then 4 m south, your displacement is not 7 m. Vector addition is not simple addition.

Vector addition can be used to combine two or more vector quantities to give a single resultant vector.

vector addition
two or more vector quantities can be combined to produce a single resultant vector

Case 1: vectors in the same direction

Consider rowing a boat at 5 m s^{-1} E in water that is also moving east at 1 m s^{-1}. Your actual velocity is 6 m s^{-1} E, which is found by placing the two vector arrows head to tail. The **resultant** is a line drawn from the tail of the first arrow to the head of the second arrow (Figure 2).

resultant
the vector sum of two or more vectors

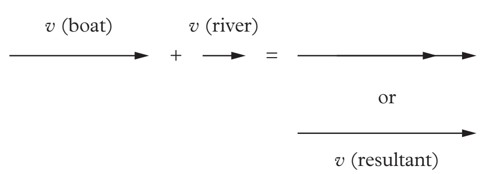


FIGURE 2 Adding vectors in the same direction

When adding vectors, the arrows should always be placed head to tail. The resultant will always start at the tail of the first arrow and end at the head of the second arrow.

Case 2: vectors in opposite directions

Consider the same boat being rowed against the current. In this case, the velocity of the river is 1 m s^{-1} W. This is in the direction opposite to that of the boat and hence will slow the boat down.

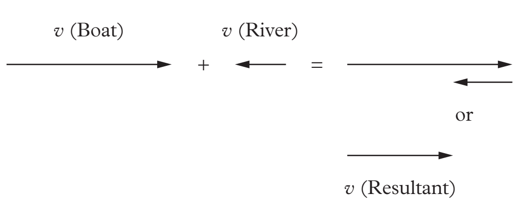


FIGURE 3 Adding vectors in opposite directions

The resultant velocity is 4 m s^{-1} E. When two vectors that are in the same line but opposite directions are added, the resultant has the same direction as the larger vector.

How do you subtract vectors?

In physics, we use subtraction to work out the change in a quantity. For example, if you heat up some water from 20°C to 30°C, you would say there was a change in temperature of 10°C. But if you cool some water from 30°C to 20°C, there would be a change of –10°C. We need to be very particular in the way we talk about "change" in a measurement, particularly a vector. In physics, "change" means subtraction:

Change in a measurement = final measurement – initial measurement

For temperature, this would read as: $\Delta T = T_{\text{final}} - T_{\text{initial}}$.

Subtraction is simple for scalar quantities such as mass, temperature and bank balances. But in physics, it is also necessary to subtract vectors. You may have learnt that subtracting a number is the same as adding its negative. For example, 10 – 6 is equivalent to 10 + (–6), and the answer is +4 either way. When subtracting vector B from vector A, the direction of vector B is changed to its opposite and then added to vector A (head to tail). Worked example 9.2A explains this further.

Worked example 9.2A

Calculating change in velocity

A ball strikes a wall at a velocity of $-10\,\text{m}\,\text{s}^{-1}$ (moving to the left) and rebounds at a velocity of $+6\,\text{m}\,\text{s}^{-1}$ (moving to the right) (Figure 4). **Calculate** the change in velocity (2 s.f.). (2 marks)

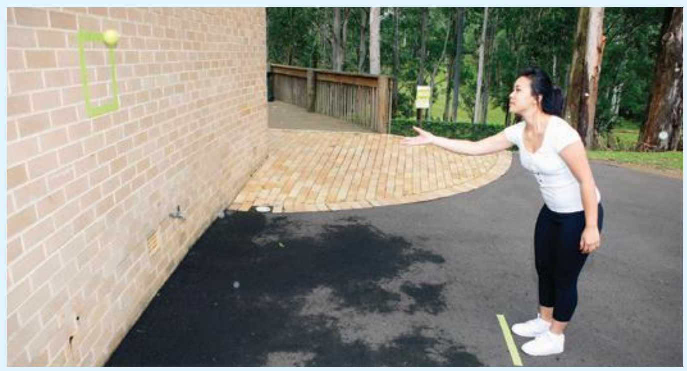
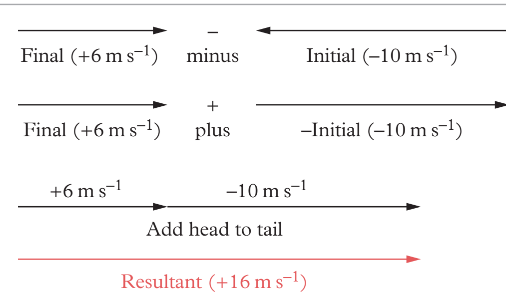


FIGURE 4 A ball strikes a wall and rebounds.

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking.	"Calculate" means to determine or find a number or answer by using mathematical processes.
Step 2: Identify the appropriate formula and gather any data that you require. This is a change of velocity question, so you should ensure that the signs for direction are included with your gathered data.	Change in velocity = final velocity – initial velocity: $\Delta v = \vec{v}_f - \vec{v}_i$ Initial (i) velocity: $\vec{v}_i = -10\,\text{m}\,\text{s}^{-1}$ Final (f) velocity: $\vec{v}_f = +6\,\text{m}\,\text{s}^{-1}$
Step 3: Substitute the known values into the formula. Find the unknown. Finalise your answer and make sure you have included the correct units.	$\Delta v = \vec{v}_f - \vec{v}_i$ $= +6\,\text{m}\,\text{s}^{-1} - (-10\,\text{m}\,\text{s}^{-1})$ (1 mark) $= +16\,\text{m}\,\text{s}^{-1}$ (1 mark) The positive value means that the change was directed to the right.
Note: this question can also be solved graphically. When subtracting graphically, we need to make it an addition because we have a head-to-tail rule for addition. So, we reverse the direction of the initial velocity vector and then add it on.	

Your turn

The fastest ball ever delivered in Australian cricket had a velocity of 44 m s^{-1} and it was struck directly back at the bowler at a speed of 52 m s^{-1}. **Calculate** the change in velocity of the ball (2 s.f.). (2 marks)

How do you multiply vectors

Multiplication of a vector (magnitude + direction) by a scalar (magnitude only) will change the magnitude of the vector but will leave its direction unchanged. If you are travelling in car A at a velocity of 10 m s^{-1} E, this can be represented by the vector $\vec{v}_A$ as shown in Figure 5 (left). If car B passes you at a velocity three times your velocity, we can represent this pictorially as $\vec{v}_B = 3 \times \vec{v}_A$, as shown in Figure 5 (right).

We could also represent this symbolically as $\vec{v}_A = +10\ \text{m s}^{-1}$; $\vec{v}_B = +30\ \text{m s}^{-1}$.

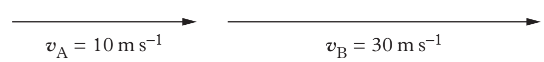


FIGURE 5 Multiplying a vector by 3 (graphically) means increasing its length by 3 times.

Study tip

Multiplication of vectors does not appear in the syllabus but has appeared in external exams. You would be wise to know what it means.

Check your learning 9.2

Check your learning 9.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the two ways to represent a vector quantity. Provide an example of each using a cricket ball moving east at 40 m s^{-1}. (2 marks)

2 **Calculate** the change in velocity for each of the cases in the following table (2 s.f.).

	Initial velocity	Final velocity
a	20 m s^{-1} south	30 m s^{-1} north (2 marks)
b	50 m s^{-1} west	10 m s^{-1} east (2 marks)
c	25 m s^{-1} north	35 m s^{-1} south (2 marks)
d	50 m s^{-1} south	20 m s^{-1} north (2 marks)

3 **Calculate** the magnitude and direction of the resultant vector (to the nearest whole number) obtained by:

a adding displacements of 30 m east and 20 m east (2 marks)

b adding velocities of –6 m s^{-1} and +3 m s^{-1} (2 marks)

c moving object Z forwards at three times its original velocity of +20 m s^{-1}. (2 marks)

4 **Determine** graphically the change in velocity for each of the cases in the following table.

	Initial velocity	Final velocity
a	20 m s^{-1} east	30 m s^{-1} west (2 marks)
b	50 m s^{-1} south	10 m s^{-1} north (2 marks)

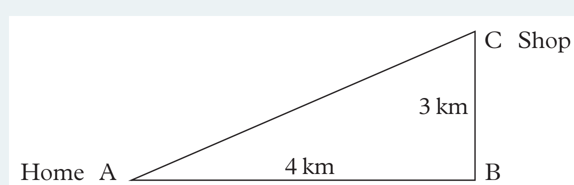
5 **Calculate** the magnitude and direction of the resultant vector (2 s.f.) obtained by adding

a displacements of 30 m north and 20 m north (2 marks)

b velocities of 16 m s^{-1} north and 30 m s^{-1} south. (2 marks)

Analytical processes

6 Two students leave home (A) and go to the shop (C), as shown in the figure. One student heads in a straight line for C, but the other student goes to C via B.



a **Determine** the distance travelled by the person going directly to C (1 s.f.). (2 marks) b **Determine** the distance travelled by the person going to C via B. (1 mark)

c **Calculate** the displacement (magnitude and direction) of the person at point B ($\vec{s}_B$ = ?) (1 s.f.). (2 marks)

d **Calculate** the displacement at point C ($\vec{s}_C$ = ?) (1 s.f.). (4 marks)
Remember to include the direction by stating the value of the angle CAB.

7 A toy train is moving around a circular track of diameter 120 cm. Imagine it starts at the most northerly point. **Determine** the distance travelled and its displacement after

a half a lap (3 marks)

b one full lap (2 marks)

c two laps (2 marks)

d quarter of a lap. (3 marks)

Knowledge utilisation

8 If you start in the middle of the oval and walk 100 m, consider where you could end up. **Evaluate** this with reference to the following questions.

a Can you cover a distance of 100 m and end up where you started? (2 marks)

b Can you have a displacement of 100 m and end up where you started? (2 marks)

c Can your 100 m distance travelled ever be greater than your displacement? (2 marks)

d Can your displacement ever be greater than your 100 m distance travelled? (2 marks)

Lesson 9.3
Speed and velocity

Learning intentions and success criteria

Key ideas

→ Speed is the rate at which a distance is covered; it is a scalar quantity.

→ Velocity is the rate of change of displacement of an object; it is a vector quantity.

Are speed and velocity the same thing?

The terms "speed" and "velocity" are often used as if they mean the same thing. If you read a news report that mentions a high-speed car chase, you know what it means. But why are hunting rifles referred to as being high-velocity? Media reports may refer to high-velocity atomic particles, but also talk of a cyclone's wind speed. Such media reports often mean the same thing by speed and velocity. But they are not the same quantities.

What is average speed?

speed
the rate at which distance is covered

In physics, speed and velocity have slightly different meanings. **Speed** is a scalar quantity whereas velocity is a vector quantity. If it takes 2 h to drive the 120 km from town A to town B, then the average speed is 60 km h^{-1}. Speed is the rate at which distance is covered. The word "rate" is a clue that something is being divided by time. Speed is always measured in terms of a unit of distance divided by a unit of time, such as metres per second.

Average speed is the rate of change of distance. It is found by dividing distance travelled by time taken.

$$\text{Average speed} = \frac{\text{total distance travelled}}{\text{time taken}}$$

$$v_{av} = \frac{s}{t}$$

Note that the symbols are not shown as vectors because speed, distance and time are all scalar quantities.

In the driving example, it doesn't mean that the car drove at 60 km h^{-1} all the way. Sometimes the car would have travelled at 100 km h^{-1} and at other times it would have been stationary. When the car's speedometer was reading 60 km h^{-1}, the car was actually travelling at a speed of 60 km h^{-1} for that moment. This is called its **instantaneous speed**.

instantaneous speed
speed as measured over a very small period (an instant) of time

What is average velocity?

When we talk of a car's speed as being 60 km h^{-1}, we have no idea about the direction in which it is travelling. Speed is a scalar quantity. **Velocity** is sometimes defined as speed in a particular direction (such as 60 km h^{-1} north), but the official definition is that velocity is the rate of change of displacement. As displacement is a vector quantity, so too is velocity.

velocity
the rate of change of displacement of an object (symbol, v; SI unit, m s^{-1}).

$$\text{Average velocity} = \frac{\text{displacement}}{\text{time taken}}$$

$$\vec{v}_{av} = \frac{\vec{s}}{t}$$

A simple way to make the distinction is to consider a person running one lap of the school oval (400 m) in 80 s. The average speed is 5 m s^{-1} and the average velocity is 0 m s^{-1}. The displacement is zero as the runner finishes where they started.

Velocity is a vector quantity and the direction must be stated. If the rate of change is measured at an instant in time, then this is an **instantaneous velocity**.

instantaneous velocity
rate of change of displacement over an instant of time

Worked example 9.3A

Calculating speed and velocity of a cyclist

A person rides a bicycle 6.5 km east and then 2.5 km west, as shown in Figure 1. The trip takes 1.5 hours.

Calculate (2 s.f.)

a total distance travelled (1 mark)
b average speed (1 mark)
c displacement (1 mark)
d average velocity. (2 marks)

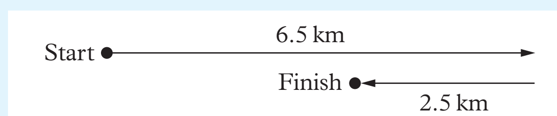


FIGURE 1 Diagram of a bicycle trip

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply various formulas and find the values for distance, speed, displacement and velocity. The mark allocation is varied, so we must gather the correct information, correctly apply the formulas and complete the calculations as required.
Step 2: Identify the appropriate formulas and gather any data that you require.	$\text{Average speed} = \frac{\text{total distance travelled}}{\text{time taken}}$ $\text{Average velocity} = \frac{\text{displacement}}{\text{time taken}}$ Distances: 6.5 km, 2.5 km Time: 1.5 h

Think	Do
Step 3: For part **a**, find total distance by adding the individual distances, regardless of direction. Make sure you have included the correct units and expressed your answer to 2 s.f.	**a** Total distance = 6.5 + 2.5 = 9.0 km (1 mark)
Step 4: For part **b**, calculate average speed using the formula. Make sure you have included the correct units and expressed your answer to 2 s.f.	**b** Total distance = 9 km; time = 1.5 h Average speed $= \frac{\text{total distance travelled}}{\text{time taken}}$ $= \frac{9.0\,\text{km}}{1.5\,\text{h}}$ $= 6\,\text{km}\,\text{h}^{-1}$ (1 mark)
Step 5: For part **c**, identify the displacement data, using appropriate sign convention (remember that east is positive (+) and west is negative (–))	**c** Displacements: +6.5 km, –2.5 km
Step 6: Perform vector addition of the displacements. Make sure you have included the correct units and expressed your answer to 2 s.f. State the direction (E or W).	Displacement = +6.5 + (−2.5) = +4.0 km = 4.0 km E (1 mark for magnitude and direction)
Step 7: For part **d**, calculate average velocity using the formula. The direction is the same direction as the displacement vector (E, or +). Make sure you have included the correct units and expressed your answer to 2 s.f.	**d** Average velocity $= \frac{\text{displacement}}{\text{time}}$ $= \frac{4.0\,\text{km}}{1.5\,\text{h}}$ $= 2.7\,\text{km}\,\text{h}^{-1}$ E (1 mark for magnitude; 1 mark for direction)

Your turn

A dog runs 50 m up the driveaway to the front gate in 10 s, turns around and runs half-way back in a further 6.0 s. **Calculate** (2 s.f.)

a total distance travelled (1 mark)
b average speed (1 mark)
c displacement (1 mark)
d average velocity. (2 marks)

Check your learning 9.3

Check your learning 9.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 An archer can fire an arrow at 390 m s^{-1}. **Calculate** the time an arrow would take to hit a target 100 m away (2 s.f.). (2 marks)

Analytical processes

2 In 1979 Sam Barrett is estimated to have reached a speed of 1,190.4 km h^{-1}, in his rocket-engine three-wheeled car at Edwards Airforce Base. **Determine** the time it would have taken him to cover the 1.6 km test distance (2 s.f.). (2 marks)

3 A student rides a bicycle to a shop by travelling 300 m north along a straight road and then by travelling west for another 400 m. Assume the trip takes 3 minutes.

Determine (2 s.f.)

a the average speed (2 marks)
b the average velocity (magnitude only). (2 marks)

4 When driven by an experienced racing driver, a Ferrari Testarossa can cover 400 m from a standing start in 14.2 s. **Determine** its average speed, if it crosses the 400 m line at a speed of 203 km h^{-1} (3 s.f.). (2 marks)

Knowledge utilisation

5 A student runs around the oval at 5 m s^{-1} anticlockwise and argues that because their direction is constantly anticlockwise they have constant velocity. **Evaluate** the student's argument. (3 marks)

Lesson 9.4
Graphs of linear motion – constant velocity

Key ideas

→ Linear motion graphs show data about objects moving at constant (uniform) velocity.
→ The gradient of a displacement–time graph is a measure of the instantaneous velocity.
→ The area under a velocity–time graph is a measure of displacement.

How do we analyse constant velocity?

Have you ever been in a car travelling along a straight open road at constant velocity and let your mind wander to think: am I moving or is the ground moving past me? With constant velocity it is hard to tell without looking out the window. It is even harder on a plane.
The simplest kind of motion to study is an object moving with **constant velocity** and therefore zero acceleration. Examples include:

- a car being driven straight ahead at 60 km h^{-1}
- ball bearings being rolled on a very smooth horizontal surface
- a person jogging steadily along a straight flat track
- water flowing in a straight pipe
- light in air.

It is often useful to show data about motion in the form of a graph. The most basic form is a displacement vs time (*s*–*t*) graph. Not only does it show us how far an object has moved, but we can also use this graph to work out how fast the object was going. The second type of graph is velocity vs time (*v*–*t*). Both these types of graphs will be used to analyse motion that is at a constant velocity. Lesson 9.5 will look at accelerated motion graphs.

Learning intentions and success criteria

constant velocity
motion where the speed and direction of the object relative to the observer is not changing; this includes an object at rest (no acceleration)

Study tip
The term "as a function of" is used to show the value of one variable in terms of (function of) another.

What are displacement–time graphs?

One of the simplest types of graphs is the **displacement–time (*s*–*t*) graph**, which shows the displacement of an object as a function of time.

For example, the position of a horse during a race along a straight track was recorded at six different times (Table 1) and a displacement–time graph was plotted (Figure 1).

When drawing a displacement–time graph, it is usual to show the time elapsed on the horizontal axis and the displacement on the vertical axis, as in Figure 1.

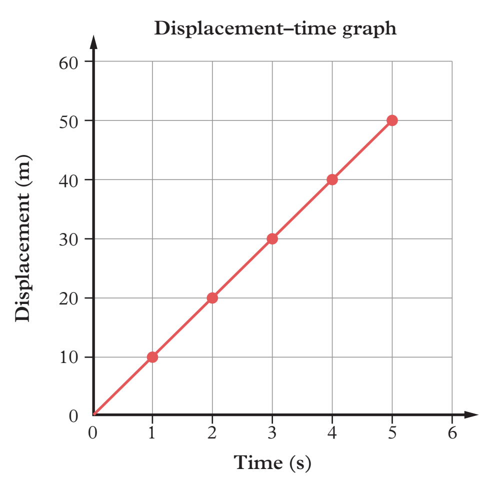


FIGURE 1 Displacement of racehorse as a function of time

displacement–time graph
depicts the displacement of an object as a function of time, the gradient of which is the instantaneous velocity

TABLE 1 Displacement and time measurements for a horse

Time elapsed, t (s)	0.0	1.0	2.0	3.0	4.0	5.0
Displacement, s (m)	0.0	10.0	20.0	30.0	40.0	50.0

The six points plotted on the graph are the six observations of the horse. When a line is drawn between these points, we are assuming the motion was uniform. This is called interpolation (Latin "inter" = "between", "polire" = "polish" – to "polish up" data by supplying in-between points). When a line is extended past the first or last data points, this is called extrapolation (Latin "extra" = "beyond").

The horse's average velocity over the 5 seconds is calculated by dividing the displacement by the time taken. This is the same as calculating the gradient (slope) of the line.

The gradient of any line is given by change in y divided by the change in x ("rise over run"):

$$\text{Gradient} = \frac{\Delta y}{\Delta x} = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1}$$

For the horse:

$$\text{Gradient} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{50 - 0}{5 - 0} = 10\,\text{m s}^{-1}$$

From a displacement–time graph, the gradient is given by:

$$v_{av} = \frac{\Delta y}{\Delta x} = \frac{\text{displacement}}{\text{time}}$$

The gradient of a displacement–time graph equals the velocity.

We can check this:

$$v_{av} = \frac{\text{displacement}}{\text{time}} = \frac{100\,\text{m}}{10\,\text{s}} = 10\,\text{m s}^{-1}$$

Can the displacement–time graph show negative values?

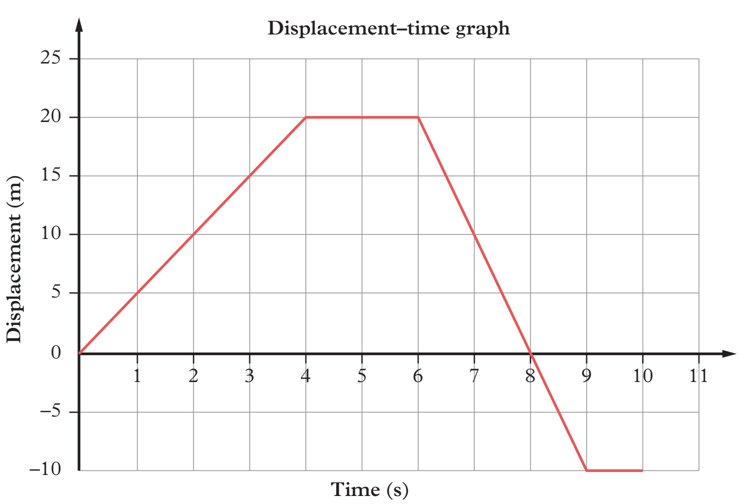


FIGURE 2 Motion of a beach buggy up and down a beach

Displacement can be both positive and negative, so a graph may need to display negative values. For example, imagine driving a beach buggy up the beach for 4 seconds and going 20 m, then sitting there for 2 s before driving back 10 m past the starting point in another 3 s, then sitting in this location for an additional 1 s. The motion is shown on the graph in Figure 2. We can break up the diagram into four stages based on each time the line changes direction.

The four stages of the motion are summarised in Table 2.

TABLE 2 Displacement, time and gradient data for motion of a beach buggy

Stage	Time (s)	Displacement = final position – initial position (m)	Gradient m (v_{av}) = $\frac{y_2 - y_1}{x_2 - x_1}$
1	0–4	$s = (+20 - 0) = +20\,\text{m}$	$v_{av} = \frac{+20 - 0}{4 - 0} = +5\,\text{m s}^{-1}$
2	4–6	$s = (0 - 0) = 0\,\text{m}$	$v_{av} = \frac{+20 - (+20)}{6 - 4} = +0\,\text{m s}^{-1}$
3	6–9	$s = -10 - (+20) = -30\,\text{m}$	$v_{av} = \frac{-10 - (+20)}{9 - 6} = -10\,\text{m s}^{-1}$
4	9–10	$s = (0 - 0) = 0\,\text{m}$	$v_{av} = \frac{-10 - (-10)}{10 - 9} = +0\,\text{m s}^{-1}$

Other calculations:

- The displacement after 10 s is –10 m (negative 10 m).
- The total distance travelled is the sum of distances for each of the four stages: $20 + 0 + 30 + 0 = 50\,\text{m}$. As distance is not a vector quantity, the total distance is just the sum of the absolute values of displacements.
- The average velocity for the 10 s is displacement divided by time: $v_{av} = \frac{s}{t} = \frac{-10}{10} = 1\,\text{m s}^{-1}$.
- The average speed for the 10 s is distance divided by time: $v_{av} = \frac{\text{distance}}{\text{time}} = \frac{50}{10} = 5\,\text{m s}^{-1}$.

Worked example 9.4A shows how to approach s–t graphical questions.

Worked example 9.4A

Displacement–time graph for a sprinter

Figure 3 is the displacement–time graph of a sprinter who sprints 100 m in 10 s, rests for 20 s, and then runs back to the starting point in the next 30 s.

Using the graph, **calculate** (2 s.f.) the sprinter's

a average velocity in the first 10 s (2 marks)

b average velocity from $t = 30$ s to $t = 60$ s (2 marks)

c distance travelled for the whole race (1 mark)

d displacement for the whole race. (1 mark)

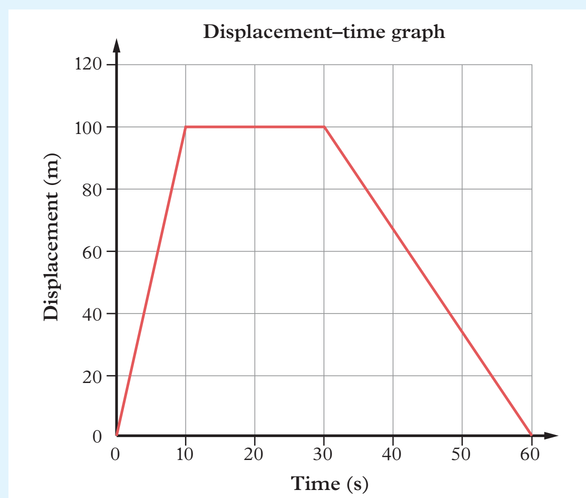


FIGURE 3 Displacement–time graph of a sprinter

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply a formula to and find the values for average velocity, distance and displacement. The mark allocation is varied, so we must gather the correct information, correctly apply the formula and complete the calculation as required.
Step 2: Identify the appropriate formula and gather any data that you require. Identify the graph as an s-t graph.	v_{av} = gradient $= \frac{\Delta y}{\Delta x}$ $= \frac{\text{change in position}}{\text{time taken}}$

Think	Do
Step 3: For part **a,** recall that gradient is equal to velocity. The sprinter's average velocity in the first 10 s is the gradient of the line over that time. Substitute the known values into the formula. Find the unknown.	**a** v_{av} = gradient $= \frac{\Delta y}{\Delta x}$ $= \frac{100\,\text{m} - 0\,\text{m}}{10\,\text{s} - 0\,\text{s}}$ (1 mark) $= 10$
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures.	$v_{av} = 10\,\text{m}\,\text{s}^{-1}$ (1 mark)
Step 5: For part **b**, calculate average velocity the same way as for part **a**, using $t = 30\,\text{s}$ to $t = 60\,\text{s}$.	**b** $v_{av} = \frac{0 - 100}{60 - 30}$ (1 mark) $= -3.3\,\text{m}\,\text{s}^{-1}$ (1 mark) Note that when the gradient of the line is positive, the velocity is in the positive direction. When the gradient is negative, the velocity is negative (which means the direction of motion has reversed).
Step 6: For part **c**, the distance travelled is the distance for the two parts added together.	**c** d (distance) = 100 + 100 = 200 m (1 mark)
Step 7: For part **d**, the displacement is the change in position. As the sprinter is back at the start, the change in position is zero.	**d** s (displacement) = 0 m (1 mark)

Your turn

For the motion of the sprinter shown in Figure 3, **calculate** (2 s.f.) the average

a speed of the sprinter over the whole 60 s (2 marks)

b velocity over the whole 60 s. (2 marks)

What are velocity–time graphs?

velocity–time graph
depicts the velocity of an object as a function of time, the gradient of which is the acceleration, and the area under the curve is the displacement

The second type of graph useful for constant velocity motion is a **velocity–time (v–t) graph**. Consider the situation in which an object is moving at constant speed (not accelerating). For example, the displacement–time graph of the horse shown earlier is shown again in Figure 4A. Note that the horse increases its displacement by 10 metres for every 1 second elapsed. We calculated its average velocity to be $10\,\text{m}\,\text{s}^{-1}$ and can plot this on a velocity–time graph (Figure 4B).

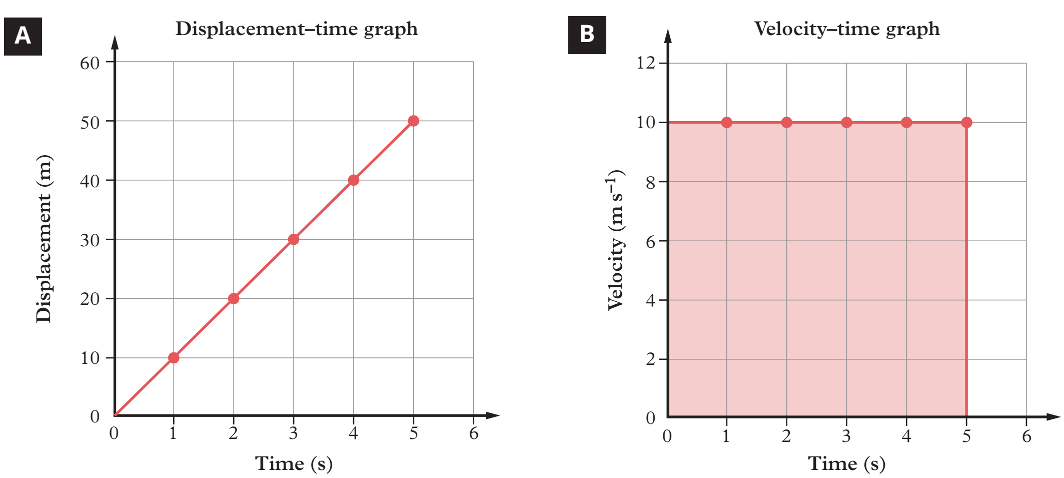


FIGURE 4 (A) Displacement–time graph of the horse; (B) velocity–time graph of the same data

The formula for velocity, $v = \frac{s}{t}$, can be rearranged to give $s = vt$. That is, the product of $v \times t$ is displacement, but it is also the area under the velocity–time curve (shaded). This area is $10\,\mathrm{m\,s^{-1}} \times 5\,\mathrm{s} = 50\,\mathrm{m}$, which is the final displacement of the horse after 5 s.

Summary

Relationships:

- Gradient of a displacement–time graph equals the velocity.
- Area under a velocity–time graph equals the displacement.

Graph shapes:

For an object travelling at constant speed, we can summarise graph shapes and their properties as shown in Figure 5.

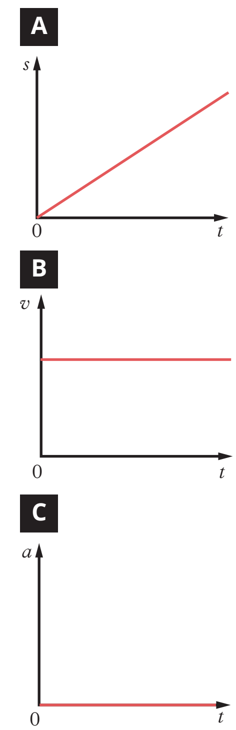


FIGURE 5 Graphs of constant velocity motion showing corresponding (A) displacement–time, (B) velocity–time and (C) acceleration–time relationships

How do we determine instantaneous velocity?

We have been looking at constant velocity motion, but obviously objects do change their speed and velocity. Imagine you are stopped at the traffic lights. When they turn green you take off and your velocity increases from zero to $60\,\mathrm{km\,h^{-1}}$. Your displacement increases but it is not a uniform increase – it increases at an increasing rate and is said to be non-linear. It means you are accelerating. Let's consider a displacement–time graph for this motion. Note, however, that the main discussion about accelerated motion is in the next lesson. This is just about *s*–*t* graphs and instantaneous velocity.

A car's speedometer displays the instantaneous speed of the car. If it reads $60\,\mathrm{km\,h^{-1}}$, then at that speed you would cover 60 kilometres in 1 hour. However, you could be accelerating and the speedometer might be gradually changing from $50\,\mathrm{km\,h^{-1}}$ to $100\,\mathrm{km\,h^{-1}}$. When it reads $60\,\mathrm{km\,h^{-1}}$, this is the car's instantaneous speed. If a direction is also specified, you would be talking about its instantaneous velocity.

Consider a car stationary at traffic lights. It takes off and gradually increases its speed. Figure 6 shows a typical graph.

To calculate the instantaneous velocity at 2.0 s and 3.5 s, tangents are drawn to the curve at those times. The blue tangent is at 2.0 s, and the yellow tangent is at 3.5 s. The velocities can then be determined by calculating the gradients of the tangents. Dotted lines have been drawn to allow you to estimate the change in *y*, and the change in *x* for each triangle.

$$\text{Gradient (2.0 s)} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{5.0 - 0.0}{3.2 - 1.0} = 2.3\,\mathrm{m\,s^{-1}}$$

$$\text{Gradient (3.5 s)} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{13.5 - 1.0}{5.0 - 2.0} = 4.2\,\mathrm{m\,s^{-1}}$$

It can be seen that the instantaneous velocity has changed from $2.3\,\mathrm{m\,s^{-1}}$ to $4.2\,\mathrm{m\,s^{-1}}$ over this period of time.

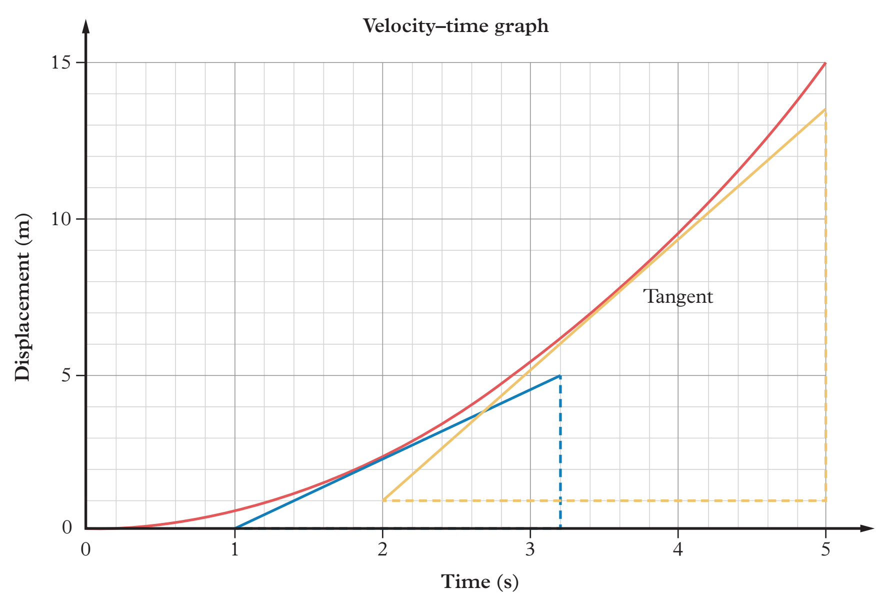


FIGURE 6 Displacement–time graph of a car taking off from traffic lights

Worked example 9.4B shows the steps for calculating instantaneous velocity for a non-linear graph.

Worked example 9.4B

Calculation of instantaneous velocity

Consider the case of a car accelerating away from traffic lights. Its velocity is increasing with time, so the displacement–time graph is a curve (Figure 7). **Calculate** the instantaneous velocity at 2.5 s. The data is recorded to 2 s.f. (3 marks)

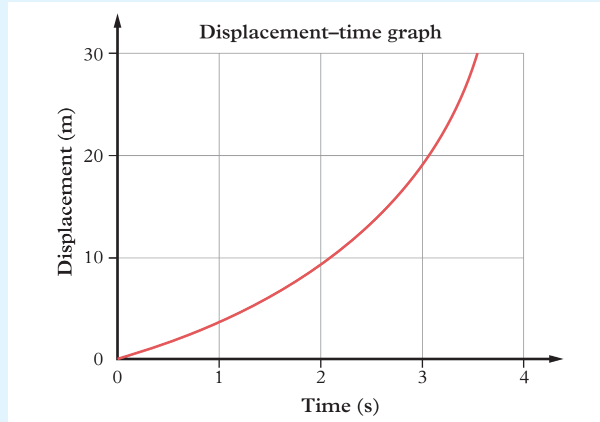
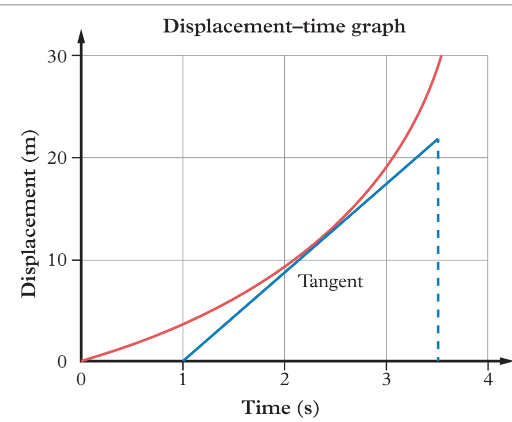


FIGURE 7 Displacement–time graph with an exponential curve

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply a formula to find the value for instantaneous velocity of an accelerating car. The question is worth 3 marks.
Step 2: Identify the appropriate formula and gather any data that you require.	Gradient $= \frac{y_2 - y_1}{x_2 - x_1}$ Identify the graph as an s–t graph for non-uniform motion. Tangent gives the instantaneous velocity.
Step 3: To calculate the instantaneous velocity at 2.5 s, draw a tangent to the curve at the 2.5 s mark. The tangent is a line that just touches the curve at that point.	 (1 mark)
Step 4: Calculate the gradient.	Gradient $= \frac{y_2 - y_1}{x_2 - x_1}$ $= \frac{20 - 0}{3.5 - 1.0}$ (1 mark) $= 8.8\,\text{m}\,\text{s}^{-1}$
Step 5: Finalise your answer and make sure you have expressed your answer to the correct number of significant figures. In this case, we use 2 s.f. because the values with the least precision in this question are both stated in the question to have 2 significant figures (y and x).	The instantaneous velocity at $t = 2.5$ s is $8.8\,\text{m}\,\text{s}^{-1}$. (1 mark)

Your turn

Consider the case of a car accelerating away from traffic lights as shown in Figure 7. **Calculate** the instantaneous velocity at 3.0 s (2 s.f.). (3 marks)

Study tip

The syllabus requires you to be able to determine instantaneous velocity from graphs. You should be able to calculate the gradient for linear and non-linear *s*–*t* graphs.

Check your learning 9.4

Check your learning 9.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** what the gradient of a displacement–time graph represents. (2 marks)

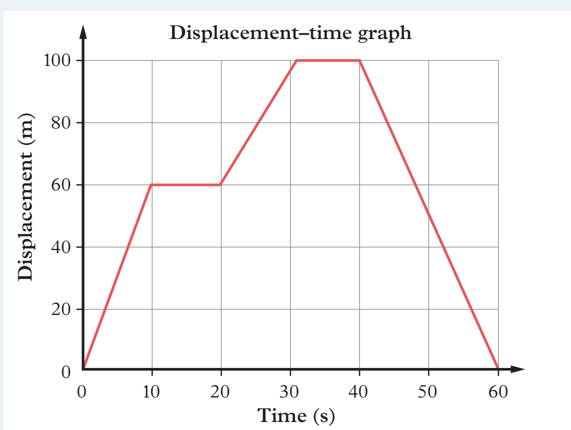
2 **Explain** how a student running around a school oval can be accelerating when they are travelling at constant speed. (3 marks)

3 A displacement–time graph for a rollerskater is shown. **Calculate** (2 s.f.) the skater's

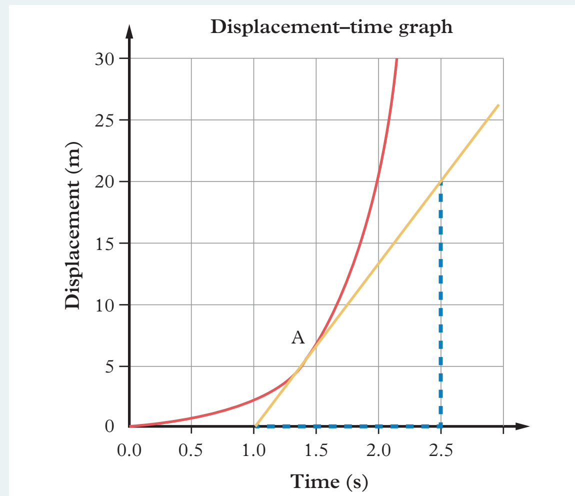
a average velocity for each of the five stages of the graph (8 marks)

b average velocity for the whole journey (2 marks)

c average speed for the whole journey. (2 marks)



4 The following is the displacement of an object rolling down a gradient. **Calculate** (2 s.f.) the instantaneous velocity at point A (t = 1.4 s). The tangent has been drawn in for you. (2 marks)



Analytical processes

5 The table records the motion of a dog chasing a ball.

Time elapsed, t (s)	0	1	2	3	4	5	6	7	8	9
Displacement, s (m)	0	2	4	4	4	6	6	4	2	0

a **Sketch** a displacement–time graph of the motion and **describe** it in words. (3 marks)

b **Determine** when the dog was stationary. (1 mark)

c **Determine** when the dog's displacement was increasing. (1 mark)

d **Determine** when the dog was moving with the greatest speed. (1 mark)

Lesson 9.5
Graphs of uniformly accelerated motion

Key ideas

→ Acceleration is the change in velocity over a particular time.
→ Displacement and acceleration can be calculated from velocity–time graphs.
→ Change in velocity can be calculated from acceleration–time graphs.

Learning intentions and success criteria

acceleration
the rate of change in the velocity of an object (symbol: a; SI unit: $\mathrm{m\,s^{-2}}$)

Study tip
Remember that 'u' comes before 'v' in the alphabet, just as initial velocity (u) comes before final velocity (v).

What is acceleration?

When you are in a car that takes off from the traffic lights, you feel pressed back into your seat. The velocity of a car increases when it starts moving from rest and decreases when the brakes are applied and the car slows down. Cars can thus accelerate (speed up) or decelerate (slow down). The rate at which the velocity changes is called its **acceleration**.

Acceleration is a vector quantity because velocity is a vector quantity.

$$\begin{aligned}\text{Acceleration} &= \frac{\text{change in velocity}}{\text{time}}\\ &= \frac{\Delta v}{t}\\ &= \frac{\text{final velocity} - \text{initial velocity}}{t}\\ \vec{a} &= \frac{\vec{v} - \vec{u}}{t}\end{aligned}$$

We use the symbols u and v to represent initial and final velocities respectively.

What is uniform acceleration?

In this lesson we will look at objects that are undergoing uniform acceleration; that is, when they are getting faster or slower in a uniform way.

uniformly accelerated motion
motion for which the velocity is changing in magnitude or direction in a regular manner

Examples of **uniformly accelerated motion** are easy to find and include:

- objects falling freely under gravity
- a car moving away uniformly from a traffic light
- a ball rolling down an incline.

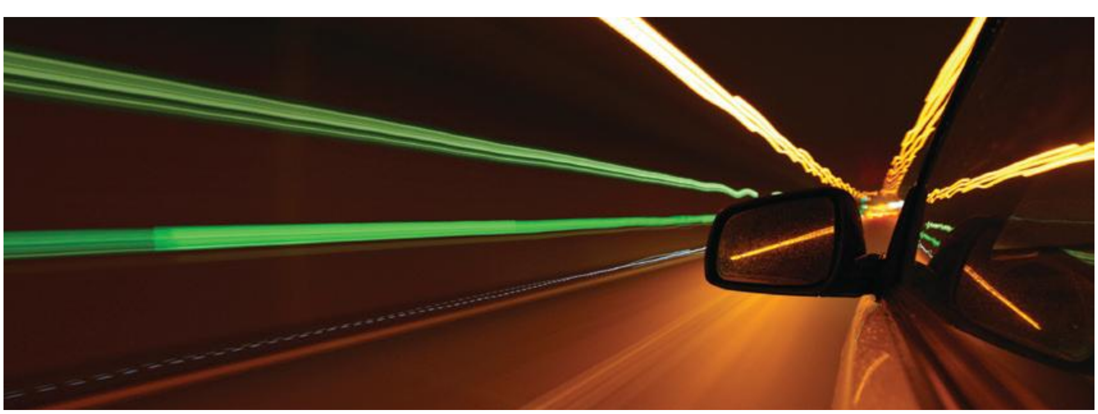


FIGURE 1 One example of uniform acceleration is when a car driving along a straight road increases its speed steadily.

What are uniform acceleration graphs?

So far we've looked at graphs where acceleration is zero. These are constant velocity situations. We found that the gradient of an *s*–*t* graph is the instantaneous velocity, and the area under a *v*–*t* graph is displacement. Now we can look at similar relationships for cases in which the object is undergoing constant acceleration. We will find out what gradients and areas might mean for *v*–*t* and *a*–*t* graphs.

Worked example 9.5A

Drawing *s*–*t*, *v*–*t* and *a*–*t* graphs

The measurements for a car taking off from the traffic lights are shown in the table.

Time elapsed, *t* (s)	Displacement, *s* (m)	Velocity, *v* (m s^{-1})
0	0	0
1	1	2
2	4	4
3	9	6
4	16	8
5	25	10

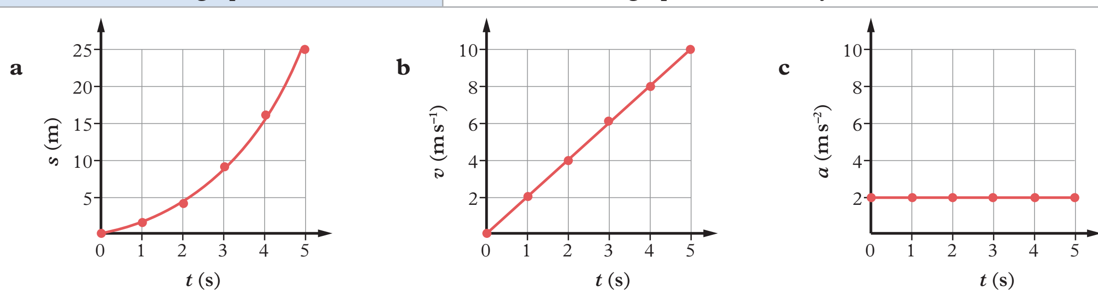
Sketch graphs of

a displacement vs time (1 mark)

b velocity vs time (1 mark)

c acceleration vs time. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Sketch" means to represent data with a diagram or graph. We must sketch three graphs to represent the data in Table 1. Two marks are available for each graph.
Step 2: Identify the data as motion and time data. Recall that in motion vs time graphs, time, the independent variable, goes on the *x*-axis. Gather any data that you require.	From Table 1: • the car's velocity is changing by 2 m s^{-1} every second. Its acceleration is said to be 2 m s^{-1} per second, or 2 m s^{-2}. This is constant. • the change of displacement is increasing for every second elapsed. In the 1st second, the displacement changes by 1 m, but in the 2nd second, the displacement changes by 3 m.
Step 3: Sketch the three graphs.	You can see how graphs of uniformly accelerated motion are related.



For graphs **a** and **b**: 1 mark forcorrectly labelled axes, correct sketch and line of best fit. For graph **c:** 1 mark for correctly labelled axes, 1 mark for plotting a constant acceleration of 2 m s^{-2}.

Think	Do
Step 4: Check that the three graphs align.	A non-linear *s*–*t* graph will give a sloped line for a *v*–*t* graph and a horizontal line for the *a*–*t* graph.

Your turn

The displacement and velocity of a ball rolling down an incline gave the following results.

Time, *t* (s)	Displacement, *s* (cm)	Velocity, *v* (cm s^{-1})
0	0	0
1	5	10
2	20	20
3	45	30

Sketch graphs of

a displacement vs time (1 mark)

b velocity vs time (1 mark)

c acceleration vs time. (2 marks)

How do you interpret accelerated motion graphs?

Velocity–time graphs are used to show the changes in the velocity of an object with time. The graph in Figure 2 represents a car accelerated from rest to 20 m s^{-1} in 10 s and then held at that speed for 10 s before the driver slows down to a stop over the next 20 s.

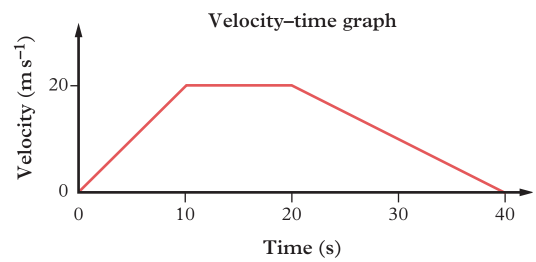


FIGURE 2 Velocity–time graph of a car

A straight line sloping upwards indicates constant acceleration, while a straight line sloping down indicates deceleration. A horizontal line indicates zero acceleration, which is constant velocity. The formula for acceleration $a = \frac{v - u}{t}$ is equivalent to $\frac{\Delta y}{\Delta x}$, so acceleration is equal to the gradient of a velocity–time graph.

Assuming an unchanging direction, the displacement can be calculated by finding the area under the line. This is demonstrated in Worked example 9.5B.

Worked example 9.5B

Interpreting motion graphs

Use the graph of the car's motion in Figure 2 to answer the following questions.

a **Calculate** the acceleration of the car at

i 5 s (2 marks)

ii 15 s (2 marks)

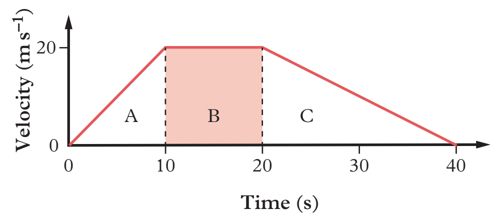
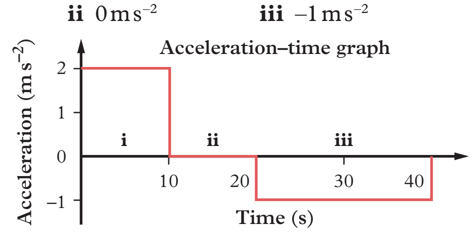
iii 30 s. (2 marks)

b **Calculate** the displacement after 40 s (2 s.f.). (3 marks)

c **Calculate** the average velocity (2 s.f.). (2 marks)

d **Sketch** an acceleration–time graph (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. In this question, 11 marks are for calculating values from a graph. There are also 3 marks for sketching a graph from calculated values.

Think	Do
Step 2: For part **a** (**i**), identify this as a motion question using graphs. State the relationship between acceleration and gradient of a v–t graph.	**a** **i** The acceleration at 5 s is equal to the gradient at 5 s.
Step 3: Calculate the gradient. Finalise your answer and make sure you have included the correct units.	a = gradie $= \frac{20-0}{10}$ (1 mark) $= 2\,\text{m}\,\text{s}^{-2}$ (1 mark)
Step 4: For part **a** (**ii**), calculate the gradient at 15 s and state the acceleration.	**a** **ii** Gradient equals zero, so acceleration is zero. (1 mark for identifying gradient as zero, 1 mark for correctly stating value of acceleration)
Step 5: For part **a** (**iii**), calculate the gradient at 30 s and state the acceleration. Finalise your answer and make sure you have included the correct units.	**a** **iii** a = gradient $= \frac{0-20}{40-20}$ (1 mark) $= -1\,\text{m}\,\text{s}^{-2}$ (1 mark)
Step 6: For part **b**, gather any data that you require. Recall that the displacement is the area under the curve.	**b** 
Step 7: Calculate the area of each of the three stages and add together. Take care that the sign of the area is used when calculating displacement. That is, if the section you are considering is below the x-axis, then the height of the figure will be negative and so the area will be negative. In this case all areas are above the line so they are all positive.	Total area = area A + area B + area C (1 mark) $= \frac{10 \times 20}{2} + 10 \times 2 + \frac{20 \times 20}{2}$ (1 mark) $= 100 + 200 + 200$ $s = 500\,\text{m}$ (or $5 \times 10^{2}\,\text{m}$) (1 mark)
Step 8: For part **c**, identify the formula for average velocity.	**c** Average velocity $= \frac{\text{displacement}}{\text{time}}$
Step 9: Substitute the known values into the formula and solve. Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The s.f. is not stated, but 2 s.f. is appropriate, as data given has 2 s.f.	$v_{av} = \frac{s}{t}$ $= \frac{500}{40}$ (1 mark) $= 12.5\,\text{m}\,\text{s}^{-1}$ $= 13\,\text{m}\,\text{s}^{-1}$ (2 s.f.) (1 mark)
Step 10: For part **d**, gather any data that you require to sketch the acceleration–time graph. Recall that data from part **a** showed acceleration values. Restate the values and draw the graph. Recall that time, as the independent variable, goes on the x-axis.	**d** **i** $2\,\text{m}\,\text{s}^{-2}$ **ii** $0\,\text{m}\,\text{s}^{-2}$ **iii** $-1\,\text{m}\,\text{s}^{-2}$  (1 mark for correctly labelled axes, 1 mark for correct graphing. Allow the second mark as a carry-forward error if calculated values are wrong but correctly plotted.)

Your turn

The motion of a polar bear hunting for food was recorded and plotted as the graph shown in Figure 3.

a **Calculate** the acceleration of the bear (2 s.f. in m s^{-1}) at
  i 1 minute (2 marks)
  ii 3 minutes (2 marks)
  iii 6.5 minutes. (2 marks)

b **Calculate** the displacement after 7.0 minutes (2 s.f.). (5 marks)

c **Calculate** the average velocity (2 s.f.). (2 marks)

d **Sketch** an acceleration–time graph for the 7 minutes. (3 marks)

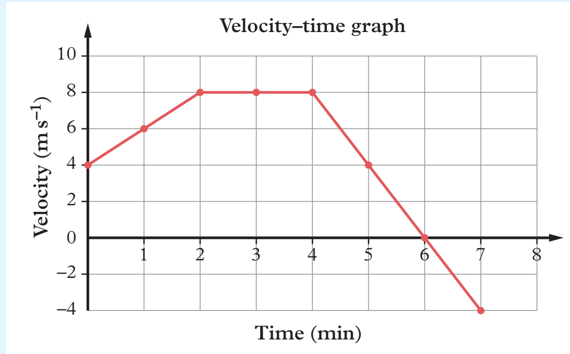


FIGURE 3 Velocity–time graph of a polar bear's motion

How do you deal with negative velocities?

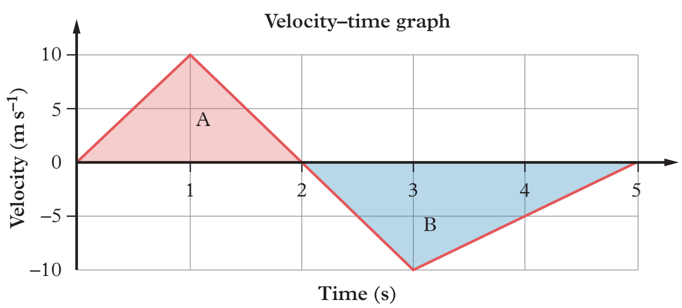


FIGURE 4 The motion of a person on a bungee ride

For cases in which the velocity becomes negative, the area beneath the x-axis is also negative and this must be taken into account when calculating displacement.

For example, consider the motion of a person on a slingshot ride attached to a bungee cord and being shot upwards and then coming down (Figure 4). You want to calculate the distance travelled and the displacement over the 5 s.

The displacement after 5 s is the area under the curve for the 5 seconds.

$$\begin{aligned}\text{Area under curve} &= \text{area A} + \text{area B}\\ &= \frac{\text{base of A} \times \text{height of A}}{2} + \frac{\text{base of B} \times \text{height of B}}{2}\\ &= \frac{2\times 10}{2} + \frac{3 \times -10}{2} \quad \text{(note that the height of triangle B is 10 m s}^{-1}\text{)}\\ &= 10 + (-15)\\ &= -5\,\text{m}\end{aligned}$$

However, the "distance travelled" after 5 s is not a vector quantity and the area underneath the x-axis for triangle B is not considered as negative. We just use the absolute values and ignore the positive and negative signs. The distance travelled is 25 m (10 m up plus 15 m back down).

$$\begin{aligned}\text{Area under curve} &= \text{area A} + \text{area B}\\ &= \frac{\text{base of A} \times \text{height of A}}{2} + \frac{\text{base of B} \times \text{height of B}}{2}\\ &= \frac{2\times 10}{2} + \frac{3 \times 10}{2}\\ &= 10 + 15\\ &= 25\,\text{m}\end{aligned}$$

How is the area under an acceleration–time graph interpreted?

We have already considered the area under a velocity–time graph: it equals the displacement. What, then, does the area under an acceleration–time graph mean? Acceleration is the rate of change of velocity. That is:

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time}}$$

The area under an a–t graph is acceleration (y-axis) multiplied by time (x-axis), and this equals change in velocity, Δv. Thus, the area under an a–t graph equals change in velocity. It is a vector quantity so the sign for acceleration (+/–) must be taken into account.

Here is an example from Worked example 9.5B. The final diagram shows the acceleration as a function of time for a car:

There are three stages: (i) the acceleration stage, (ii) the constant velocity stage, (iii) the negative acceleration stage. (Note: it is always better to use the term "negative acceleration" rather than "deceleration". You will learn more about this in Lesson 9.7). These are summarised in Table 3.

TABLE 3 Motion data for a car

Stage	Time, t (s)	Area (base × height) (m^2)	Change in velocity, Δv ($m\,s^{-1}$)
(i) Positive acceleration	0–10 s	(10 – 0) × (+2 – 0) = +20	$+20\,m\,s^{-1}$
(ii) No acceleration	10–20 s	0 (zero)	$0\,m\,s^{-1}$ (constant)
(iii) Negative acceleration	20–40 s	(40 – 20) × (–1 – 0) = –20	$-20\,m\,s^{-1}$

The total area under the graph is equal to 20 + (–20) = 0. Thus, we can say that there has been no overall change in velocity over the 40 s. The car started at $0\,m\,s^{-1}$ and finished at $0\,m\,s^{-1}$. But that is only for this example. In other cases the total area may not be zero but a positive or negative value.

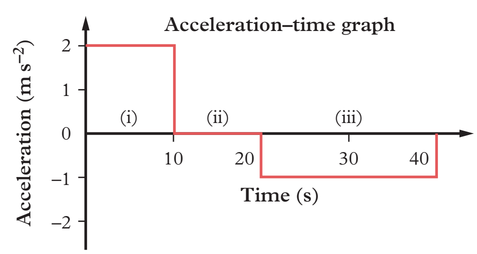


FIGURE 5 Acceleration–time graph for a car

Summary

Relationships:

- Gradient of a displacement–time graph equals the instantaneous velocity.
- Gradient of a velocity–time graph equals the acceleration.
- Area under a velocity–time graph equals the displacement.
- Area under an acceleration–time graph equals the change in velocity.

Graph shapes:

For an object travelling with uniformly accelerated motion, we can summarise graph shapes and their properties as shown in Figure 6.

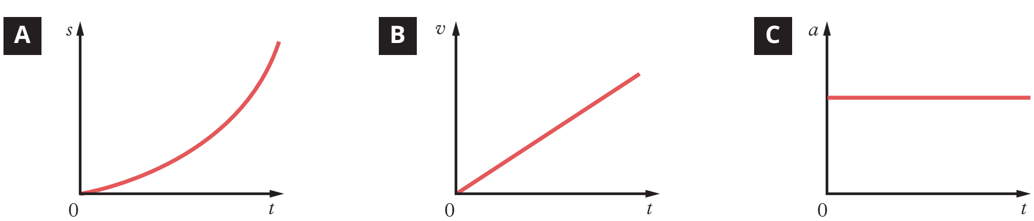


FIGURE 6 Motion graphs showing corresponding (A) displacement–time, (B) velocity–time and (C) acceleration–time relations for situations of uniform acceleration.

Study tip

You may come across the term "Plot" in practice exam papers. "Plot" means to draw a graph accurately, showing the relationship between two or more variables. This is similar to "Sketch".

Challenge

Train times

The 8.00 am express train from Cleveland to Brisbane arrives at 9.00 am, and the 8.30 am from Brisbane to Cleveland arrives at 9.30 am. Assuming both trains travel at constant speed, at what time should they pass each other? (3 marks)

FIGURE 7 At what time will the trains travelling in opposite directions pass each other?

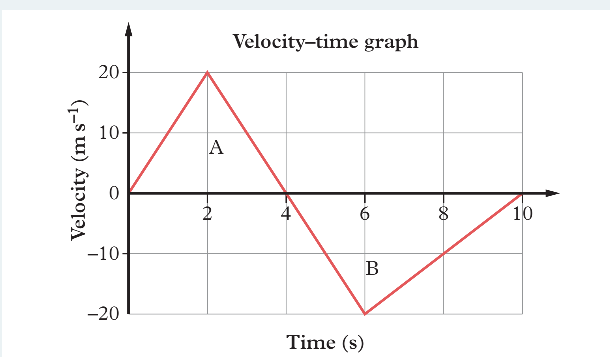
Check your learning 9.5

Check your learning 9.5: Complete these questions online or in your workbook.

Retrieval and comprehension

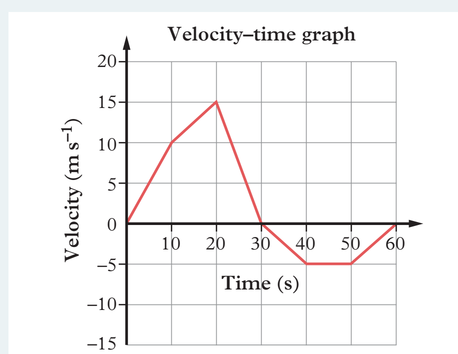
1 **Recall** what each of the following represents.
  - a Gradient of a s–t graph (1 mark)
  - b Gradient of a v–t graph (1 mark)
  - c Area under a v–t graph. (1 mark)

2 The graph shows the motion of a bungee jumper.
  - a Use the graph to



    - i **calculate** the bungee jumper's displacement and the distance travelled after 10 s (4 marks)
    - ii **calculate** the bungee jumper's acceleration at 1 s, 5 s and 8 s (3 marks)
    - iii **sketch** an acceleration–time graph (3 marks)
    - iv **calculate** the change in velocity using the acceleration–time graph. (2 marks)
  - b **Identify** when the bungee jumper was stationary. (1 mark)
  - c **Identify** when the bungee jumper's acceleration was constant but not zero. (3 marks)
  - d **Identify** when the bungee jumper's velocity was constant but not zero. (1 mark)

3 The graph illustrates the motion of a skateboard rider.



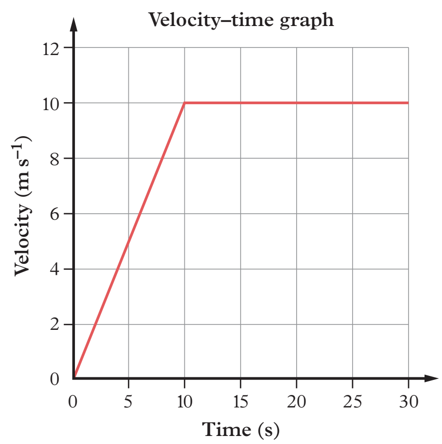
  - a **Calculate** the skater's displacement after 1 minute (3 s.f.). (2 marks)
  - b **Calculate** how far the skater travelled in the minute (2 s.f.). (1 mark)
  - c **Identify** the stage when the magnitude of the skater's acceleration was the greatest. (1 mark)

d **Identify** when the skater was stationary. (1 mark)

e **Identify** when the skater's acceleration was negative and constant. (1 mark)

f **Identify** when the skater's velocity was constant but not zero. (1 mark)

4 A runner is attempting to improve their stamina. They run along a straight track and their motion is shown on the graph.



a **Calculate** the distance covered in the first 20 s (2 s.f.). (2 marks)

b **Calculate** their instantaneous speed at 5 s (2 s.f.). (1 mark)

c **Calculate** their average speed for the whole 30 s (2 s.f.). (2 marks)

5 You may have heard the story about a hare who ridicules a slow-moving tortoise. Tired of the hare's boastful behaviour, the tortoise challenges the hare to a race. The hare soon leaves the tortoise behind and, confident of winning, takes a nap midway through the race. The hare awakes to find that the tortoise, crawling slowly but steadily, has arrived at the finish line first.

a **Sketch** a displacement–time graph to show how the tortoise won. (3 marks)

b **Sketch** a velocity–time graph to show how the tortoise won. (3 marks)

c **Sketch** an acceleration–time graph of the same motion. (3 marks)

Analytical processes

6 The table shows the data of a ball rolling down an incline.

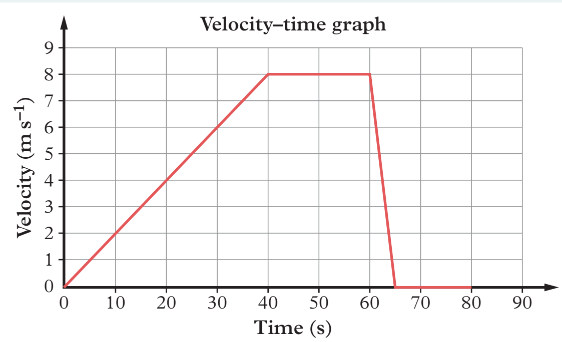
Time elapsed, t (s)	Displacement, s (m)	Velocity, v (m s^{-1})
0	0	0
1	3	6
2	12	12
3	27	18
4	48	24
5	75	30

a **Sketch** an s–t graph and a v–t graph of the data. (4 marks)

b **Determine** the acceleration of the rolling ball. (2 marks)

c **Consider** whether this is an example of uniformly accelerated motion. **Explain** your reasoning. (2 marks)

7 The motion of an object is depicted in the graph.



a **Calculate** the displacement of the object in the first 60 s (to the nearest whole number). Show your working. (2 marks)

b **Determine** the magnitude of the object's acceleration from 60 s to 65 s (2 s.f.). Show your working. (2 marks)

Practical

Learning intentions and success criteria

Video demonstration

Lesson 9.6
Displacement–time and velocity–time graphs for a ball on an incline

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Lesson 9.7
Equations of motion

Key ideas

→ The definitions of velocity and acceleration can be turned into formulas for solving problems algebraically.

→ These formulas can be rearranged and combined to produce new formulas.

→ For uniform acceleration of an object from rest, the final velocity is twice the average velocity.

→ Negative acceleration can mean slowing down or speeding up, depending on the direction of travel.

Learning intentions and success criteria

How else can we analyse motion?

Graphs are one way of analysing motion, but we can also do the same using algebra. In this lesson, we will see how the equations used so far can be combined to provide other useful ways of calculating and describing the motion of objects.

How can we develop motion formulas using the *suvat* variables?

The definitions of velocity and acceleration can be turned into formulas for use in solving problems algebraically. Many of the formulas can also be rearranged or combined to produce new formulas. Several examples are presented here along with worked solutions and practice problems. Teachers commonly call these formulas the "*suvat*" formulas (Table 1).

Note that the vector sign from the variables s, u, v and a has been omitted. The sign convention for positive motion and the oppositely directed negative motion has been used.

TABLE 1 The "*suvat*" variables

s	*u*	*v*	*a*	*t*
displacement	initial velocity	final velocity	acceleration	time

1. Rearrangement

We can start with the definition of acceleration as the rate of change of velocity and rearrange it:

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time}}$$
$$= \frac{\text{final velocity} - \text{initial velocity}}{\text{time}}$$
$$a = \frac{v-u}{t}$$
$$v = u + at \qquad \text{(equation 1)}$$

2. Substitution

Two separate formulas for average velocity can be combined:

$$\text{Average velocity} = \frac{s}{t}, \text{ which also equals } \frac{u+v}{2}$$
$$\frac{u+v}{2} = \frac{s}{t}$$
$$s = \frac{(u+v)t}{2} \qquad \text{(equation 2)}$$

We can then substitute equation (1) into (2):

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

Note, the definition of average velocity is $v_{av} = \frac{s}{t}$. You can also use $v_{av} = \frac{v+u}{2}$, but this only works if acceleration is constant. In a lot of your practical work, you will use the first formula to get the average velocity and then double it to get the final velocity if the object started at rest. It is more common for acceleration to be constant, including zero, in your experiments and problems.

3. Other substitution

We can further substitute one equation into another:

From equation (1) we get $t = \frac{v-u}{a}$. Substituting this into equation (2), we get:

$$s = \frac{u+v}{2} \times \frac{v-u}{a}$$
$$2as = (u+v)(v-u)$$
$$= v^2 - u^2$$
$$v^2 = u^2 + 2as$$

Summary of motion formulas

The motion formulas using *suvat* variables are summarised in Table 2.

TABLE 2 Motion formulas using *suvat* variables

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

Skill drill

Measuring the speed of a projectile

Science inquiry skills: Processing and analysing data (Lesson 1.7)

A student is investigating the motion of a projectile. They fire a Nerf bullet from a Nerf gun in the horizontal direction. The distance travelled and the time taken for the Nerf bullet to come to rest is analysed using video analysis software. Table 3 shows the results for three trials.

TABLE 3 Results for investigation of Nerf bullet motion

Trial	Distance, *s* (m)	Time, *t* (s)	Speed, *v* (m s^{-1})
1	3.25	0.230	14.1
2	2.95	0.220	
3	3.40	0.250	13.6

Practise your skills

1 **Calculate** the speed of the Nerf bullet in the second trial in Table 3. Give your answer to 1 decimal place. (2 marks)

2 **Determine** the absolute uncertainty (1 d.p.) and percentage uncertainty (1 s.f.) of the speed of the Nerf bullet. (3 marks)

Worked example 9.7A

Calculations using *suvat* equations

1 A car starts from rest and reaches a velocity of 60 km h^{-1} (16.67 m s^{-1}) in 8.0 seconds. Assume the acceleration is constant. **Calculate** (2 s.f.)

- **a** the acceleration (2 marks)
- **b** its displacement in this time interval. (2 marks)

2 A train starting from rest travels 30 m in 6.0 s. **Calculate** (2 s.f.)

- **a** the acceleration (assumed constant) (3 marks)
- **b** its velocity after 6.0 s. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do. Identify that all questions are motion calculations.	"Calculate" means to determine or find a number or answer by using mathematical processes. In this question, we need to apply formulas and find values for different types of motion.
Step 2: For question **1**, part **a**, identify the appropriate formula and gather the data that you require.	$v = u + at$ $u = 0$, $v = 16.67\ \text{m s}^{-1}$, $t = 8\ \text{s}$, $a = ?$; $s = ?$
Step 3: For part **a**, rearrange the formula so that you can calculate acceleration (a).	**1 a** $v = u + at$ $a = \frac{v - u}{t}$
Step 4: Substitute the known values into the formula and solve.	$a = \frac{v - u}{t}$ $= \frac{16.67 - 0}{8.0}$ (1 mark) $= 2.084$
Step 5: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The question requests 2 s.f.	$a = 2.1\ \text{m s}^{-2}$ (1 mark)

Think	Do
Step 6: For question **1**, part **b**, identify the appropriate formula to calculate displacement (s), substitute the known values into the formula and solve. Note: use the unrounded version of the acceleration (2.084) rather than the rounded one (2.1). This avoids compounding errors as we progress through the steps.	**b** $s = ut + \frac{1}{2}at^2$ $= 0 + \frac{1}{2} \times 2.084 \times 8.0^2$ (1 mark) $= 66.69$
Step 7: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The question requests 2 s.f.	$s = 67\,\text{m}$ (1 mark)
Step 8: For question **2**, part **a**, identify the appropriate formula to calculate acceleration (a) and gather the data that you require.	**2 a** $s = ut + \frac{1}{2}at^2$ (1 mark) $u = 0$, $s = 30\,\text{m}$, $t = 6.0\,\text{s}$
Step 9: Substitute the known values into the formula and solve.	$s = ut + \frac{1}{2}at^2$ $30 = 0 + \frac{1}{2} \times a \times 6.0^2$ $30 = 18a$ $a = 1.67$ (1 mark)
Step 10: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The question requests 2 s.f.	$a = 1.7\,\text{m}\,\text{s}^{-2}$ (1 mark)
Step 11: For question **2**, part **b**, identify the appropriate formula to calculate velocity (v), substitute the known values into the formula and solve. Use the unrounded value of a.	**b** $v = u + at$ $= 0 + 1.67 \times 6.0$ $= 10.02$ (1 mark)
Step 12: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. The question requests 2 s.f.	$v = 10\,\text{m}\,\text{s}^{-1}$ (1 mark)

Your turn

1 A runner starts from rest and reaches a velocity of $8.0\,\text{m}\,\text{s}^{-1}$ in 3.0 seconds. Assume acceleration is constant. **Calculate** (2 s.f.)

a their acceleration in this time interval (2 marks)

b their displacement in this time interval. (2 marks)

2 A ball rolling down an incline starts from rest and travels 1.2 m in 3.0 s. **Calculate** (2 s.f.)

a its acceleration, assumed constant (2 marks)

b the velocity after 3.0 s. (2 marks)

What is negative acceleration?

Acceleration is often negative, and you might think it just means the object is slowing down. This may not be the case. The negative sign is also an indicator of direction; hence, negative acceleration means the object is accelerating (getting faster) in the negative direction. It is often confused with "deceleration", which just means slowing down irrespective of the direction. It is best to avoid the term "negative deceleration" as it is very confusing. Here is a table to help you understand it.

Let an object move along a line between the positive and negative direction:

Acceleration, *a*	If travelling in the negative direction	If travelling in the positive direction
$+10\,\text{m}\,\text{s}^{-2}$	getting slower	getting faster
$-10\,\text{m}\,\text{s}^{-2}$ (acceleration due to gravity)	getting faster (ball dropped off a cliff)	getting slower (ball thrown up in the air)

Real-world physics

Speed cameras that use average velocity instead of instantaneous velocity

For many decades police have used radar cameras to measure the instantaneous speed of a car. The outward beam from the camera is reflected back to the detector and the system can determine how far the car moved in a given time. The problem is that a car could travel over the speed limit and just slow down for the camera. A newer system called "point-to-point" measures the average speed between two points using separate cameras located some distance apart, from less than 1 km through to 80 km.

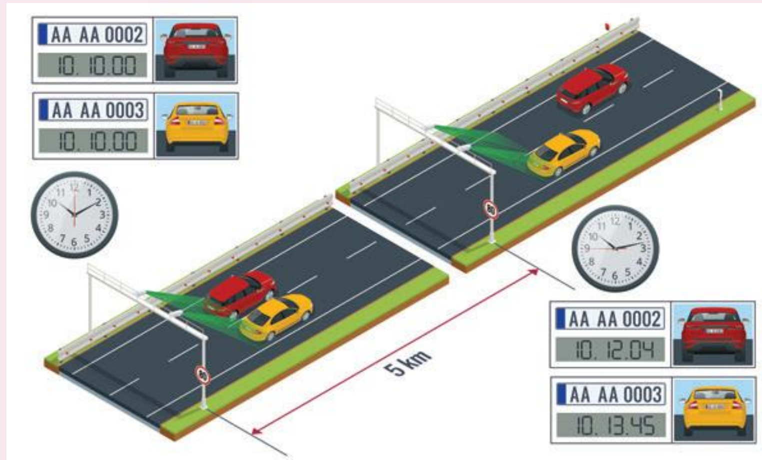


FIGURE 1 How the point-to-point average speed system works

The camera technology matches vehicle number plates at the two camera sites and calculates the time interval between them.

The average speed of a vehicle is calculated by dividing the distance between two camera sites by the time taken for the vehicle to travel between the two sites. If the average speed is greater than the speed limit, then a speeding ticket is issued.

Apply your understanding

1 **Explain** why there was a need for the average speed system to be introduced. (2 marks)

2 **Determine** whether a car could travel at twice the speed limit at any time between the cameras and still have an average speed below the limit. (3 marks)

Challenge

Army troop ride

A column of troops 3 km long is marching along a road. An officer rides a horse from the rear to the head of the column and back to the rear of the column of troops. He reaches the rear of the column just as an advance of 4 km has been made from where he first left. How far did he ride? (4 marks)

FIGURE 2 How far did the officer ride along the column of troops?

Check your learning 9.7

Check your learning 9.7: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Identify** the formula that links the symbols s, u, t and a. (1 mark)

2 One of the '*suvat*' formulas has been rearranged to give $v^2 - u^2 = ?$ **Identify** the original formula and complete the one presented here. (2 marks)

3 **Explain** what a negative value for acceleration means in terms of motion of an object. (2 marks)

4 A person travels from A to B at 30 km h^{-1}. **Calculate** how fast they must return to average 40 km h^{-1} for the whole trip. (3 marks)

5 A bus travelling in a straight line accelerates from 60 km h^{-1} to 100 km h^{-1} in 1 minute. **Calculate** the acceleration in m s^{-2}. (3 marks)

6 A car travelling at 30 m s^{-1} decelerates at a uniform rate of 1.5 m s^{-2}. **Calculate** how many seconds it will take the car to stop and how far it will travel in this time. (4 marks)

7 A cyclist starts from rest and attains a velocity of 21 m s^{-1} in 3.5 seconds. **Calculate** (2 s.f.) the

a acceleration (assumed constant) (2 marks)

b displacement. (2 marks)

Analytical processes

8 **Structure** $v = u + at$ so that t is the subject of the equation: $t = ?$ (1 mark)

9 Copy and complete the table to **determine** equations of motion (2 s.f.). Remember that change in velocity $\Delta v = v - u$. (2 marks per row)

	v (m s^{-1})	u (m s^{-1})	Δv (m s^{-1})	t (s)	a (m s^{-2})
a	18	10		2.0	
b	42		4		4.0

10 Copy and complete the table to **determine** the missing values (2 s.f.). (2 marks per row)

	s (m)	u (m s^{-1})	v (m s^{-1})	a (m s^{-2})	t (s)
a		0		2.5	3
b	100	0			2.4
c		10	25	2	

11 Copy and complete the table to **determine** the missing values (2 s.f.). (2 marks per row)

	s (m)	u (m s^{-1})	v (m s^{-1})	a (m s^{-2})	t (s)
a		+10	+30		2
b		+30	+10		2
c		–10	30		2
d		–30	–10		2

12 A road-tested acceleration for a standard production car of 0 to 96.5 km h^{-1} (26.8 m s^{-1}) in 3.98 s was reported for a Ferrari F40 in 1989. **Determine** the acceleration of the car. (2 marks)

13 The head of a rattlesnake can accelerate at 50 m s^{-2} when striking a victim. **Determine** how many seconds it would take for a car to reach a speed of 27 m s^{-1} (100 km h^{-1}) from rest if it could match the snake's acceleration. (2 marks)

14 The click beetle (*Athous haemorrhoidalis*) experiences an acceleration of 24,000 m s^{-2} over a distance of 5 mm when it jack-knifes into the air to avoid predators. **Determine** the time duration over which this acceleration occurs. (4 marks)

15 Two cars accelerate at 2 m s^{-2} for 10 seconds. **Deduce** whether they will both cover the same distance, and justify your reasoning with data. (5 marks)

Lesson 9.8
Acceleration due to gravity

Key ideas

→ For acceleration due to gravity, the upwards direction is regarded as positive.

→ Objects near the surface of Earth have a free-fall acceleration due to gravity of $-9.8\ \text{m s}^{-2}$.

Learning intentions and success criteria

What is motion due to gravity?

gravity
a fundamental interaction that causes mutual attraction between all things with mass

One of the most common examples of uniformly accelerated motion in a straight line is an object that falls freely due to **gravity**. Until Galileo (1564–1642), people thought that heavy objects fell faster than light objects. They saw no need for experiments that might have confirmed or refuted these beliefs. They relied on the theories of Aristotle, who believed that objects fell at speeds that depended on their weight. Galileo performed some of the earliest experiments that showed that both heavy and light objects in the absence of air and other resistance fell with constant acceleration. Thus, two objects of different masses, dropped from the same height at the same time, should strike the ground simultaneously. He also worked out a relationship between time and the distance a ball rolled down an inclined plane (Figure 1).

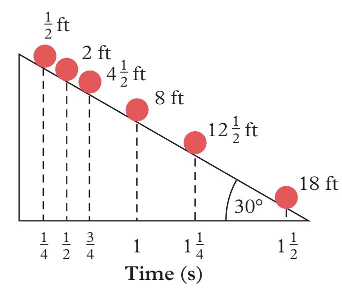


FIGURE 1 Galileo's data from his inclined plane experiments

Motion due to gravity can take two main forms: vertical motion and projectile motion. Vertical motion involves an object moving in one dimension only (up and down). Projectile motion involves an object moving horizontally as well as vertically, such as a stone thrown off a cliff. This module deals only with vertical motion. In Unit 3, projectile motion, which involves both vertical and horizontal motion, is dealt with in detail.

What are the types of free-fall motion?

free-fall motion
any motion of a body where gravity is the only force acting upon it

Vertical **free-fall motion** can be grouped into two classes:

1 The object is being dropped or thrown down.

2 The object is being thrown vertically upwards.

When dealing with calculations involving acceleration due to gravity, we need to assign a positive and negative direction of motion. Unless otherwise stated, we will use the convention of upwards as positive and downwards as negative (this is the most common).

Acceleration due to gravity

Acceleration due to gravity near Earth's surface is constant at $9.8\,m\,s^{-2}$. The net force on a free-falling object will be downwards, which is in the negative direction. Hence, the acceleration due to gravity is negative, $g = -9.8\ m\ s^{-2}$. This means an object will increase its velocity in the negative direction by $9.8\,m\,s^{-1}$ every second.

As we learnt in Lesson 9.7, students often think a negative acceleration means deceleration or slowing down, but this is not always so. If an object is moving in the negative direction (down) and has negative acceleration, such as on Earth with a free-fall acceleration of $-9.8\ m\ s^{-2}$, then the object will get faster in that negative direction. If the object is moving in the positive direction (upwards) and has a negative acceleration, then the object will slow down in that positive direction. That means an object moving upwards, but in free fall, has acceleration directed downwards (in the negative direction) of $-9.8\,m\,s^{-2}$, so it is slowing down as it moves upwards. Eventually it slows to a halt and then starts to move down and speed up. Every time you throw a ball up in the air you would notice this. It seems confusing at first, but practice with the formulas will help you come to terms with this.

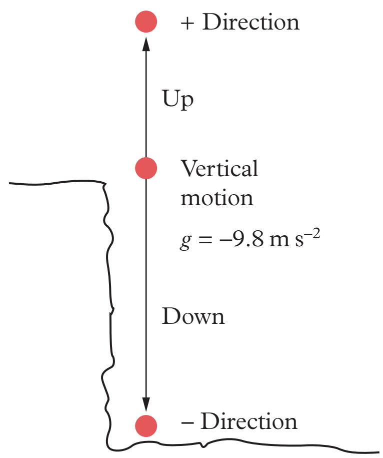


FIGURE 2 The most common convention is upwards as positive and downwards as negative.

What effect does dropping or throwing an object down have?

Dropping or throwing an object down typically involves dropping it from a high place such as a cliff or throwing it vertically downwards. In both cases the velocity increases in the negative direction. The only difference is the initial velocity. When an object is dropped, the initial velocity (u) is zero. When an object is thrown down, the velocity begins at a negative value (because down is negative). An object dropped from above you will also have some initial velocity (with a negative value) as it passes you on the way down. In all cases, the velocity becomes more negative. Eventually, the object will strike the ground. Its velocity at impact is called the impact velocity.

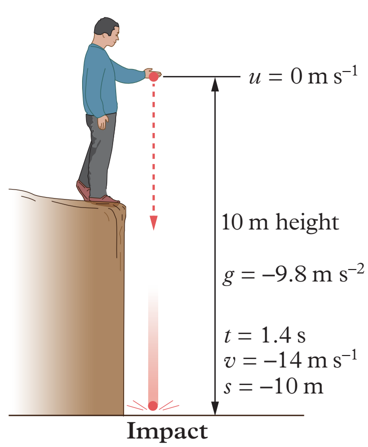


FIGURE 3 A person drops a ball off a cliff from a 10 m height. The displacement at the base of the cliff is −10 m. The velocity with which the ball strikes the ground – its impact velocity – is also negative ($-14\,m\,s^{-1}$).

Worked example 9.8A

Calculations for an object dropped

A spanner is dropped from a sixth-floor window and takes 2.2 s to hit the ground. **Calculate** (2 s.f.) the

a height from which it was dropped (2 marks)

b impact velocity. (2 marks)

Think	Do
Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply formulas and find values for different types of motion. Each part of this question is worth 2 marks.
Step 1: For part **a**, identify this as an acceleration due to gravity question. Identify the relevant data and select the appropriate formula.	**a** $u = 0\,\text{m s}^{-1}$; $a = -9.8\,\text{m s}^{-2}$; $t = 2.2\,\text{s}$ $s = ut + \frac{1}{2}at^2$
Step 2: Substitute the values into the formula to find the height (displacement (s)) and solve.	$s = ut + \frac{1}{2}at^2$ $= 0 + \frac{1}{2} \times -9.8 \times (2.2)^2$ $= -23.7\text{m}$ (1 mark)
Step 3: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Note that the displacement is –24 m but the height of the building is a scalar value so it has no sign. It is just 24 m.	Height = 24 m (1 mark) (–24 m is acceptable.)
Step 4: For part **b**, identify the relevant data and select the appropriate formula.	**b** $u = 0\,\text{m s}^{-1}$; $a = -9.8\,\text{m s}^{-2}$; $t = 2.2\,\text{s}$ $v = u + at$
Step 5: Substitute the values into the formula to find the velocity (v) and solve.	$v = u + at$ $= 0 + -9.8 \times 2.2$ (1 mark) $= -21.56$
Step 6: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Velocity is measured in m s^{-1} and 2 s.f. are requested. The negative means it has a speed of –22 m s^{-1} or 22 m s^{-1} in the negative direction. As velocity is a vector quantity, you must state the direction, either by including the negative sign or using the words "vertically down".	$v = -22\,\text{m s}^{-1}$ (1 mark for both magnitude and direction)

Your turn

A golf ball is dropped from a second-floor balcony and takes 1.1 s to hit the ground. **Calculate** (2 s.f.) the

a height from which the ball was dropped (2 marks)

b ball's impact velocity. (2 marks)

Worked example 9.8B

Calculations for an object thrown down

A hot air balloon is descending (going down) at $5\,\text{m}\,\text{s}^{-1}$ when a person on board drops their phone overboard. It takes the phone 6.0 s to reach the ground below. Assume air resistance is negligible. **Calculate** (2 s.f.) the

a height from which the phone was dropped (2 marks)

b phone's impact velocity. (2 marks)

Think	Do
Look at the cognitive verb and mark allocation to determine what the question is asking you to do. Identify that both questions are motion calculations.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply formulas and find values for different types of motion. The questions are worth 2 marks each, so we must gather the correct information and correctly apply the formula to complete the calculations.
Step 1: For part **a**, identify this as an acceleration due to gravity question. Identify the relevant data and select the appropriate formula. Note that the initial velocity is downwards, so it is negative.	**a** $u = -5.0\,\text{m}\,\text{s}^{-1}$; $a = -9.8\,\text{m}\,\text{s}^{-2}$; $t = 6.0\,\text{s}$ $s = ut + \frac{1}{2}at^2$
Step 2: Substitute the values into the formula to find the height (displacement (s)) and solve.	$s = ut + \frac{1}{2}at^2$ $= -5.0 \times 6.0 + \frac{1}{2} \times -9.8 \times (6.0)^2$ $= -206.4\,\text{m}$ (1 mark)
Step 3: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f.). Note that the displacement is –210 m but the height of the balloon is a scalar value, so it has no sign. It is just 210 m.	Height = 210 m (1 mark) (–210 m is acceptable.)
Step 4: For part **b**, identify the relevant data and select the appropriate formula.	**b** $u = -5.0\,\text{m}\,\text{s}^{-1}$; $a = -9.8\,\text{m}\,\text{s}^{-2}$; $t = 6.0\,\text{s}$ $v = u + at$
Step 5: Substitute the values into the formula to find the velocity (v) and solve.	$v = u + at$ $= -5.0 + -9.8 \times 6.0$ $= 63.8$ (1 mark)
Step 6: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures. Velocity is measured in $\text{m}\,\text{s}^{-1}$ and 2 s.f. is requested. The negative means it has a speed of $-64\,\text{m}\,\text{s}^{-1}$ or $64\,\text{m}\,\text{s}^{-1}$ in the negative direction. As velocity is a vector quantity, you must state the direction, either by including the negative sign or using the words "vertically down".	$v = -64\,\text{m}\,\text{s}^{-1}$ or $v = 64\,\text{m}\,\text{s}^{-1}$ vertically down (1 mark)

Your turn

A window is being lowered by a construction crane at a speed of $1.5\,\text{m}\,\text{s}^{-1}$ when the rope breaks and the window plummets to the ground below. It takes 2.0 s to hit the ground. Assuming air resistance is negligible, **calculate** (2 s.f.)

a the height from which it was dropped (2 marks)

b its impact velocity. (2 marks)

What happens when you throw an object upwards?

Trajectory of an object thrown vertically

When a ball is thrown vertically upwards, it starts at a high initial velocity in the positive direction, gradually slows to a halt at the top of its flight and then gradually increases velocity (in the negative direction) until it returns to the ground.

Figure 4 shows the flight of a ball thrown vertically upwards. Note: although its downwards path is exactly the same as the upwards path, it is drawn slightly to the right for clarity.

Notice that:

- velocity equals zero at the top of flight
- time of flight up equals time down
- acceleration is constant at $-9.8\,\text{m}\,\text{s}^{-2}$, even at the top of flight when velocity is zero
- final speed equals initial speed
- final velocity equals the negative of the initial velocity
- air resistance is negligible; it can be ignored for our purposes.

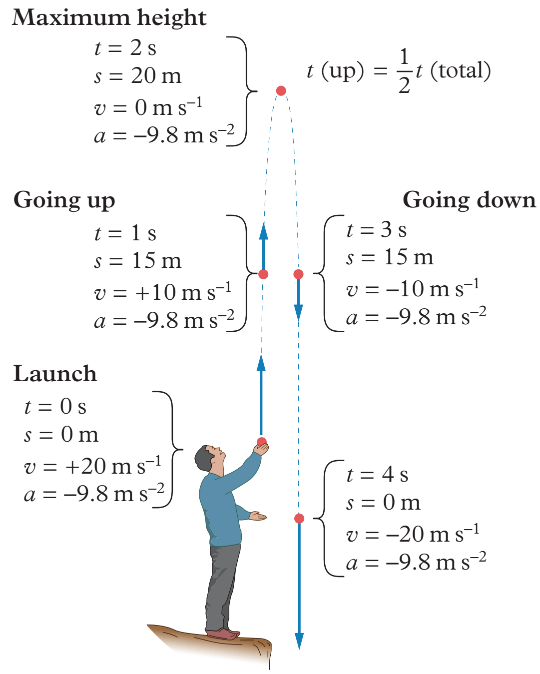


FIGURE 4 Flight of a ball thrown vertically upwards

Worked example 9.8C

Calculations for object thrown upwards

A ball is launched vertically upwards at $20\,\text{m}\,\text{s}^{-1}$. Ignore air resistance and take $g = -9.8\,\text{m}\,\text{s}^{-2}$.
Calculate (2 s.f.)

a how high the ball goes (3 marks)
b the time it takes to reach this height (2 marks)
c the time it takes to reach the ground from the highest point (2 marks)
d the final velocity (2 marks)
e total time of flight. (2 marks)

Think	Do
Look at the cognitive verb and mark allocation to determine what the question is asking you to do. Identify that all questions are motion calculations.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply formulas and find values for different types of motion. This question is worth a total of 11 marks.
Step 1: Identify this as an acceleration due to gravity question. Identify the relevant data.	$u = +20\,\text{m}\,\text{s}^{-1}$, $g = -9.8\,\text{m}\,\text{s}^{-2}$ At the top of the ball's flight $v = 0\,\text{m}\,\text{s}^{-1}$.
Step 2: For part **a**, select the appropriate formula.	**a** $v^2 = u^2 + 2as$ (1 mark)

Think	Do
Step 3: Substitute the values into the formula to find the height (displacement, s).	$0 = (+20)^2 + 2 \times -9.8 \times s$ $19.6 \times s = 400$ $s = 20.4$ (1 mark)
Step 4: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f. requested).	$s = 20$ m up in the air (1 mark) Note that it is a positive value.
Step 5: For part **b**, select the appropriate formula.	**b** $v = u + at$
Step 6: Substitute the values into the formula to find the time.	$0 = +20 + -9.8t$ $t = 2.04$ (1 mark)
Step 7: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f. requested).	$t = 2.0$ s (1 mark)
Step 8: For part **c**, select the appropriate formula.	**c** $s = ut + \frac{1}{2}at^2$
Step 9: Substitute the values into the formula to find the time. Recall that the ground is 20.4 m in the negative direction from the top of flight. Hence, $s = -20.4$ m.	$-20.4 = 0 + -4.9t^2$ $t^2 = \frac{-20.4}{-4.9}$ $t = 2.04$ (1 mark)
Step 10: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f. requested). Note that it is the same time as the time to travel up to highest point.	$t = 2.0$ s (1 mark)
Step 11: For part **d**, select the appropriate formula to find final velocity and substitute the values into the formula. As before, finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f. requested).	**d** $v = u + at$ $= 0 + -9.8 \times 2.04$ $= -20\,\text{m s}^{-1}$ (1 mark for substitution; 1 mark for correct direction and magnitude)
Step 12: For part **e**, recall that time up = 2.04 s; time down = 2.04 s. Hence, total time of flight is 4.08 s. Using the equations of motion, it can be shown that when the displacement is zero, the time for this to occur is 0 s (the start) and 4.08 s (the finish). Select the appropriate formula to find time (t) and substitute the values into the formula.	**e** $s = ut + \frac{1}{2}at^2$ $0 = 20 \times t + 4.9t^2$ $t = \frac{20}{4.9}$ $= 4.08$ (1 mark)
Step 13: Finalise your answer and make sure you have included the correct units and expressed your answer to the correct number of significant figures (2 s.f. requested).	$t = 4.1$ s (1 mark) (4.0 s is acceptable if you have doubled the 2.0 s up and 2.0 s down.)

Your turn

A rock is fired vertically upwards from the ground at $50\,\text{m s}^{-1}$. Ignore air resistance and take $g = -9.8\,\text{m s}^{-2}$. **Calculate** (2 s.f.)

a how high the rock goes (2 marks)
b the time it takes to reach this height (2 marks)
c the time it takes to reach the ground from the highest point (2 marks)
d the final velocity (2 marks)
e total time of flight. (2 marks)

What are graphs of free-fall motion?

The two most common types of free-fall motion (dropped down and thrown upwards) can be examined graphically.

Dropped down

Figure 5 shows the relationship between an acceleration–time graph and the corresponding velocity–time graph for an object dropped off a cliff. The downwards direction is negative as usual.

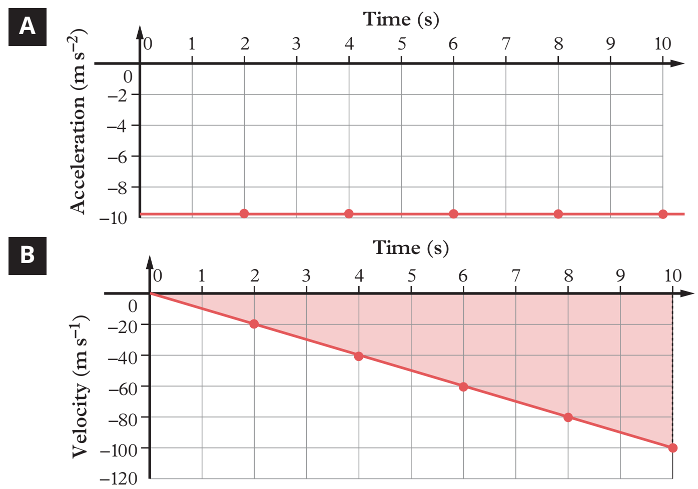


FIGURE 5 (A) An acceleration–time graph; (B) a velocity–time graph (shaded area indicates the displacement)

Thrown upwards

Figure 6 shows the graphs of motion of an object (such as a ball) thrown upwards into the air and allowed to return to its starting position. Note that the acceleration is constant, even at the top of flight when the ball is stationary. Again, down is negative.

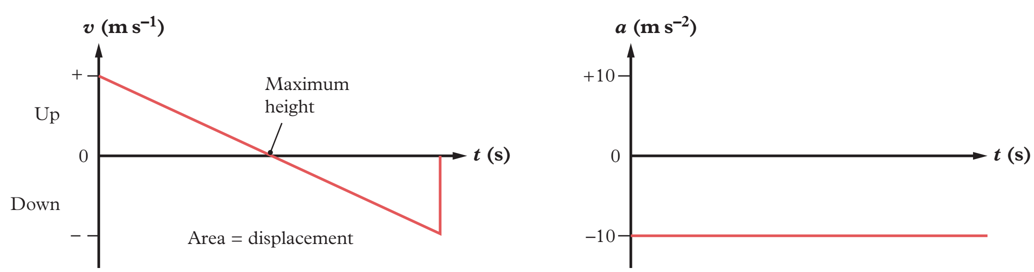


FIGURE 6 Graphs of the motion of an object thrown vertically upwards

Check your learning 9.8

Check your learning 9.8: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** why the acceleration of an object thrown upwards is not zero at the top of its flight. (3 marks)

2 **Explain** why the velocity of an object at maximum height is zero. (1 mark)

3 A rock is dropped off a cliff and it takes 4.0 s to reach the base below. **Calculate** the height of the cliff (2 s.f.). (3 marks)

4 A rock is launched vertically upwards from the ground at a starting speed of $35\,m\,s^{-1}$.

- **a** **Calculate** the maximum height reached (2 s.f.). (3 marks)
- **b** **Calculate** the time taken to reach this maximum height (2 s.f.). (3 marks)
- **c** **Calculate** the time taken for the rock to fall from maximum height back to the ground again (2 s.f.). (2 marks)

5 A person is in a hot-air balloon moving vertically upwards at a constant speed of $4.9\,m\,s^{-1}$. They drop a sandbag when the balloon is at an elevation of 98 m.

- **a** **Calculate** the velocity of the sandbag on impact (2 s.f.). (3 marks)
- **b** **Calculate** the time it will take the sandbag to hit the ground (2 s.f.). (2 marks)

Analytical processes

6 A pot plant falls 25.0 m from a windowsill and bounces off a rubber mat on the ground below. It reaches a height of 2.0 m.

- **a** **Determine** its impact velocity (2 s.f.). (3 marks)
- **b** **Determine** its change in velocity on the rubber mat (2 s.f.). (2 marks)

7 Driving along a country road, a couple has a dispute about reading the map. The driver gets out of the car, stands on the edge of a cliff, and throws their wedding ring vertically upwards. As the ring passes them on the way down 3.4 seconds later, they drop their other ring – an engagement ring – off the cliff.

- **a** **Calculate** how many seconds apart the two rings strike the rocks 50 m below. Assume air resistance is negligible. (10 marks)
- **b** **Describe** the magnitude and direction of the acceleration the rings experience from the time they leave the driver's hand until they each reach the ground. (2 marks)

Knowledge utilisation

8 **Assess** the accuracy of this statement: "Acceleration due to gravity is $+9.8\,m\,s^{-2}$ on the other side of Earth." (3 marks)

9 A startled armadillo leaps upwards and rises 54.4 cm in the first 0.20 s, and keeps rising.

- **a** **Calculate** the armadillo's initial speed. (2 marks)
- **b** **Calculate** its speed at 54.4 cm (2 s.f.). (3 marks)
- **c** **Predict** how much higher it goes (2 s.f.). Show your working. (4 marks)
- **d** **Evaluate** this statement: "The armadillo's maximum acceleration was at push-off from rest." (2 marks)

Practical

Lesson 9.9

Acceleration due to gravity by linearising time–displacement graphs

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

MODULE 9

Lesson 9.10
Review: Linear motion

Summary

9.1
- A vector quantity needs both magnitude and spatial direction to specify it fully.
- Horizontal and vertical coordinates are used to represent direction.
- Vector quantities can be represented pictorially and symbolically.
- Scalar quantities have magnitude but no spatial direction.

9.2
- Distance describes the total length of the pathway taken between the origin and the destination point; a scalar quantity.
- Displacement describes change in position in a given direction and is a vector quantity.
- Two or more vector quantities can be added to produce a single resultant vector.
- Vector quantities can also be subtracted. Change in a vector measurement means subtraction.
- Multiplication of a vector (magnitude + direction) by a scalar (magnitude) will change the magnitude of the vector but will leave its direction unchanged.

9.3
- Speed is the rate at which a distance is covered; it is a scalar quantity.
- Velocity is the rate of change of displacement of an object; it is a vector quantity.

9.4
- Linear motion graphs show data about objects moving at constant (uniform) velocity.
- The gradient of a displacement–time graph is a measure of the instantaneous velocity.
- The area under a velocity–time graph is a measure of displacement.

9.5
- Acceleration is the change in velocity over a particular time.
- Displacement and acceleration can be calculated from velocity–time graphs.
- Change in velocity can be calculated from acceleration–time graphs.

9.6
- Practical: Displacement–time and velocity–time graphs for a ball on an incline

9.7
- The definitions of velocity and acceleration can be turned into formulas for solving problems algebraically.
- These formulas can be rearranged and combined to produce new formulas.
- For uniform acceleration of an object from rest, the final velocity is twice the average velocity.
- Negative acceleration can mean slowing down or speeding up, depending on the direction of travel.

9.8
- For acceleration due to gravity, the upwards direction is regarded as positive.
- Objects near the surface of Earth have a free-fall acceleration due to gravity of $-9.8\ \mathrm{m\,s^{-2}}$.

9.9
- Practical: Acceleration due to gravity by linearising time–displacement graphs

Key formulas

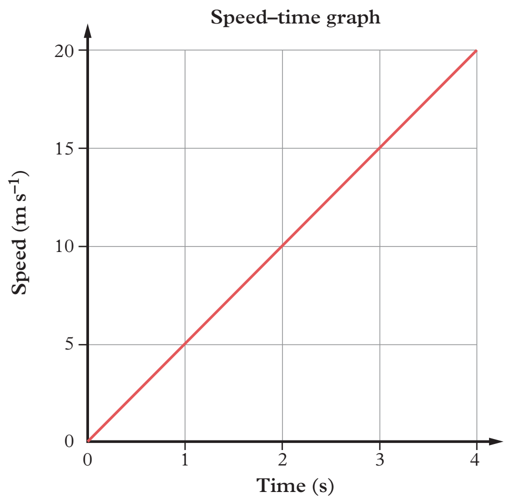
Motion formula (velocity)	$v = u + at$
Motion formula (displacement)	$s = ut + \frac{1}{2}at^2$
Motion formula	$v^2 = u^2 + 2as$
Average velocity	$\vec{v}_{av} = \frac{\vec{s}}{t}$

Review questions 9.10A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 This is a speed versus time graph for an object moving in a straight line.



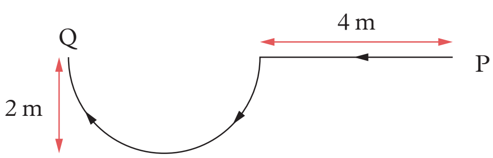
The distance travelled by the object during the first 4 seconds is

A 80 m. **B** 40 m.
C 20 m. **D** 5 m.

2 Which of the following quantities can be determined from a speed–time graph of a particle travelling in a straight line?

A Only the magnitude of the acceleration at a given instant
B Both the velocity and the acceleration at a given instant
C Only the distance travelled in a given time
D Both the distance travelled in a given time and the magnitude of the acceleration at a given instant

3 Samantha walks along a horizontal path in the direction shown. The curved part of the path is a semicircle.



The magnitude of her displacement from point P to point Q is approximately

A 4 m. **B** 6 m.
C 8 m. **D** 10 m.

4 A ball is thrown upwards and caught at the same height as it comes back down. In the absence of air resistance, the speed of the ball just before it is caught would be

A less than the speed it had when thrown upwards.
B more than the speed it had when thrown upwards.
C the same speed it had when thrown upwards.
D 0 m s^{-1}.

5 A car accelerates at 2 m s^{-2}. Assuming the car started from rest, how much time will it need to accelerate to a speed of 20 m s^{-1}?

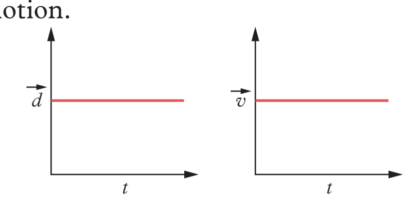
A 2 s **B** 10 s
C 20 s **D** 40 s

6 An object travels 5 m east, then changes direction and travels 7 m north. The magnitude of its displacement is

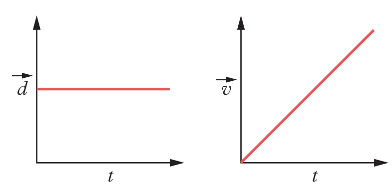
A 2.0 m. **B** 8.6 m.
C 13 m. **D** 74 m.

7 Identify which pair of graphs show the same motion.

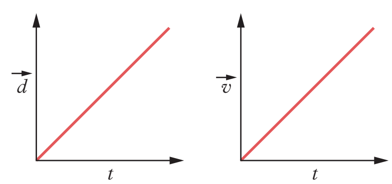
A



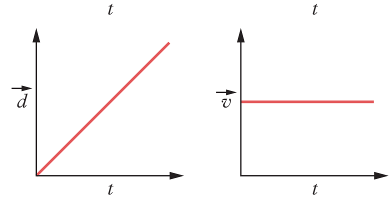
B



C



D



8 A vehicle travels 120 m east in 20 seconds, then turns around and travels 50 m west in another 8 seconds. Determine the average velocity of the vehicle.

A 2.5 m s^{-1} east **B** 2.5 m s^{-1} west
C 6.1 m s^{-1} east **D** 6.1 m s^{-1} west

9 A cyclist travels 20 m from point A to point B along a track. The cyclist has a speed of 4 m s^{-1} at point A, and a speed of 7 m s^{-1} at point B. Determine how long it takes the cyclist to travel from point A to point B. (Assume the cyclist has uniform acceleration.)

A 0.825 s **B** 1.5 s
C 3.6 s **D** 11 s

10 An object accelerates uniformly from 1.5 m s^{-1} to 4 m s^{-1} in 2 seconds. Determine the distance travelled by the object during these 2 seconds.

A 1.25 m **B** 2.75 m
C 5.50 m **D** 7.50 m

Review questions 9.10B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

11 **Describe** these terms in the context of a car taking off from a stationary start at traffic lights: acceleration, change in speed, change in velocity, displacement, distance, linear motion, speed, vector and velocity. (8 marks)

12 **Identify** whether the following statements about motion are true or false.

a When a ball is thrown vertically, it has an acceleration of –9.8 m s^{-2} on its way up and down, but zero acceleration at the top. (1 mark)

b When an object travels in a straight line, the displacement equals distance travelled. (1 mark)

c An object slowing down has negative velocity. (1 mark)

d Time is a vector quantity because it has a forwards and backwards direction. (1 mark)

13 The best time by an Australian in the 42.2 km marathon is 2 h 7 min 51 s. **Calculate**

a their average speed in km h^{-1} (2 marks)

b the time it would take a 100 m sprint champion if they ran the 42.2 km distance at a sprint speed of 10.15 m s^{-1}. (2 marks)

14 A person runs in a straight line 84 m south in 9.0 s and then 160 m north in 18.0 s. **Calculate** (2 s.f.) the runner's

a displacement (magnitude only) (1 mark)

b average speed (2 marks)

c average velocity (magnitude only). (2 marks)

15 **Calculate** the missing values and complete the table to practise applying the acceleration formula (2 s.f.). (1 mark per row)

	v (m s^{-1})	u (m s^{-1})	t (s)	a (m s^{-2})
a	100	40	3.5	?
b	60	130	0.85	?
c	250	?	1.5	4.0

16 A car with an initial velocity of 3.0 m s^{-1} has a velocity of 34 m s^{-1} after 3.0 s. **Calculate** (2 s.f.)

a its acceleration (2 marks)

b its average velocity (4 marks)

c how far it moved in its third second of motion (from t = 2 s to t = 3 s) (5 marks)

d its speed after travelling 20 m. (2 marks)

17 **Calculate** the missing data to complete the table (2 s.f.). (2 marks per row)

	s (m)	u (m s^{-1})	v (m s^{-1})	a (m s^{-2})	t (s)
a		0		3	1.5
b	200	0			1.4
c		20	65	2.6	

18 A cyclist is travelling at a constant 10 m s^{-1} along a flat road when they arrive at a small hill. They let the bike 'coast' up the hill without pedalling. Assume the cyclist decelerates uniformly at 1.8 m s^{-2}. **Calculate**

a how far the cyclist will travel up the hill before coming to rest (2 s.f.) (2 marks)

b how many seconds this will take (2 s.f.). (2 marks)

19 In the 1993 British Motorcycle Grand Prix, Kevin Schwantz was eliminated after a crash. *Australian Motorcycle News* described the crash: "Schwantz was the first to crash after asking too much of a cold rear tyre. He hit the grass at 290 km h^{-1} and slid to a halt in a set of sand traps 50 m down the track." **Calculate** Schwantz' deceleration in this accident (2 s.f.). (2 marks)

20 Suppose a rocket ship in deep space moves with a constant acceleration of 9.8 m s^{-2}, which gives the illusion of normal gravity during the flight.

a If the rocket starts from rest, **calculate** the time it will take to reach a speed one-tenth that of the speed of light (speed of light is 3×10^8 m s^{-1}) (2 s.f.). (3 marks)

b **Calculate** how far in metres it will travel in doing so (2 s.f.). (2 marks)

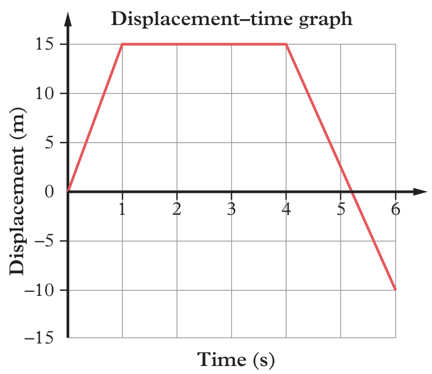
21 A stone is dropped off a bridge 50 m above the water. Exactly 1 s later another stone is thrown down and both stones strike the water together.

a **Calculate** the initial speed of the second stone (2 s.f.). (4 marks)

b **Sketch** a velocity–time graph of both stones on the same graph. (3 marks)

Analytical processes

22 The graph shows the displacement of a radio-controlled car being driven in a straight line.



Determine

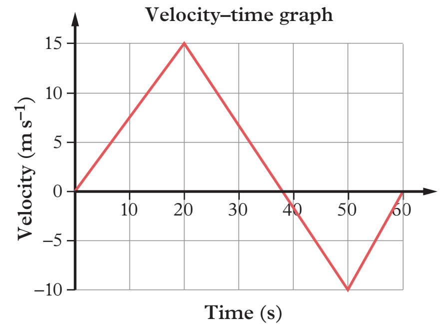
a at what stage its velocity was the greatest (1 mark)

b when the car was stationary (1 mark)

c when its velocity was constant but not zero (1 mark)

d its velocity at 5 s. (2 marks)

23 The graph shows the motion of a girl on rollerblades as a function of time.



a **Calculate** her displacement after 50 seconds (2 s.f.). (2 marks)

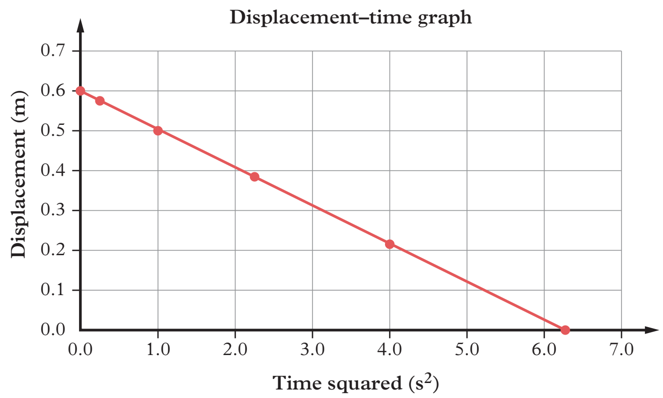
b **Calculate** the distance she travelled in the minute (2 s.f.). (1 mark)

c **Determine** at what stage her acceleration was the greatest. (1 mark)

d **Determine** when she was stationary. (1 mark)

e **Determine** whether her velocity was ever constant but not zero. (1 mark)

24 An experiment is conducted in which a ball is released from rest and timed to roll down an inclined plane from different displacements up the incline. The processed data is shown in the graph.

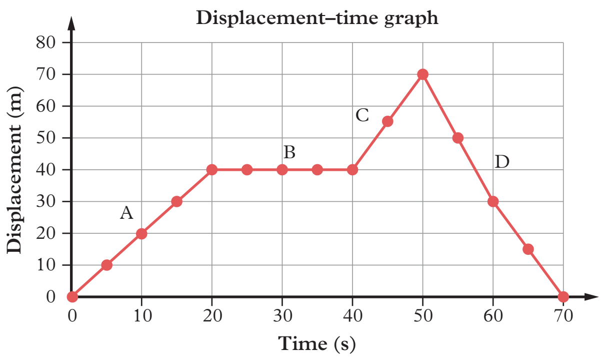


The equation for the line of best fit is given by $s = (-0.096 \pm 0.016)t^2 + (0.60 \pm 0.10)$ m.

a **Determine** the maximum and minimum values for the displacement, s, at a time of 1.0 s. (4 marks)

b **Determine** the magnitude of the acceleration. No uncertainty is required. (3 marks)

25 **Consider** this displacement–time graph for an object.



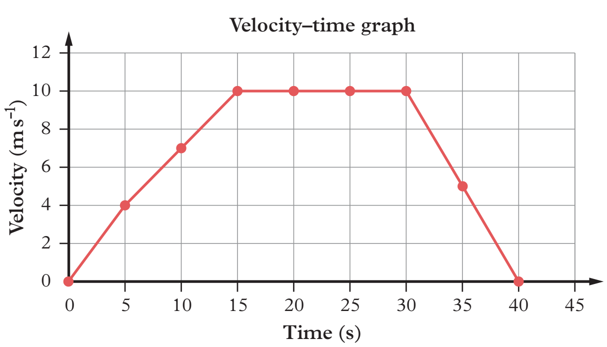
a **Identify** the section in which the object was stationary. (1 mark)

b **Identify** the section in which the object's speed was greatest. **Justify** your response. (2 marks)

26 Two shopping trolleys, A and B, of equal mass, are 20 m apart and on a collision course with each other. Trolley A is travelling east with a speed of 1.5 m s^{-1}, while trolley B is travelling west at 2.5 m s^{-1}. **Determine** how long before the trolleys collide (2 s.f.). (5 marks)

27 A ball is thrown vertically upwards with a velocity of 15 m s^{-1}. Ignoring air resistance and taking $g = -9.8$ m s^{-2}, **determine** the velocity of the ball on its downwards journey as it passes the point at which it was released. Use the correct number of significant figures. (2 marks)

28 A cyclist's travels are shown in the velocity–time graph. **Determine** the displacement of the cyclist after 40 s (2 s.f.). (2 marks)



29 The single cable supporting a construction elevator breaks when the elevator passes the sixth floor (25 m) on its way up while at a speed of 3.0 m s^{-1}.

a **Calculate** the elevator's velocity on impact. Use the correct number of significant figures. (3 marks)

b **Determine** how much time will elapse before the elevator strikes the ground. Use the correct number of significant figures. (2 marks)

30 A basketball player, standing near the basket to grab a rebound, jumps 76.0 cm vertically.

a On his way up, **calculate** (2 s.f.) how much time he spends

i in the bottom 15 cm of his jump (4 marks)

ii in the top 15 cm of his jump. (4 marks)

b **Consider** whether this helps explain why such players seem to hang in the air at the tops of their jumps. (3 marks)

31 Imagine two rocks are dropped off a cliff 1 s apart. **Determine** whether the distance between them gets bigger as they fall to the ground below. (7 marks)

32 A juggler tosses balls vertically into the air. **Determine** how much higher the balls must be tossed if they are to spend twice as much time in the air. Use the correct number of significant figures. (8 marks)

33 A person standing on the edge of a cliff throws a ball straight up with speed u, and allows it to crash onto the rocks below. The person then throws a ball with the same speed u straight down. **Determine** which ball has the higher speed when it hits the rocks. Ignore air resistance. (3 marks)

Knowledge utilisation

34 Perform simple calculations to **solve** for the missing values in the table. (3 marks)

	Displacement, *s*	Time, *t*	Velocity, *v*
a	300 m	6 s	
b	150 km	4 h 30 min	
c		30 s	340 m s^{-1}

35 The Sukhoi Su-29 is a Russian-built two-seat aerobatic competition aircraft becoming popular in Australia. Imagine that this aircraft was flying at its cruising speed of 160 knots (298 km h^{-1}) and an altitude of 1,000 m, and suddenly encountered terrain sloping upwards at 4.3° (an amount difficult to detect). **Determine** how much time the pilot would have to make a correction if they were to avoid flying into the ground (2 s.f.). (4 marks)

36 An article in a newspaper quoted a safety expert as saying: "An unrestrained child in a 50 km h^{-1} car crash suffers the same effects as being dropped onto concrete from a building's second floor." **Evaluate** this comment, making whatever approximations are required. (3 marks)

Data drill

Acceleration of a ball on an incline

A student set up an experiment to investigate the acceleration of a steel ball rolling down an inclined plane. The aim was to construct and interpret displacement–time and velocity–time graphs. The student varied the release point (displacement) of the ball up the plane from the bottom and measured the time it took for the ball to roll to the bottom. The data is given in Table 1. A graph of final velocity vs time is plotted in Figure 1.

TABLE 1 Data from inclined plane experiment

Displacement, *s* (m)	Time, *t* (s)				Uncertainty for time	
	Test 1	Test 2	Test 3	Average	Absolute ± δ (s)	Percentage ± δ%
0.20	1.15	1.24	1.33	1.24	0.090	7.3
0.40	1.66	1.75	1.84	1.75	0.090	5.1
0.60	2.02	2.15	2.37	2.18	0.182	8.3
0.80	2.38	2.48	2.62	2.49	0.120	4.8
1.00	2.59	2.77	2.95	2.77	0.180	6.5
1.20	2.86	3.04	3.22			

Linear trendline: $y = 0.2597x - 0.0031$

Maximum linear trendline: $y = 0.298x - 0.07$

Minimum linear trendline: $y = 0.220x + 0.07$

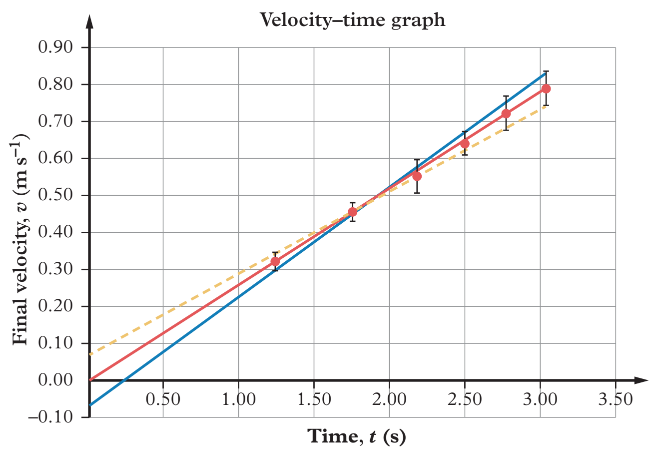


FIGURE 1 Graph of processed data

Apply understanding

1 **Calculate** the average time for the ball released from a displacement of 1.20 m. (2 d.p.) (1 mark)

2 **Calculate** the absolute uncertainty and percentage uncertainty for the ball released from a displacement of 1.20 m (2 s.f.). (2 marks)

Analyse data

3 **Identify** a mathematical relationship between the final velocity and the time, including the uncertainty of the gradient and uncertainty of the y-intercept. (3 marks)

Interpret evidence

4 **Draw a conclusion** that quantifies the magnitude of the acceleration, including the absolute or percentage uncertainty in the value you determine. Show your reasoning. (4 marks)

Module 9 checklist: Linear motion

Quizlet: Revise key terms online to test your understanding

MODULE 10 Classical mechanics

Introduction

For a feat of strength from the natural world, you have to admire Robert Galstyan of Armenia. In 1992, Galstyan set a world record by pulling two carriages a distance of 7 m with his teeth. It seems incredible that a man could start railway wagons moving just by pulling on a rope with his teeth. How could a 100 kg man accelerate 220 tonnes of railway carriages from rest? Perhaps he knew about Newton's laws of motion, and that's why he tried. A small force applied to a large mass will result in an appreciable speed given enough time.

There have been many misconceptions about forces. Many of these go back 2,000 years to Aristotle's idea that a moving object had an internal source of "impetus", which it was given when first thrown or moved. The concept of "impetus" has been refined over the centuries to what Newton called momentum. Anything that has mass and velocity has momentum, and momentum is conserved whether it be in ballet leaps, bombs exploding or baseballs being struck.

Prior knowledge

Prior knowledge quiz

Check your understanding of forces, Newton's laws and gravity before you start.

Subject matter

Science understanding

→ Describe the three laws of motion of classical mechanics and give examples of each.
→ Identify forces acting on an object.
→ Construct free-body diagrams representing forces such as the force due to gravity (weight), the normal force, tension, friction, drag and applied forces acting on an object.
→ Determine the resultant force acting on an object in one dimension.
→ Solve problems using of the laws of classical mechanics and $a = \frac{F_{net}}{m}$.
→ Describe the concepts of momentum and impulse.

- → Describe the principle of conservation of momentum.
- → Solve problems involving momentum, impulse, the conservation of momentum and collisions in one dimension using $p = mv$ and $\sum mv_{\text{before}} = \sum mv_{\text{after}}$.
- → Analyse the area under a force–time graph using geometric methods.

Science as a human endeavour

- → Appreciate the significant contributions of scientists such as Isaac Newton and Émilie du Châtelet.
- → Explore historical models and theories used to describe motion and force, and how evidence was used to build upon and improve on earlier understandings.
- → Consider how knowledge of forces and motion has led to improvements in car safety through the development of technologies such as seatbelts, crumple zones and airbags.
- → Understand the study of biomechanics applies the laws of forces and motion, and through direct measurement, computer simulation and mathematical modelling lead to a better understanding of human movement and improved athletic performance.
- → Appreciate that the laws of motion proposed by Isaac Newton provided an explanation for a range of previously unexplained physical phenomena, which were confirmed by multiple experiments performed by a multitude of scientists.

Science inquiry

- → Investigate a linear elastic collision between two objects.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Practicals

oxforddigital **This lesson is available on Oxford Digital.**

Lesson 10.10 Linear elastic collision between trolleys – conservation of momentum

Lesson 10.1
Measuring forces

Key ideas

→ Forces can be contact or non-contact.
→ When forces are balanced, there is no change in motion. However, when forces are unbalanced, there is a change in motion.
→ Forces are vector quantities measured in the SI unit of newtons.
→ A resultant force is the vector sum of all forces acting on an object.

Learning intentions and success criteria

force
a push or pull between objects that may cause an object or both objects to change speed and/or the direction of their motion or change their shape (symbol: *F*; SI unit: newton; unit symbol: N)

What is a force?

Force is a push or pull between objects that may cause one or both objects to change speed and/or the direction of their motion (and as such accelerate) or change their shape.

Scientists have identified four fundamental forces: gravitational, electromagnetic (involving both electrostatic and magnetic forces), weak nuclear force and strong nuclear force. All interactions between matter can be explained as the action of one, or a combination, of these four fundamental forces. There are other forces you will come across, such as the normal force, applied force, tension, friction, elastic force and centripetal force. These are just labels for examples of the fundamental forces.

It is easy to think of forces as being made up of an agent (that produces the force) and a receiver (that responds to the force). But sometimes it is not clear which one came first, so the distinction is irrelevant. The important thing to remember is that a force only acts when there is something for it to act on.

Contact and non-contact forces

Forces can be simply divided into two types: contact and non-contact.

contact force
a force where the object and the action producing the force touch each other

non-contact force
an action-at-a-distance force that acts on an object without coming physically in contact with it

- **Contact forces** are those where the objects interacting touch each other. Examples are everyday pushes and pulls (lifting a bag, walking, throwing a ball, pushing a car, friction, tension in a rope).
- **Non-contact forces** are action-at-a-distance forces such as gravity, magnetism and electrostatic forces. They are sometimes called "field forces" because they act by way of a field, such as a magnetic field or a gravitational field.

FIGURE 1 Forces can be contact (such as the pushing of pieces of plasticine to mould them into shape) or non-contact (such as the magnetism that allows a maglev train to operate).

For example, maglev trains float on opposing magnetic fields; gravity pulls a rock towards Earth through its gravitational field; rub a pen on your jumper and you can pick up little bits of paper with an electrostatic force in an electric field.

Students often ask, "What does 'contact' mean?" At a microscopic level, when two objects are in contact, it is simply one electron cloud pushing against another electron cloud, and the atoms do not touch. It's enough that if any part of an atom touches another part, "contact" has been made.

Balanced and unbalanced forces

To study the effect of forces acting on an object, we need to distinguish between **balanced forces** and **unbalanced forces**. When forces acting are equal in magnitude and in opposite directions, the object remains at rest because the forces are balanced. We say that balanced forces do not cause a change in the motion of an object. By "change", we mean the object remains at rest or at constant velocity. It does not accelerate.

The opposite is true: if the forces are no longer equal and/or no longer acting in opposite directions, they are unbalanced. We say that unbalanced forces cause a change in the motion of the object – the object accelerates (speeds up, slows down or changes direction).

balanced forces
two forces acting in opposite directions on an object, and equal in size; they do not cause a change in the motion of an object

unbalanced forces
forces that cause a change in the motion of an object

How is force measured?

The unit of force is named after one of the world's greatest physicists, Isaac Newton. The newton (N) is commonly measured in the laboratory with a spring balance (Figure 2). This has a spring that extends when masses are hung on it or when other forces are applied. It therefore gives a measurement of the magnitude of a force. The scale is calibrated in grams for mass or newtons for force. Because the direction of the force is important, force is a vector quantity.

To use a spring balance, it must first be adjusted to read zero when held vertically. When you pull gently on the spring balance, you can pull to feel forces of 1 N, 2 N, 3 N, etc. The "feel" of a newton helps you in your problem solving. If you hang masses on the hook of the spring balance, it will show what force is needed to hold them up. A 100 g mass will show a gravitational force of about 1 N.

FIGURE 2 A school spring balance with a scale in grams. This balance also has a scale in newtons.

Representing forces

To help solve problems involving forces, it is helpful to understand the magnitude and direction of the forces involved. There are two ways to express a force as a vector quantity:

- by arrows (→) – the length of the arrow represents the magnitude of the vector quantity, and the direction of the arrow shows the direction of the force. Recall that these arrows are sometimes called "directed line segments".
- by using an arrow above the symbol, such as $\vec{F}$.

We use a plain symbol F when we are just interested in the magnitude of the force and not considering its vector nature. All symbols for physical quantities in this book are set in italics (sloped), but you don't need to do that.

We can also depict forces using free-body diagrams. You will learn more about these later.

Study tip

When the symbol for force, $\vec{F}$, is shown with an arrow above it, we are considering force as a vector (magnitude and direction). If we are talking about the magnitude of the force, then the symbol is the plain F.

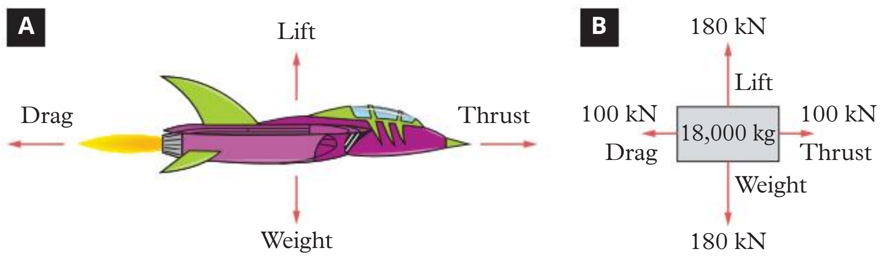


FIGURE 3 (A) Swatkat turbo-jet fighter in flight; (B) simplified free-body diagram of the jet fighter with arrows representing the force vectors

Figure 3A shows four forces acting on a Swatkat turbo-jet fighter plane in flight.

When the thrust and drag are equal and opposite, the jet flies at constant speed. When lift and weight are equal and opposite, the jet maintains its altitude. Figure 3B is a simplified free-body diagram of the jet fighter with arrows representing the force vectors. Their length is proportional to their magnitude.

How do you calculate resultant forces?

resultant force
a single force that has the same effect as all the forces acting on an object combined; also called net force, F_{net}

Have you ever played tug of war, in which two teams pull on opposite ends of a rope? Each team can apply a huge force, but the rope and the people hardly move. If one team can pull harder, the rope moves in their direction and they win. By understanding the magnitude and direction of forces acting on an object such as the rope, we can calculate the **resultant force** $\vec{F}_{net}$ and make conclusions about the object's motion. Resultant force takes into account the magnitude and direction of all forces acting on an object to show a single force that has the same effect as all the forces combined. It is also called the net force.

Consider the following: When spring balances are hooked onto either end of a cart at rest and given equal pulls in opposite directions (Figure 4), the carts remain at rest because the forces are balanced – they are equal and opposite. When there is no change in the motion of the object we say that the resultant force is 0 N.

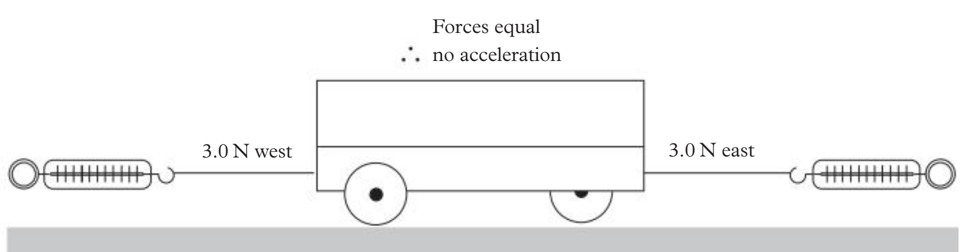


FIGURE 4 The forces on the cart are balanced – they are equal and opposite in direction.

If the pull on the balance to the right was increased to 5.0 N (Figure 5), then the forces would become unbalanced and the cart would start to move in the direction of the larger force (to the right).

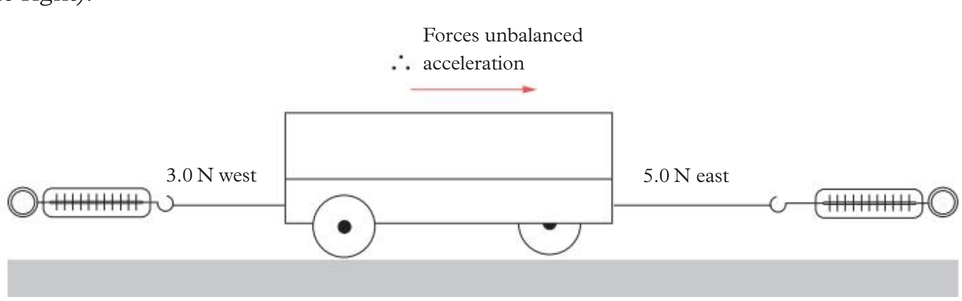


FIGURE 5 The forces on the cart are unbalanced – the force is greater to the right than to the left.

How do you use free-body diagrams?

There are many ways forces can push or pull an object. But we can reduce the complexity of any situation by replacing the images of an object with a square that represents any object regardless of how complex its real shape. Here are three cases that introduce **free-body diagrams** and how the vector addition formulas apply. The lengths of the arrows represent the magnitudes of the forces, so we draw them to scale. In Unit 2, we are considering only forces in a straight line for mathematical calculations, but you could be expected to draw diagrams representing forces in two dimensions, like the fighter plane in Figure 3A.

free-body diagram
a diagram used to show the relative magnitude and direction of all forces acting on an object in a given situation; also called a force diagram

Case 1: Two forces in the same direction

Figure 6 shows forces of 50 N and 70 N acting towards the right (positive direction) on an object represented as a free-body diagram. We will use the convention that the positive direction is to the right, and negative direction is to the left.

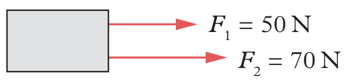


FIGURE 6 Two forces in the same direction

The lengths of the arrows are drawn approximately to scale. Intuitively, the resultant force is 120 N to the right. We can set this out in a formula:

$$\begin{aligned}\vec{F}_{net} &= \vec{F}_1 + \vec{F}_2\\ &= (+50)+(+70)\\ &= +120\,\text{N (to the right)}\end{aligned}$$

Case 2: Forces in opposite directions

Figure 7 shows forces of 70 N to the left (negative direction, –) and 50 N to the right (positive direction, +), again represented as a free-body diagram.

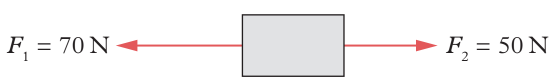


FIGURE 7 Two forces in opposite directions

It seems obvious that the resultant force (F_{net}) is 20 N to the left, or –20 N. We can solve this using the formula:

$$\begin{aligned}\vec{F}_{net} &= \vec{F}_1 + \vec{F}_2\\ &= (-70)+(+50)\\ &= -20\,\text{N (to the left)}\end{aligned}$$

Case 3: Multiple forces

Figure 8 shows one force acting to the left (–) and two forces to the right (+) on a free-body diagram.

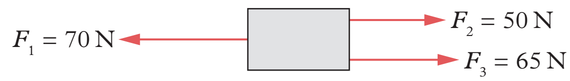


FIGURE 8 Three forces acting in a straight line

It seems simple enough that the resultant force is 45 N to the right (+). Here is the formula and solution:

$$\begin{aligned}\vec{F}_{net} &= \vec{F}_1 + \vec{F}_2 + \vec{F}_3 \\ &= (-70)+(+50)+(+65) \\ &= +45\,\text{N (to the right)}\end{aligned}$$

We can now go back and consider the two forces in Figure 5 to see the thinking processes for this scenario. Worked example 10.1A demonstrates the process in arriving at a solution.

Worked example 10.1A

Calculating resultant forces

Calculate the resultant force acting on the cart in Figure 5. Show your working. Your answer should include a free-body diagram. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to consider the magnitude and direction of all forces involved and find the resultant force. The question is worth 4 marks, so we must gather the correct information and complete the calculation.
Step 2: Gather any data required. The answer seems obvious, but it is important to get the setting-out correct. The vector quantities indicate direction, so the symbol *F* should be used. You don't have to have the arrow above the *F*.	$\vec{F}_1 = 5.0\,\text{N east}$ $\vec{F}_2 = 3.0\,\text{N west}$
Step 3: Draw a labelled free-body diagram. The arrows do not have to be in proportion to the force but it helps.	 (1 mark for correct directions, 1 mark for correct magnitudes and approximate scale)
Step 4: Complete the calculation. Because the forces are in opposite directions, we can think that they are + and – values.	$\vec{F}_{net} = \vec{F}_1 + \vec{F}_2$ $= 5.0\,\text{N east} + 3.0\,\text{N west}$ $= 5.0\,\text{N east} + (-3.0\,\text{N east})$ $= 2.0\,\text{N east}$ (1 mark for equation and substitution, 1 mark for correct answer)

Your turn

An 816 g ball is dropped off a cliff. Gravity acts downwards with a force of 8.0 N but at a particular moment air resistance is acting upwards with a force of 1.5 N. **Calculate** the resultant force on the ball and include a free-body diagram in your answer. Show clearly how the vectors have been added. (4 marks)

Check your learning 10.1

Check your learning 10.1: Complete these questions online or in your workbook.

Retrieval and comprehension

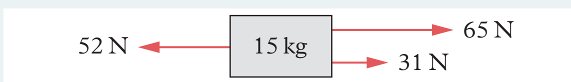
1 **Explain** 'force' with examples of a contact force and a non-contact force. (3 marks)

2 **Identify** two differences between a balanced force and a unbalanced force. (2 marks)

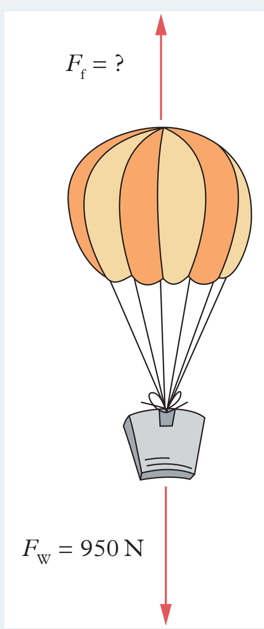
3 **Explain** what the length of a vector arrow represents. (2 marks)

4 **Describe** how the Swatkat jet (Figure 3) maintains altitude. (1 mark)

5 Forces of 65 N and 31 N to the right are applied to a box. Another force acts in the opposite direction, as shown. **Determine** the resultant force (magnitude and direction) on the box. Show your working. (2 marks)



6 The figure shows a parachute and its load experiencing a downwards gravitational force of 950 N due to its weight. It also experiences an upwards force due to the friction of the air F_f. The resultant force is 20 N downwards. **Determine** the force of friction, stating its magnitude and direction. Show your working. (2 marks)



Analytical processes

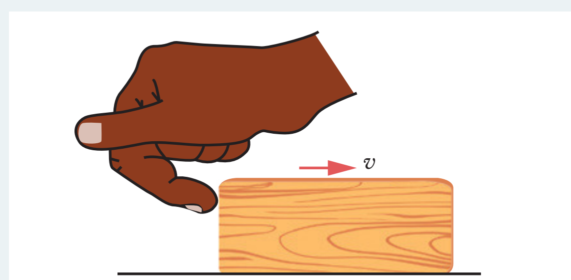
7 **Construct** a free-body diagram for a shopping trolley that is being pushed to the right by a force of 100 N, and pushed to the left by forces of 50 N and 75 N. Make the vectors (arrows) in correct proportion. (3 marks)

8 **Contrast** balanced and unbalanced forces, using examples. (4 marks)

9 **Assess** mathematically (using a formula) whether scenarios A and B produce the same resultant force (magnitude and direction). Show your working. (4 marks)

10 The average gravitational force (weight, expressed in newtons) on Sumo wrestlers in 1994 was 1,360 N. In 2024, their average weight had risen to 1,680 N. If this trend continues, **predict** whether they will still be able to stand up in 2050, given that the maximum force two legs can stand is 1,800 N. Show your working. (4 marks)

11 **Propose** whether the block of wood is being pushed or pulled. **Justify** your answer. (3 marks)



Lesson 10.2
Newton's first law of motion

Key ideas

→ Newton's first law of motion states that an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force.

Learning intentions and success criteria

What is Newton's first law of motion?

We have no trouble today saying what causes a change in motion. You will have learnt that it is a push or a pull. However, it was not always seen like that. The greatest scientific minds in history have struggled with working out the causes of motion. Aristotle (384–322 BCE), Ptolemy (100–170 CE), Copernicus (1473–1543), Galileo (1564–1642) and Newton (1642–1727) developed many complex models and theories describing motion and force.

An early idea of motion was developed by Aristotle more than 2,000 years ago. He proposed that objects had a natural state and that, if left alone, would try to attain this state. By the time of Galileo, it was evident that this idea had serious problems. Galileo showed that Aristotle was wrong about forces being necessary to keep objects in motion. Although a force is needed to start an object moving, Galileo showed that once an object is moving, no force is needed to keep it moving except for the force needed to overcome **friction**.

friction
the force that resists motion between two surfaces in contact

When friction is absent, a moving object needs no force to keep it moving – it will remain in motion all by itself. Galileo used wooden balls on a ramp to show this: the balls rolled rather than slid, and friction was very low. Figure 1 summarises Galileo's investigation.

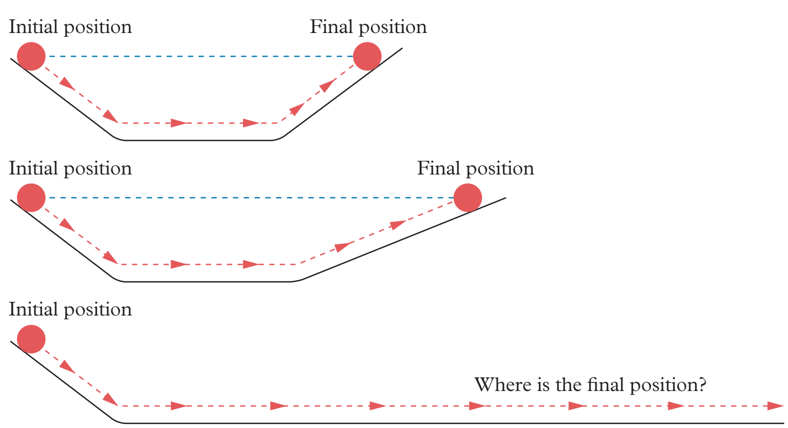


FIGURE 1 Galileo's investigation showed that once an object is moving, it needs no force to keep it moving.

In the first test, the arms of the incline plane are at the same height and a ball, once released, travels along the ramp and rises to the same height. We are assuming there is no friction, which is quite appropriate for rolling friction. When the second arm is longer, the ball travels further but continues until it finds the same height. In the third test, Galileo realised that if the second arm didn't rise, then the ball would travel at constant speed forever.

Newton put Galileo's ideas into the form of a universal physical law – a law that is obeyed throughout the universe. This eventually became his first law. Over time, Newton developed many complex models and theories that were based on a range of evidence, some of which was provided by predecessors such as Ptolemy, Aristotle, Copernicus and Galileo. As Newton said in 1676, "If I have seen further, it is by standing on the shoulders of giants."

In 1687, Newton proposed his first law of motion (translated from the Latin):

Newton's first law of motion: an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force.

It is also known as the "first law of motion", as referred to in your QCE Physics syllabus. The tendency of an object to resist change in its motion is called **inertia**.

Newton's first law
an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force; also known as the first law of motion

inertia
the tendency of an object to resist a change in its motion

Examples of Newton's first law of motion

Table 1 contains examples that show Newton's first law applied to real life.

TABLE 1 Examples of Newton's first law in real life

Element of Newton's first law	Example
At rest and stays at rest	Some magicians can jerk a tablecloth out from under a dinner setting of glasses and cutlery, leaving them at rest on the table.
In motion and stays in motion	In a head-on car crash, the passengers tend to continue in their state of motion and move forwards towards the dashboard. It is usually the seatbelts that restrain them.
Continuing in the same direction	As a car goes around a corner, your body continues in a straight line. The car door presses against you as the car moves sideways. People often say they are flung against the car door, but it is actually the door that is flung against them.
Experiencing balanced forces and constant velocity	Consider a diagram of the forces acting on a car travelling along a road at constant velocity (Figure 2). When this car travels at constant velocity, the downwards force of the car on the road (its weight) is balanced by the upwards force of the road on the car. The force produced by the engine is balanced by the friction of the tyres on the road and the air resistance, as well as friction within the moving parts of the car. As long as these forces remain balanced, the car will not accelerate.

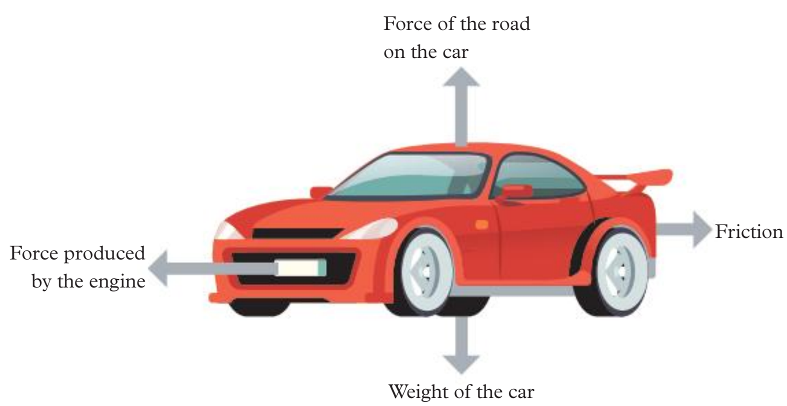


FIGURE 2 If the forces are equal and opposite (balanced), the car will not accelerate.

Check your learning 10.2

Check your learning 10.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** Aristotle's original proposal about objects having a natural state and how it is not supported by observations. (3 marks)

2 **Explain** how observations refuted Aristotle's proposal of motion. (2 marks)

3 **Explain** Newton's first law in the context of flicking your hands to remove excess water. (2 marks)

4 **Describe** examples of Newton's first law when an object is
  a at rest and stays at rest (2 marks)
  b in motion and stays in motion (2 marks)
  c continuing in the same direction (2 marks)
  d experiencing balanced forces and constant velocity. (2 marks)

Analytical processes

5 You spin an open umbrella to remove excess rainwater and the faster you spin, the more water you remove. **Infer** how this works in terms of the first law of motion. (2 marks)

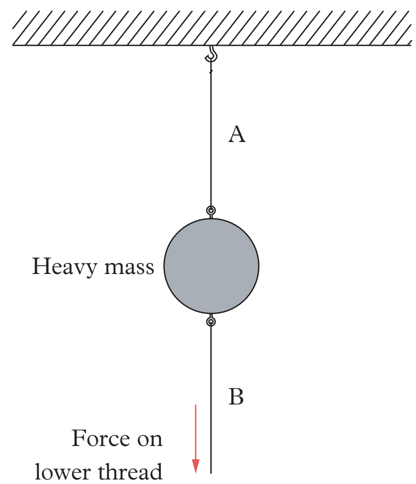
Knowledge utilisation

6 A spacecraft is initially travelling at a constant velocity in space when it veers off course due to the gravitational attraction of a large planet. **Assess** how the first law of motion applies in the initial state and in the second state as the spacecraft nears the planet. (4 marks)

7 **Propose** a reason in terms of Newton's first law why shaking a bottle of tomato sauce helps get the contents out. (2 marks)

8 At the bottom of a loop on a rollercoaster ride you change direction from downwards to upwards. Newton's first law says this should not happen unless an external force acts. **Hypothesise** the source of the external force in this case. (2 marks)

9 A thread supports a mass hanging from the ceiling. Another identical thread is tied to the bottom of the mass as shown. **Predict** and **explain** which thread is likely to break if the bottom thread is pulled
  a slowly (2 marks)
  b quickly. (2 marks)



Lesson 10.3
Newton's second law of motion

Key ideas

→ Newton's second law of motion states that the acceleration of an object is in the direction of the net external force acting on it, proportional to the size of the force, and inversely proportional to its mass.

What is Newton's second law of motion?

Learning intentions and success criteria

Newton's first law deals with cases where the forces are balanced, and the conditions necessary to unbalance them. It is a qualitative law and no mathematical or quantitative relationship is included. Newton's second law (the second law of motion) deals with the mathematical relationship between force and motion.

Everyday experience tells us that a given force will produce different accelerations in different objects. Kick a football and it moves off quickly, but kick a car and it hardly moves. The difference is their resistance to a change in motion, which is known as "mass" – the car has a greater mass than the ball as it resists a change in motion more. **Mass** is measured in units of kilograms, although grams and tonnes are widely used.

Newton's second law of motion: the direction of the acceleration of an object is in the direction of the net external force acting on it, proportional to the size of the force and inversely proportional to the mass:

$$a_{net} = \frac{F_{net}}{m}$$

where a_{net} is the acceleration of the object, F_{net} is the net force acting on the object, and m is the mass of the object.

mass
a characteristic of a body's resistance to change in motion; a measure of the amount of inertia

Newton's second law
the acceleration of an object is in the direction of the net external force acting on it, proportional to the size of the force, and inversely proportional to the mass; also known as the second law of motion

Examples of Newton's second law of motion

Some real-life examples of Newton's second law are:

- throwing a shot. In the sport of shotput, a heavier ball (shot) won't be accelerated as quickly as a lighter shot, so it doesn't travel as far.
- a bullet travelling out of a rifle barrel. A greater charge of propellant (gunpowder) produces a greater force and hence greater acceleration.
- driving away from traffic lights. The force produced by the engine is greater than the friction of the tyres and air resistance, so a car will accelerate.
  - A heavy car requires more force to give the same acceleration as a light car.
  - The faster you want to accelerate, the greater the force needed.
  - The acceleration occurs in the direction of the unbalanced force.
- using a parachute. When you are free-falling from an aircraft and you open your parachute, your acceleration reduces as the net force downwards get smaller.
- space shuttle launch. As the rocket fuel is gradually used up, the shuttle gets less massive so it accelerates more. Additionally, in the thinner air of the upper atmosphere, there is less friction so the net force gets bigger.

Study tip

Mass has different meanings depending on the context. Earlier, in nuclear physics, we saw that mass could be expressed in terms of energy using the formula $\Delta E = \Delta mc^2$. With Newton's laws of motion, we use the idea of inertial mass, $F = ma$. Later, you will also look at gravitational mass, $F_g = mg$. The current evidence is that they are all equal to each other, but scientists keep checking to see if it could be otherwise.

FIGURE 1 Examples of Newton's second law of motion include a car progressing through an intersection when the traffic light changes to green, and a space shuttle at lift-off.

Newton's second law accounts for all of these phenomena. Newton derived his relationship from theory, not from experiment. It has since been verified experimentally – many, many times!

Remember that the unit of force is the newton (N); thus, a newton is defined as the force needed to accelerate a 1 kg object by $1\,m\,s^{-2}$ for each second that it acts.

Worked example 10.3A

Calculating acceleration using the second law of motion

An unbalanced force of 48 N west is applied to a 6.0 kg cart. **Calculate** the cart's acceleration both in magnitude and direction (2 s.f.). Show your working. (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply Newton's second law of motion. The question is worth 3 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$a_{net} = \frac{F_{net}}{m}$ $F_{net} = 48\,\text{N}$, $m = 6.0\,\text{kg}$, $a = ?$
Step 3: Substitute the known values into the formula and find the unknown.	$a_{net} = \frac{48\,\text{N west}}{6.0\,\text{kg}}$ (1 mark for substitution) $= 8.0$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	$8.0\,\text{m s}^{-2}$ west (1 mark for magnitude, 1 mark for direction)

Your turn

A 57 g tennis ball experiences a net gravitational force of 0.558 N that acts vertically downwards. **Calculate** the acceleration of the ball both in magnitude and direction (2 s.f.). Show your working. (3 marks)

Study tip

When solving problems involving Newton's second law, it is common to write the equation in its non-vector form and leave out the subscripts "net", as this is understood. The formula then becomes $a = \frac{F}{m}$ or $F = ma$.

How does a net force change motion?

It is important to remember that a net force will cause an object to accelerate. If it is at rest, it will start to move. If it is moving, then it will speed up, slow down or move sideways depending on the direction of the net force.

Skill drill

Evaluating data related to Newton's second law

Science inquiry skills: Evaluating evidence (Lesson 1.8)

Students conduct an experiment in which the time taken for a trolley, with differing mass, to travel 1.0 m is measured. A constant force is applied to the trolley in all trials. Their results are shown in Table 1.

TABLE 1 Effect of mass on time a trolley takes to travel 1.0 m with a constant force applied.

Mass (kg)	Time taken (s)			
	Trial 1	Trial 2	Trial 3	Mean
0.6 (trolley only)	1.15	1.06	1.11	1.11
0.8	1.32	1.26	1.24	1.27
1.0	1.13	1.35	1.81	1.43
1.2	1.55	1.54	1.60	1.56
1.4	1.69	1.64	1.73	1.69

Practise your skills

1 **Determine** if there is both sufficient and relevant data included to allow a valid and justified conclusion to be made relating to Newton's second law of motion. If the dataset could be improved, **propose** how. (4 marks)

Check your learning 10.3

Check your learning 10.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** Newton's second law, using a tennis ball as an example. (2 marks)

2 **Explain** the relationship between Newton's second law and the formula $a_{net} = \frac{F_{net}}{m}$. (2 marks)

3 **Calculate** the missing quantities in the table. (10 marks)

	F_{net}	m	u	v	a	t
a		1,000 kg	rest	25 m s^{-1}		8.5 s
b	25 N	15 kg	rest			2.0 s
c	1,000 N		10 m s^{-1}	40 m s^{-1}	10 m s^{-1}	
d		200 g	0.85 m s^{-1}	0.60 m s^{-1}		1.5 min
e	150 N			rest	–2.2 m s^{-2}	4 s

4 A car of mass 2,000 kg slows down from 30 m s^{-1} to rest in a distance of 100 m. **Calculate** the net force required to stop the car. (4 marks)

Analytical processes

5 Racing driver David Purley survived a change in velocity from 173 km h^{-1} to zero in a distance of 66 cm in a crash at Silverstone, United Kingdom, in 1977. He suffered 29 fractures, three dislocations and six heart stoppages, and he made it into the "Guinness Book of Records" for surviving the biggest deceleration of all time. His body mass at the time was 55 kg. **Determine** the net horizontal force acting on him in the crash. (6 marks)

6 In an experiment to find out how the motion of a trolley was related to the force acting on it, a 1.5 kg trolley was accelerated by various forces. The results are summarised in the table.

Net force, F_{net} (N)	0.00	0.10	0.20	0.30	0.40	0.80
Acceleration, a (m s^{-2})	0.00	0.07	0.13	0.20	0.27	0.53

a Construct a graph for the data in the table. (3 marks)

b Calculate the gradient of the graph (2 s.f.). (1 mark)

c Using the linearised graph, draw a logical conclusion regarding the relationship suggested by the data. (2 marks)

d Identify the physical quantity represented by the gradient. (1 mark)

Knowledge utilisation

7 **Evaluate** the following claims.

a It requires a greater force to accelerate a 2,000 kg car from rest to 15 m s^{-1} than from 15 m s^{-1} to 30 m s^{-1} in the same time. (2 marks)

b Twice the force is needed to accelerate a 1.5 tonne car from rest to 60 km h^{-1} over 100 m than is required over 200 m. (3 marks)

c An object always accelerates in the direction of the net force. (2 marks)

d A lower net force is needed to accelerate an object from rest to 10 m s^{-1} than is required to accelerate it from rest to 20 m s^{-1}. (2 marks)

Lesson 10.4
Newton's third law of motion

Key ideas

→ Newton's third law of motion states that whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first.

Learning intentions and success criteria

What is Newton's third law of motion?

In 1688, Isaac Newton argued that if he pushed on a stone there would be an equal and opposite force pushing back. Newton wrote this as his third law and in Latin used the words "actiones" (actions) and "reactionem" (reaction) in his statement. The law is often stated as "for every action, there is an equal and opposite reaction", but this implies that the reaction follows the action. In reality, the action and reaction are actually occurring simultaneously (at the same time). Newton's third law has since been greatly simplified to a modern version that avoids the idea of an action first and then a reaction.

Newton's third law
whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first; also known as the third law of motion

Newton's third law of motion: whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first.

In other words, if body A is exerting a force on body B, then body B is exerting an equal and opposite force on body A. Note that the two forces are acting on different objects (A acts on B, B acts on A). You need to think of the symbol F_{AB} as meaning $F_{\text{on A by B}}$. Mathematically, and using vector notation, it could be put as:

$$\vec{F}_{AB} = -\vec{F}_{BA}$$

with the negative sign indicating they are in opposite directions. If we were just looking at the magnitudes of the forces, we would write: $F_{AB} = F_{BA}$.

Study tip
Learn that when using symbols, the subscript AB means "on A by B".

For example, if you exert a force on a nail by hitting it with a hammer, the nail exerts an equal and opposite force on the hammer. If you lean against a wall, the wall pushes back on you with an equal force. Push a rock and the rock pushes back.

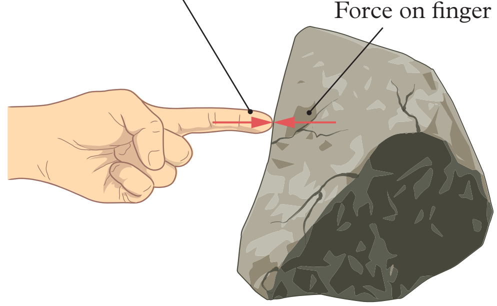


FIGURE 1 Newton proposed that if you press a stone with your finger, your finger is also pressed by the stone.

Importantly, in Newton's third law, the forces acting on each other must, of necessity, be the same type of force: gravitational field and gravitational field, or contact and contact, and so on.

Examples of Newton's third law of motion

Third law force pairs are given in Table 1. The simplest way to work out the pairs is to reverse the order of the two objects. These are sometimes called a "third law pair".

third law force pair
an equal and opposite pair of forces involved when two objects interact; the force on one object is equal and opposite to the force acting on the other object; the forces cannot act on the same object; also called a "third law pair"

TABLE 1 Third law force pairs

Force on A by B (F_{AB})	Force on B by A (F_{BA})
Exhaust gases (A) are forced out by the rocket (B).	Rocket (B) is forced forwards by the gas (A).
Starting blocks (A) are pushed by sprinter (B).	The sprinter (B) is pushed by the blocks.
The road (A) is pushed by a tyre (B).	The tyre (B) pushes back on the road (A).
A softball (A) is hit by a bat (B).	The bat (B) pushes back on the softball (A).
An orbiting satellite (A) experiences a force of gravity by the Earth (B).	Earth (B) experiences a force of gravity by the satellite (A). This is discussed in Lesson 10.5.
A vase of flowers on a table (A) experiences a force of gravity by the Earth (B).	Earth (B) experiences a force of gravity by the vase of flowers (A). It is not 'the vase is pushed up by the table'. The table does push up on the vase, but it is not a third law pair. See Lesson 10.5 for why this is so.

In summary, for Newton's third law, the paired forces will be:

- the same magnitude but in opposite directions. Learn this as "equal and opposite"
- acting on different objects. Learn this as "A acts on B; B acts on A"
- the same type of force (gravity and gravity, contact and contact). Learn this as "like for like".

Check your learning 10.4

Check your learning 10.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 You lean against a wall. **Describe** how the third law applies to this situation. (2 marks)

2 **Explain** Newton's third law, in the context of a horse pulling a cart along a road. Note: you might need to consider more than one third law pair, and they should be stated in the form "on A by B" and "on B by A". (3 marks)

3 **Explain** why it is important to think of the forces in Newton's third law as occurring simultaneously rather than as an action and then a reaction. (2 marks)

Analytical processes

4 **Deduce** the paired forces in each situation and state them in the form "on A by B" and "on B by A".

  a A tennis ball is hit by a racquet. (2 marks)

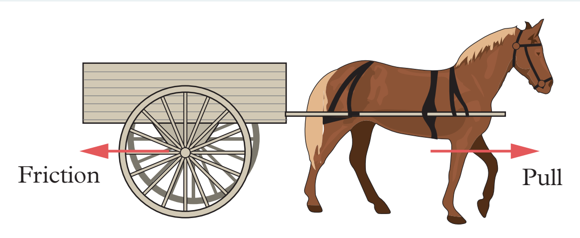
  b A click beetle jumps into the air. (2 marks)

  c A person falls out of a tree. (2 marks)

5 The main gun on the British warship HMS *Invincible* had a bore (internal diameter) of 40 cm. Its shells could penetrate 60 cm of steel armour on enemy ships. The recoil of the gun was so great that it would buckle the wooden deck and peel off the paint. **Deduce** the paired forces of the gun and the shells in the form "on A by B" and "on B by A". (2 marks)

Knowledge utilisation

6 A horse is harnessed to a cart. A student writes, "The horse tries to pull the cart, so the horse exerts a force on the cart. By Newton's third law, the cart must then exert an equal and opposite force on the horse so they can't move." **Evaluate** the student's statement including a statement in the form "on A by B" and "on B by A". (5 marks)



7 Some people say that Newton discovered the laws of motion, but others say he invented them. **Assess** who would be correct. (3 marks)

8 **Assess** in terms of the third law of motion whether the statement by the person on the right is correct. (2 marks)

Lesson 10.5

Force, weight and gravity

Key ideas

→ Gravitational forces dictate an object's weight.

→ Normal force is the perpendicular force exerted on a body by a surface against which it is pressed.

Learning intentions and success criteria

What is gravitational force?

gravitational force
a force that acts through a gravitational field between objects with mass

Objects are attracted towards Earth's centre by a pulling force – gravity. Earth is also attracted to the object by gravity. Gravity is a field or non-contact force (as distinct from a contact force where the objects physically touch, such as a tyre on the road, or a finger pressing a rock). Gravity acts through a gravitational field between objects with mass. The **gravitational force** acts over the vast distances of space past the very edge of the known universe and on to infinity. It also acts over microscopic distances such as between atoms.

Gravity causes freely falling objects to move downwards with an acceleration of $9.8\,m\,s^{-2}$. This value is fairly constant over the surface of Earth, but as Earth is not a perfect sphere and the distribution of mass is not even, it does vary from, for example, $9.76\,m\,s^{-2}$ in Peru to $9.83\,m\,s^{-2}$ in the Arctic Ocean. This value is not dependent on the mass of the object.

If you drop a rock, it will accelerate downwards at $9.8\,m\,s^{-2}$, provided that no other external forces interfere with its motion. This is called free-fall acceleration. The size of the force causing this is derived from $a_{net} = \frac{F_{net}}{m}$ or $F = ma$, according to Newton's second law. For a 1.0 kg rock, the force of gravity equals $1.0\,kg \times 9.8\,m\,s^{-2}$ or $9.8\,kg\,m\,s^{-2}$ directed downwards. This is 9.8 N and it is the weight of the rock. It has the symbol F_W. In Unit 3, the symbol F_g ("g" for gravity) is used.

What is the relationship between weight and mass?

The term "weight" has been around for a long time– hence the confusion when a common term is given a specific meaning in physics. "Weight" comes from the pre-historic German word "wegan", meaning "to carry". Its secondary use, meaning "heaviness", was an Old English adaptation. **Weight** is different from mass. One definition for mass useful for this module is that mass is a measure of an object's resistance to motion; that is, it doesn't vary no matter where in the universe the object might be taken: on Earth, the Moon, in interstellar space – mass is the same.

The formula relating mass to weight is:

$$F_W = mg$$

where g is the acceleration due to gravity in its vicinity. It is also known as the local gravitational field strength.

On Earth, $g = 9.8\,m\,s^{-2}$, but it is different on other planets and satellites, as it depends largely on the body's mass and diameter (Table 1).

FIGURE 1 Gravity is the force of attraction between two bodies with mass. On Earth, we experience it as pulling objects towards Earth's centre. Earth is also pulled towards the mass but we don't notice that because the movement is so small.

weight
a measure of the force of gravity acting on an object

TABLE 1 Acceleration due to gravity on some heavenly bodies

Celestial body	Number of Earth masses	Acceleration due to gravity ($m\,s^{-2}$)	Acceleration relative to Earth g
Sun	335,000.0	274.1	27.9
Jupiter	317.8	25.9	2.64
Saturn	95.2	11.2	1.14
Earth	1.00	9.8	1.00
Venus	0.82	8.9	0.90
Mars	0.11	3.7	0.39
Moon	0.0123	1.6	0.17

The force due to gravity also decreases with altitude (the distance above Earth's surface). At an altitude of 400 km (the orbiting altitude of the International Space Station), g is down to $8.8\,m\,s^{-2}$. This is about 90% of its surface value. You have to be about 3,000 km away from Earth before g is down to half.

What do weight and gravitational forces look like in practice?

The standing person in Figure 2 experiences the gravitational force pulling them down. Earth also experiences a gravitational force due to the person's body that pulls Earth upwards. These two forces make up a third law force pair. But the person is prevented from moving too far because the surface (the ground) stops them. Their feet press down and the ground presses up to stop them moving downwards, making another third law pair. Students often say the third law pair is the force of gravity on the person by Earth, and the force on the person by the ground. This can't be correct as one is a field force (gravity) and the other is a contact force (feet–ground). It is also incorrect as both these forces act on the same object (the person).

In Figure 2, there are two sets of third law force pairs:

- The top third law force pair is due to gravity. These forces are called field forces as they are due to the gravitational field. The force shown as F_{PE} is called the person's "weight" or F_W. The SI convention is to use F for force and different subscripts for specific types of force.
- The bottom force pair is associated with the ground pressing up and the person pressing down. These forces are called contact forces because they make physical contact with the surfaces. The force F_{PG} is called the **normal force** or F_N. It is a contact force that acts at right angles to the surface. It comes from the Latin "norma" meaning "a carpenter's square", which is at an angle of 90°.

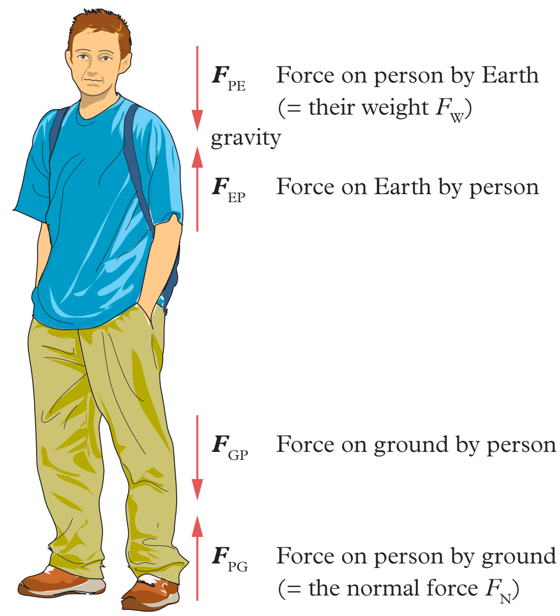


FIGURE 2 Two third law force pairs acting on a person standing on the ground: the gravitational "field" forces are one pair, the "contact" forces are the other pair.

normal force
a contact force that acts at right angles to the surface

As the person is not accelerating, we can say the net force is zero. So, in this case, the normal force is equal in magnitude to the weight: $F_N = F_W$ (or if being treated as vector quantities, $\vec{F}_N = -\vec{F}_W$).

These third law force pairs are also acting when a box sits on top of a table, as shown in Figure 3. They are also described in Table 2.

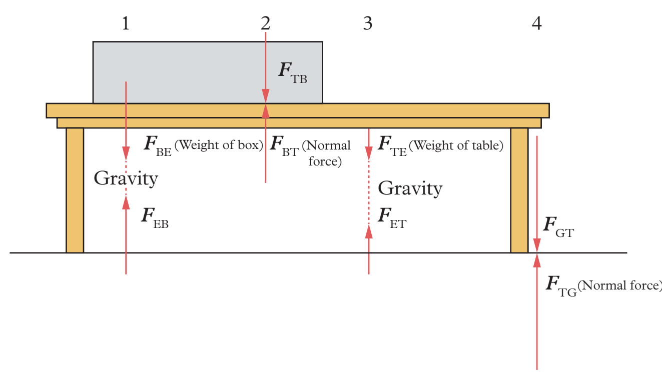


FIGURE 3 Third law forces for a box resting on a table, which is resting on the ground

TABLE 2 Downwards and upwards forces of a third law force pair

	One force of a third law pair (Force on A by B)	Other force of a third law pair (Force on B by A)
	Upwards: usually called the positive direction	Downwards: usually called the negative direction
1	F_{EB} Gravitational field force on Earth by box. Equal in magnitude to weight of box.	F_{BE} Gravitational field force on box by Earth. Called the box's weight. ($\vec{F}_{BE} = -\vec{F}_{EB}$)
2	F_{BT} Contact force on box by table. Called the normal force F_N of the table pushing up on the box.	F_{TB} Contact force on table by box. Equals the weight of the box. ($\vec{F}_{TB} = -\vec{F}_{BT}$)
3	F_{ET} Gravitational field force on Earth by table. Equal in magnitude to the weight of the table.	F_{TE} Gravitational field force on table by Earth. Called the table's weight. ($\vec{F}_{TE} = -\vec{F}_{ET}$)
4	F_{TG} Contact force on table by ground. Called the normal force F_N of the ground pushing up on the table.	F_{GT} Contact force on ground by table. ($\vec{F}_{GT} = -\vec{F}_{TG}$)

Are the normal force and weight a third law pair?

Two notable forces are $\vec{F}_{BE}$, the weight of the box acting down, and $\vec{F}_{BT}$, the normal force on the box by the table pushing up perpendicular to the surface.

These two forces are equal in magnitude and opposite in direction, but they are not a third law pair.

Students are often confused about whether the normal force acting on a body on a table and the body's weight make a third law pair. These two forces are shown in Figure 4. The third law pairs of forces haven't disappeared but they are not shown on the diagram. The net force only considers the forces on that object, not its third law pairs as well. The normal force and the body's weight are equal and opposite but they do not make a third law pair. There are two reasons:

- The two forces act on the same body in the diagram. This could be a box or a vase, or any other object. Third law pairs must act on two different bodies. We see this in the definition: A acts on B, and B acts on A, so there are two bodies A and B for the third law to apply.
- The two forces are different types. Weight is a non-contact (gravitational) force and the push upwards from the table is a contact force. Therefore, they are not a third law pair.

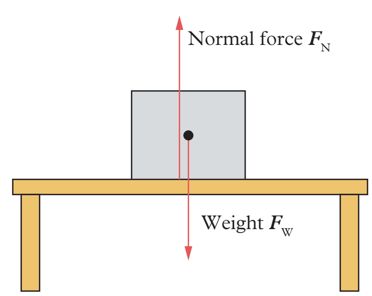


FIGURE 4 Two forces of interest acting on an object without the third law pairs being shown. If there is no acceleration, we can say $\vec{F}_N = -\vec{F}_W$ (i.e. magnitudes $F_N = F_W$). If the mass of the box was 1.0 kg, then the weight would be approximately 9.8 N down and the normal force would be 9.8 N up. The vector sum F_{net} is zero.

Is the magnitude of the normal force always equal to the weight?

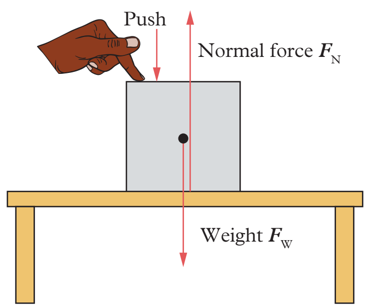


FIGURE 5 The normal force can be greater or less than the weight.

Imagine you now push downwards on the top of the box with your finger (Figure 5). The weight of the box does not change, but the normal force will now increase to be equal to the weight plus the extra force applied. As the box does not accelerate, the net force must be zero. Using vector notation with (+) being upwards and (–) being downwards:

$$\vec{F}_{net} = \vec{F}_N + \vec{F}_W + \vec{F}_{push} \quad \text{(vector sum)}$$

$$0 = F_N + (-F_W) + -(F_{push}) \quad \text{(magnitudes only)}$$

$$F_N = F_W + F_{push}$$

So, the normal force and the weight do not have to be equal.

Worked example 10.5A

Calculating weight on different heavenly bodies

An astronaut has a mass of 85.0 kg. **Calculate** the astronaut's weight on

a Earth (2 marks)

b the Moon ($g = 1.6\,\mathrm{m\,s^{-2}}$) (2 marks)

c Jupiter ($g = 24.9\,\mathrm{m\,s^{-2}}$). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the formula that relates mass to weight. The questions are worth 2 marks each, so we must gather the correct information, correctly apply the formula and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$F_W = mg$ $m = 85.0\,\mathrm{kg}$ **a** $g = 9.8\,\mathrm{m\,s^{-2}}$, $F_W = ?$ **b** $g = 1.6\,\mathrm{m\,s^{-2}}$, $F_W = ?$ **c** $g = 24.9\,\mathrm{m\,s^{-2}}$, $F_W = ?$
Step 3: Substitute the known values into the formula and find the unknowns.	**a** $F_W = 85.0 \times 9.8$ $= 833$ (1 mark) **b** $F_W = 85.0 \times 1.6$ $= 136$ (1 mark) **c** $F_W = 85.0 \times 24.9$ $= 2{,}116.5$ (1 mark)
Step 4: Finalise your answers and make sure you have included the correct units and significant figures.	**a** 830 N (2 s.f.) (1 mark) **b** 140 N (2 s.f.) (1 mark) **c** 2,120 N (3 s.f.) (1 mark)

Your turn

If your weight is 150 N on the Moon, **calculate** your weight on

a Earth (2 marks)

b Jupiter. (1 mark)

Real-world physics

Gravity and bathroom scales

When you stand on scales, gravity pulls downwards with a force we've called weight, $F_W = mg$, and the scales push up with a force normal to the surface, F_N. The value of this force F_N is converted into kilograms and shown as a "scale reading". In this case, as there is no acceleration, the magnitudes of the two forces are equal, so $F_W = F_N$, and the scales show the weight of the body but expressed as a mass in kg.

FIGURE 6 For bathroom scales, gravity and the normal force are equal to the weight of the body.

Apply your understanding

1 **Calculate** your weight (N) on Earth if your mass is 70.0 kg (2 s.f.). (1 mark)

2 **Determine** the normal force (magnitude and direction) acting perpendicular to the scales used in question **1** (2 s.f.). (2 marks)

3 **Compare** the values you calculated in questions **1** and **2** with the F_W and F_N if you weighed yourself on the Moon ($g_{Moon} = 1.6\,\mathrm{m\,s^{-2}}$). (3 marks)

Check your learning 10.5

Check your learning 10.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** what weight is in the context of Earth and the Moon. (2 marks)

2 **Explain** how gravity affects weight in the context of the surface of Earth and on the surface of another planet. (2 marks)

3 **Calculate** the weight in newtons of a 75.0 kg person under each of the following conditions.

   a Floating in water (1 mark)

   b Free-falling off the stage at a concert (1 mark)

4 A vase of mass 2.5 kg rests on a wooden kitchen table.

   a **Identify** the magnitude and direction of the normal force exerted by the table on the vase (2 s.f.). (3 marks)

   b **Calculate** the normal force if a very large mass of 500 kg was placed on the table. (3 marks)

Analytical processes

5 **Contrast** weight and mass using an example. (3 marks)

6 **Determine** how many times heavier by weight a person would be on Saturn than on Earth. (2 marks)

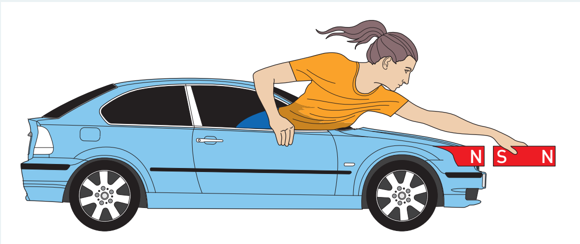
7 A marble dropped from height h on Earth takes t seconds to reach the ground. **Determine** the new height, in terms of h, that the ball would need to be dropped from on the Moon to have the same drop time t. (3 marks)

8 **Deduce** why we can say the net force acting on a person floating in a swimming pool is zero. (2 marks)

Knowledge utilisation

9 In hospitals, newborn babies have their mass recorded in kg.
If a baby was born in the "weightless" conditions of outer space, **propose** how the parents could measure the baby's mass for the benefit of relatives at home. (2 marks)

10 To make your car go forwards without using any fuel, just place a magnet in front of the car and the unlike pole on the car will be attracted forwards. **Evaluate** whether this would work. (2 marks)



11 A person used bathroom scales to measure their mass.
Calculate the gravitational force acting on the person. Express your answer in newtons, including percentage uncertainty and to the correct number of significant figures. (3 marks)

Lesson 10.6
Friction

Key ideas

→ Friction is caused by adhesion forces between two objects in contact.
→ Frictional forces oppose applied forces.
→ Friction can be overcome by applying an opposite force that is larger than the frictional force.

Learning intentions and success criteria

What would life be like without friction?

Consider what life would be like without friction. It would be a nightmare – in fact, impossible!

- You couldn't swallow, walk, hold a pen or do your homework.
- Your clothes would unravel and your shoelaces would come undone.
- Nails and screws would be useless, your house would fall down.
- Mountains would crumble and television cameras couldn't record it.
- Childbirth would be impossible.

FIGURE 1 Without friction, Olympic gymnastics would be much less exciting to watch – or perhaps more exciting?

- Life would last about one day before everyone died. The farewell party would be a disaster because you couldn't hold on to your cup and you couldn't stand up.

Friction is absolutely necessary, but it is also a hindrance. People have searched for ways of altering friction for thousands of years, but experiments only began in earnest 500 years ago.

What causes friction?

One of the first scientific studies of friction was in 1493 by Leonardo da Vinci, who discovered the various properties of friction. Friction is a force that resists motion between two surfaces in contact. It can be **dynamic**, **static** or **rolling**. In 1699, French scientist Guillaume Amontons formulated these properties of friction into the laws we have today.

At one time, it was thought that the surface roughness of materials was the cause for friction, but it is now understood to only have a small effect on friction for most materials. If the surfaces are very rough, the raised points touch each other. These raised points or "hills" interfere with sliding and cause friction because of the abrasion or wear that can take place when you slide one object against the other. This is the sandpaper effect, in which particles of the materials are dislodged from their surfaces. In such a case, the friction is caused by surface roughness.

Today, an adhesion model is accepted. When two objects are brought into contact, many atoms or molecules in one object are so close to those in the other object that electromagnetic forces attract the molecules of the two materials together. This force is called **adhesion**. Trying to slide one object across the other requires breaking these adhesive intermolecular bonds. Adhesion is the essence of friction.

Frictional forces are represented using the symbol F_f. Friction opposes the applied force.

dynamic friction
a force that acts between surfaces in motion relative to each other; also known as sliding or kinetic friction

static friction
friction between surfaces stationary relative to each other; generally higher than dynamic friction

rolling friction
friction between two surfaces rolling over each other; the smallest of all three types of friction

adhesion
the tendency of dissimilar surfaces to cling to one another by electromagnetic forces

What are applied forces and tension?

These are two other types of forces that are useful to know when it comes to friction: applied force and tension.

Applied forces

An **applied force** (F_A) is the force applied to an object by a person or another object. It can be a push or a pull. If you push a desk across the room, your hands are providing an applied force on the desk. The subscript A just stands for "applied".

applied force
an external force applied to an object; it can be a push or a pull

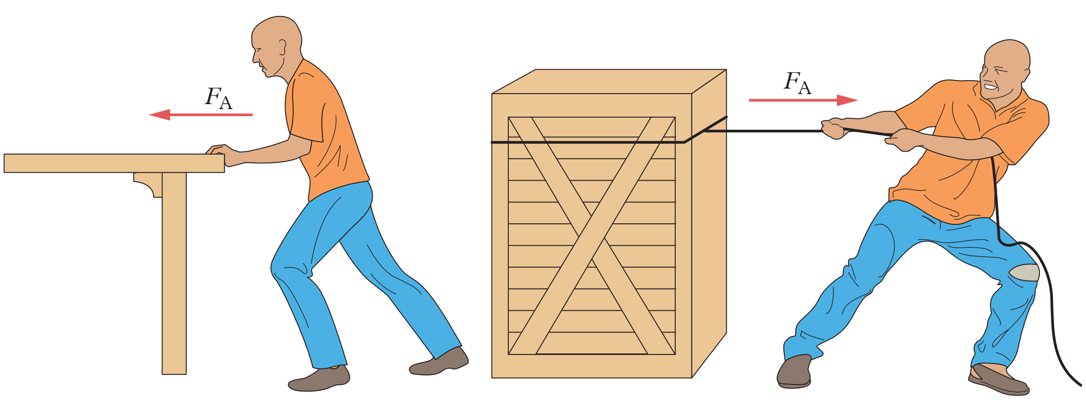


FIGURE 2 Pushing and pulling forces are applied forces on the object.

The simplest case for friction between surfaces is when an object moves across a horizontal surface such as a floor or desk. The applied force (F_A) and friction (F_f) are in line and oppose each other. We can construct a free-body diagram that shows the forces acting (Figure 3).

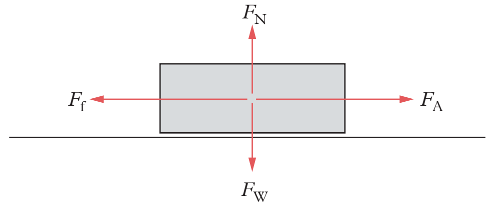


FIGURE 3 A free-body diagram is used to represent applied forces, movements and reactions on a body.

Challenge

Force applied to a cart

Figure 4 shows a cart with two masses.

1 **Calculate** the force, F_A, that must be applied for m_1 and m_2 to remain in the same positions relative to the cart. Assume the mass of the cart is M and that there is no friction between the cart and the ground, or between block m_1 and the cart. (4 marks)

2 **Predict** how the presence of friction would affect the force that must be applied. **Justify** your response. (3 marks)

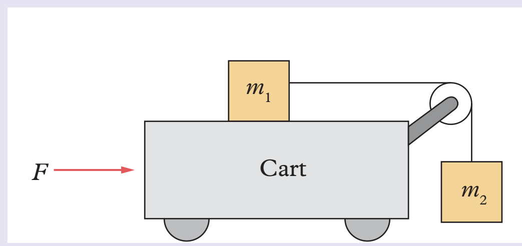


FIGURE 4 What force F has to be applied to the left for the masses to remain in the same positions relative to the cart?

Tension

tension
the pulling force transmitted along a rope, string, cable or chain on an object

If you pull a cart by a rope, then you are providing an applied force through the tension in the rope on the cart. **Tension** is the pulling force transmitted along a rope, string, cable or chain on an object. We use the symbol F_T to show that it is a force, with the subscript T to signify that it is "tension" – a pulling force and not compression or any other sort of force. In Figure 5, you can see that the frictional force F_f is in the opposite direction to the pulling tension force.

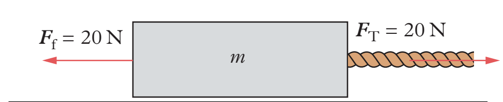


FIGURE 5 Tension is a pulling force only.

When the force of 20 N is applied to the block through the rope in Figure 5, we say the tension in the rope is 20 N.

How do you overcome friction?

Friction is a retarding force and tends to slow things down. It acts at all speeds and accelerations. The term "at constant speed" means that the applied force in the direction of motion is equal to the frictional forces, including other retarding forces such as air resistance, which resist motion. If the applied force is greater than that needed to overcome friction, there will be a net force in the direction of the applied force and the object will accelerate (Figure 6). The applied force can never be less than friction. It has to be equal to it (no change in motion) or greater than it (change in motion).

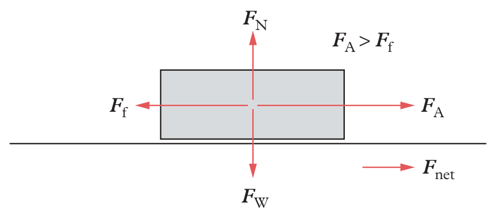


FIGURE 6 An object will accelerate if the applied force F_A is greater than friction F_f.

When F_A is greater than F_f, the net force (F_{net}) will be equal in magnitude to the difference between the two forces, and in the direction of F_A, as it is bigger. This will be equal to the product of mass and acceleration ($F_{net} = ma$) according to Newton's second law. Worked examples 10.6A–C take you through some problems involving friction and acceleration.

Worked example 10.6A

Determining the frictional force at constant speed

A 330 g wooden block is pulled along a laboratory bench at constant speed using a spring balance. The scale reading is 1.35 N. **Determine** the magnitude and direction of the friction between the block and the bench (3 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply Newton's second law of motion. The question is worth 3 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$F_{net} = ma$ $F_{net} = F_A - F_f$ (magnitudes) $F_A = 1.35\,\text{N}$, $m = 330\,\text{g}$ Speed is constant, so $a = 0\,\text{m}\,\text{s}^{-2}$. (1 mark)
Step 3: Determine the net force. Note that the mass is in grams and has to be converted to kg. The acceleration is zero, as the question says "at constant speed".	$F_{net} = \frac{330}{1000} \times 0$ $= 0\,\text{N}$
Step 4: Determine the frictional force. The forces are in opposition, so they must be subtracted.	$F_f = F_A - F_{net}$ $= 1.35 - 0$ $= 1.35\,\text{N}$ (1 mark)
Step 5: Finalise your answer and make sure you have included the correct units and significant figures. Since forces are vector quantities, remember to state the direction.	1.35 N opposite to the applied force (1 mark)

Your turn

A spring balance was used to pull a 450 g wooden block along a laboratory bench at constant speed. The scale reading was steady at 3.0 N. **Determine** the kinetic frictional force between the block and the surface (2 s.f.). Show your working. (2 marks)

Worked example 10.6B

Determining acceleration when friction is present

A horizontal force of 5.0 N is applied to a 1.0 kg wooden box resting on a laminate benchtop. **Determine** the acceleration of the box if the kinetic friction is 2.94 N (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply Newton's second law of motion. The question is worth 3 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$F_{net} = F_A - F_f$ $F_{net} = ma$ $F_A = 5.0\,N$, $m = 1.0\,kg$, $F_f = 2.94\,N$ (opposing)
Step 3: Determine the net force.	$F_{net} = F_A - F_f$ $= 5.0 - 2.94$ $= 2.06\,N$ (1 mark)
Step 4: Determine the acceleration.	$a = \frac{F_{net}}{m}$ $= \frac{2.06}{1.0}$ $= 2.06$ (1 mark)
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	$2.1\,m\,s^{-2}$ (2 s.f.) (1 mark)

Your turn

A 650 g wooden block rests on a laboratory bench. A spring balance is attached horizontally and pulled until a steady scale reading of 3.0 N is attained. It is known that the kinetic friction between the block and surface is 2.5 N. **Determine** the acceleration of the block (2 s.f.). Show your working. (3 marks)

Worked example 10.6C

Determining frictional force for an object sliding to a halt

A lunchbox with a mass of 800 g is at rest on the floor. It is kicked and moves off with a speed of $5.0\,m\,s^{-1}$. If the frictional force is 2.352 N, **determine** the distance the box will slide before it comes to rest (2 s.f.). Show your working. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply Newton's second law of motion and then the motion formula. The question is worth 4 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. The applied force is 0 N since no force is currently being applied. Velocity is 0 since the lunchbox comes to rest.	$F_{net} = F_A - F_f$ $F_{net} = ma$ $F_A = 0\,N$, $m = 800\,g$, $F_f = 2.352\,N$ $v^2 - u^2 = 2as$ $u = +5.0\,m\,s^{-1}$, $v = 0$
Step 3: Determine the net force.	$F_{net} = 0 - 2.352$ $= -2.352\,N$ (opposite to motion) (1 mark)

Think	Do
Step 4: Determine the acceleration. Remember to convert mass to kg.	$a = \frac{F_{net}}{m}$ $= \frac{-2.352}{0.800}$ $= -2.94\,\text{m s}^{-2}$ (1 mark)
Step 5: Determine the displacement.	$v^2 - u^2 = 2as$ $0^2 - 5.0^2 = 2 \times (-2.94) \times s$ $s = 4.25\,\text{m}$ (1 mark)
Step 6: Finalise your answer and make sure you have included the correct units and significant figures. The displacement is positive, so the distance moved is in the same direction as the initial direction. However, the question asks for distance (scalar), so direction is not required.	4.3 m (2 s.f.) (1 mark)

Your turn

A car of mass 2,100 kg is travelling along a flat horizontal road at a speed of 26 m s^{-1} when the brakes are applied and a frictional force of 13,400 N acts and there is no applied (driving) force from the engine to the wheels. **Determine** the stopping distance after the brakes are applied (2 s.f.). Show your working. (4 marks)

Check your learning 10.6

Check your learning 10.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** the connection between friction and adhesion in the context of metal sliding over wood. (2 marks)

2 **Describe** the forces on an object experiencing kinetic friction when the object is

  a being pulled at constant speed (1 mark)

  b accelerating due to a tension force in a rope. (1 mark)

Analytical processes

3 **Determine** whether the following are true (T) or false (F). If false, correct the sentence to make it true.

  a An applied force is needed to keep an object moving at constant velocity. (1 mark)

  b Objects always move faster when friction is decreased. (1 mark)

  c Inertia is a form of friction that determines the acceleration of an object. (1 mark)

  d Friction is never in the direction of motion. (1 mark)

  e Friction will always cause an object to slow down and stop. (1 mark)

  f Tension can be applied only as a pushing force, not a pulling force. (1 mark)

4 A horizontal force of 15 N is applied to a 1.5 kg block on a table for which the frictional force is 7.0 N. **Determine** the acceleration of the block (2 s.f.). (2 marks)

5 An object of mass 2.0 kg is at rest on a laboratory bench. A force of 7.0 N is applied horizontally and the block accelerates at 3.5 m s^{-2}. **Determine** the frictional force and its direction. Give your answer to the correct number of significant figures. (3 marks)

6 A 15 kg carton is being dragged along a horizontal surface by a force of 95 N. If friction amounts to 90 N, **determine** the motion of the carton in terms of its velocity and acceleration. (4 marks)

7 After an 8 kg schoolbag is given a kick across the floor, it is moving at a speed of 6 m s^{-1} and slides to rest in 3.0 m. **Determine** the frictional force acting. (4 marks)

Knowledge utilisation

8 Using two examples, **discuss** why it is sometimes necessary to increase friction. (4 marks)

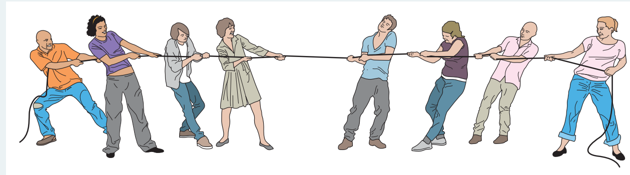
9 An experiment was conducted to measure the braking distance of a car travelling at different speeds. The experiment was carried out on different days, as rain kept intervening. There was only time to do one trial at each speed. The data is shown in the table.

Speed (km h^{-1})	Braking distance (m)
40	8
60	21
80	38
100	56
120	72

a **Draw** a justified conclusion about the results. (3 marks)

b **Explain** what other data would help improve the validity and reliability of the experiment. (3 marks)

10 **Evaluate** the game of tug of war shown and **determine** two pairs of surfaces on which friction acts. (2 marks)



Lesson 10.7
Terminal velocity and drag

Key ideas

→ Terminal velocity is reached when a falling object stops accelerating.

→ Drag force is the frictional force acting against an object moving through a fluid.

Learning intentions and success criteria

air resistance the force that acts in the opposite direction to an object moving through the air; also known as the drag force

terminal velocity the speed reached when an object falling through a fluid stops accelerating

What is terminal velocity and drag?

If you drop a rock off a cliff, it gets faster and faster as gravity causes it to accelerate towards the ground. However, as the rock speeds up, **air resistance** also increases. Eventually, the force upwards due to air resistance equals the force of gravity (down). The rock stops accelerating and falls at a constant velocity. This is called its **terminal velocity**. “Terminal” comes from the Latin word “terminus”, meaning “limit” or “the end”.

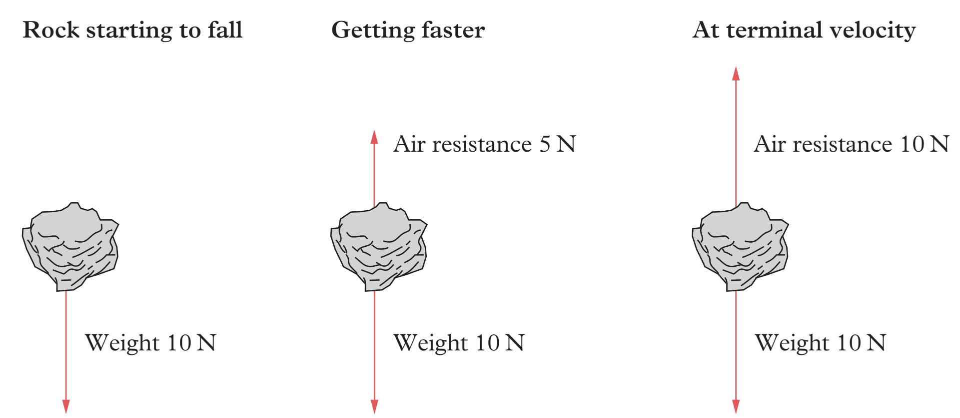


FIGURE 1 Forces acting on a rock falling freely to the ground

The terminal velocity of some objects is shown in Table 1.

TABLE 1 Terminal velocity of some objects

Object	Terminal velocity ($m\ s^{-1}$)
6 kg steel shot (shotput ball)	150
Skydiver (typical)	50
Cricket ball	40
Tennis ball	30
Rock (1 cm)	25
Basketball	20
Ping-pong ball	10
Raindrop (3 mm)	7
Insect	6
Parachutist (typical)	5

FIGURE 2 Forces acting on a parachutist

Without air resistance, objects near the surface of Earth would accelerate at $9.8\ m\ s^{-2}$ towards the ground. In general, the frictional force between an object and the fluid medium through which it is moving is called the **drag force**. In the scenario in which a parachutist is descending to Earth (Figure 2), the drag force (F_D) occurs in the opposite direction to their movement. Drag force is also relevant in other fluids; for example, the force opposing a swimmer as they complete a lap in a pool. A fluid is just a substance that has no fixed shape, such as a liquid or gas.

drag force
the force acting to oppose the motion of any object moving with respect to a surrounding fluid; symbol F_D

Real-world Physics

Surviving free fall

Parachutes are great for sport, but are also used to drop food and medical aid to people in war-torn areas or where a natural disaster has struck. Engineers can work out how big to make a parachute so that it can carry a load safely and land without the load smashing up. But what happens if you fall out of a plane without a parachute?

If you are spreadeagled in air, you will free fall for about 12 s and reach $190\ km\ h^{-1}$ in about 370 m. If you fall head-first, you will reach about $300\ km\ h^{-1}$ in that time. But you can survive free fall. Some examples are:

- While flying in a British bomber in 1944, tail-gunner Nick Alkemade bailed out after being hit by enemy fire. He fell 5,500 m without a parachute to the snow-covered ground in enemy territory. He was uninjured.
- However, airline crew member Vesna Vulović fell 10,000 m after her plane blew up over Czechoslovakia in 1972. She hit the ground and fractured her spine, legs and arms; she was in a coma for three days and had amnesia for three weeks. She did recover.

These two examples show that it is not the descent that hurts you, but the deceleration at the end.

The change in speed as you fall is not uniform. The drag force is proportional to the square of the velocity, and that makes the motion complex. For example, Figure 3 shows the graphs of motion of a tennis ball in free fall in air.

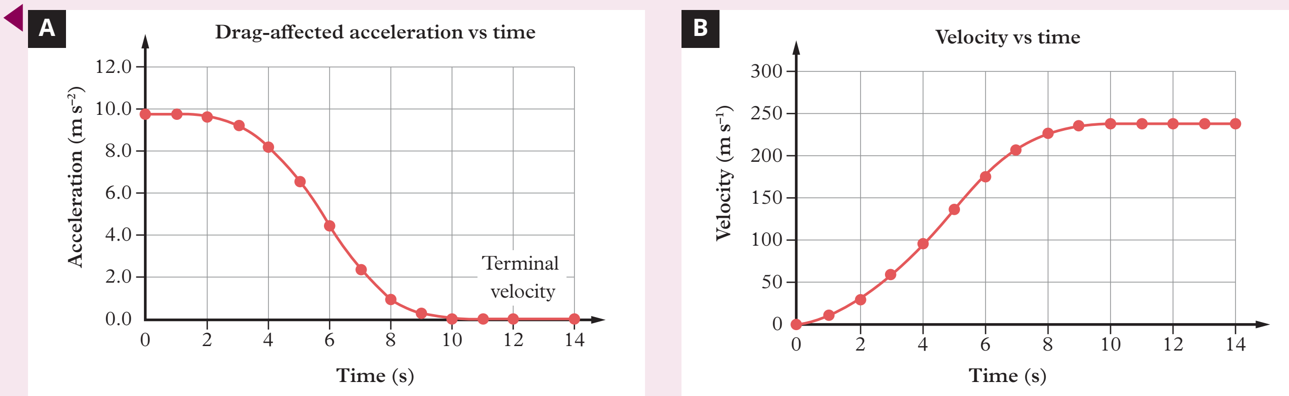


FIGURE 3 (A) Acceleration vs time and (B) velocity vs time graphs for a tennis ball in free fall

Acceleration starts off at 9.8 m s^{-2} but slows to zero over about 12 s. The velocity starts at zero and rises to about 240 m s^{-1} in the same time. Engineers can use these relationships to predict the complex motion of falling objects, to make life safe for users, such as those involved in disaster relief where food, medicine and machinery are dropped by parachute.

Apply your understanding

1 A tennis ball is allowed to free-fall in a vacuum near the surface of Earth.
 a **Calculate** the speed of the ball after 12 s (2 s.f.). (2 marks)
 b Use the graph to determine the speed of the tennis ball after 12 s falling in air (2 s.f.). (1 mark)
2 **Interpolate** the graph to estimate the time it takes the ball to reach 150 m s^{-1} in air (2 s.f.). (1 mark)
3 Using the velocity vs time graph, **calculate** the displacement over the 14 seconds. Hint: recall the meaning of the area under the curve of a velocity vs time graph (2 s.f.). (4 marks)
4 The first person to break the sound barrier in a free fall was Felix Baumgartner in 2012 from a height of 38 km. He fell to Earth at a supersonic speed of 1,358 km h^{-1}. He deployed his parachute after 4 minutes and landed safely. **Calculate** his average speed during the descent (2 s.f.). (2 marks)

Check your learning 10.7

Check your learning 10.7: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** terminal velocity in the context of a magazine falling with the cover facing down versus falling with the edge facing down. (2 marks)
2 **Identify** the factors on which drag force depends. (1 mark)
3 **Describe** the relationship between drag forces and terminal velocity in terms of a falling tennis ball. (2 marks)

Analytical processes

4 A tennis ball is thrown vertically into the air. If air resistance is taken into account, **determine** whether the time taken to travel upwards will equal the time coming back down. **Explain** using a free-body diagram. (4 marks)

Knowledge utilisation

5 A glass marble, a big foam ball and a small foam ball (from a bean bag) were dropped simultaneously from chest height. It was found that two of the balls hit the ground at the same time.
 a **Draw a conclusion** about the order in which the balls will hit the ground. **Justify** your reasoning. (3 marks)
 b **Explain** whether these two balls would be faster or slower than the third ball. (2 marks)

6 If a human and a mouse fell from the 20th storey of a high-rise building, the human would not survive, but the mouse would. **Propose** why this might be in terms of air resistance. (3 marks)

7 Two skydivers are free-falling. Before their parachutes open, they try to throw a tennis ball back and forth. **Propose** a reason why this will not be possible. **Draw a conclusion** about whether it would then be possible once their parachutes open. (3 marks)

8 When the upwards force of air resistance on a parachutist equals their weight (down), they will be stationary. **Draw a conclusion** about this statement and **justify** your reasoning. (3 marks)

Lesson 10.8

Momentum and impulse

Key ideas

→ Momentum is the product of mass and velocity.

→ A change in momentum can involve a change in velocity alone or a change in velocity and direction.

→ Impulse is the rate at which momentum changes.

Learning intentions and success criteria

What is momentum?

Momentum is the product of mass and velocity ($m \times v$). Newton showed that momentum is conserved in any interaction in which two or more bodies are involved – it doesn't change. Newton did not define momentum mathematically, but it is clear he was referring to the product of mass and velocity (Latin "movimentum", from "movere", meaning "to move").

$$\text{momentum} = \text{mass} \times \text{velocity}$$
$$p = mv$$

momentum
a vector quantity, the product of an object's mass and its velocity

Study tip

In relativistic physics (Unit 4), the formula for momentum contains modifications that are important as the velocity approaches the speed of light.

Momentum has the following characteristics:

- It is a vector quantity because velocity is a vector quantity.
- The direction of the momentum vector is the same as the direction of the velocity vector.
- Momentum is a useful quantity to describe the motion of an object.
- Momentum has the symbol p (the Latin word "petere" means "impetus", which is the old word for momentum).
- The unit of momentum does not have a special name. The unit is kg m s^{-1}, which is the same as newton seconds (N s), so this is often used.

FIGURE 1 As a rollercoaster accelerates to do a loop, its momentum increases.

How is momentum calculated?

Momentum of a single object

The momentum of a single object in motion can be simply calculated using the momentum equation.

Study tip

Make sure you know the units required for each parameter in a formula. Sometimes, you will need to convert values before you use them. Take note of the magnitude of your answer; if it looks off, you might have missed a conversion!

Worked example 10.8A

Calculating momentum of a single object

Calculate the momentum of a 2.0 kg bowling ball travelling at 8.0 m s^{-1} south (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the momentum formula. The question is worth 2 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formula and gather any data required.	$p = mv$ $m = 2.0$ kg, $v = 8.0$ m s^{-1} south, $p = ?$
Step 3: Substitute the known values into the formula and find the unknown.	$p = 2.0 \times 8.0$ (1 mark for correct substitution) $= 16$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures. Momentum is a vector quantity, so direction is required.	16 kg m s^{-1} south (1 mark for magnitude and direction)

Your turn

Calculate the momentum of a gel blaster capsule of mass 0.20 g fired at a speed of 70 m s^{-1} in an easterly direction (2 s.f.). (2 marks)

Total momentum of a system

total momentum
the vector sum of individual momenta (plural of momentum)

Two or more objects can make a "system", and we can calculate their **total momentum** by adding their independent momentum values together.

$$\begin{aligned} p_{total} &= \Sigma p = p_1 + p_2 + \ldots + p_n \\ &= \Sigma mv = m_1 v_1 + m_2 v_2 + \ldots + m_n v_n \end{aligned}$$

Worked example 10.8B

Calculating total momentum of a system of two objects

Two billiard balls roll towards each other. They each have a mass of 0.3 kg. Ball A is moving at 1 m s^{-1} to the right, while ball B is moving at 0.8 m s^{-1} to the left. **Calculate** the total momentum of the system before the collision (1 s.f.). (4 marks)

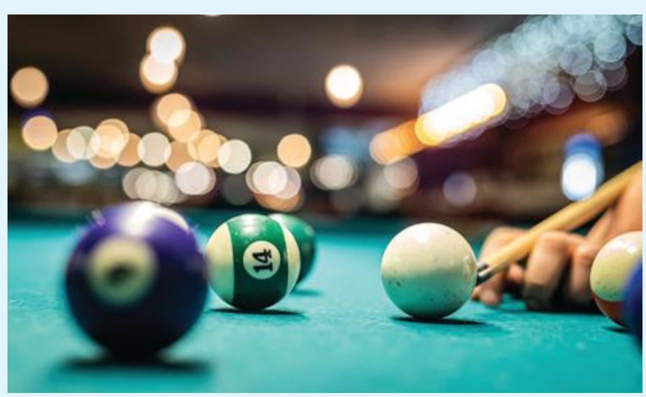


FIGURE 2 What is the momentum of billiard balls that are rolling towards each other?

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the formula for momentum of a system. The question is worth 4 marks, so we must gather the correct information and complete the calculations.
Step 2: Select the correct formula and gather any data required. Identify the sign (+/–) for directions.	$p_{total} = \Sigma p = p_1 + p_2 + \ldots + p_n$ $= \Sigma mv = m_1 v_1 + m_2 v_2 + \ldots + m_n v_n$ Let $p_1 = p_A$ and $p_2 = p_B$ $m_1 = m_A = 0.3\,kg$, $v_1 = v_A = 1\,m\,s^{-2}$ $m_2 = m_B = 0.3\,kg$, $v_2 = v_B = 0.8\,m\,s^{-2}$ Right = positive (+)
Step 3: Substitute the known values into the formula and find the unknowns. Start with the momentum of each single object.	$p_A = 0.3 \times (+1)$ $= +0.3\,kg\,m\,s^{-1}$ (1 mark) $p_B = 0.3 \times (-0.8)$ $= -0.24\,kg\,m\,s^{-1}$ (1 mark)
Step 4: Calculate the total momentum of the system.	$p_{total} = p_A + p_B$ $= +0.3 + (-0.24)$ $= +0.06$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures. Momentum is a vector quantity, so direction is required.	$0.06\,kg\,m\,s^{-1}$ (1 s.f.) to the right (1 mark for correct magnitude; 1 mark for correct direction)

Your turn

An oxygen molecule of mass $2.7 \times 10^{-28}\,kg$ travelling at $410\,m\,s^{-1}$ is about to collide head on with a nitrogen molecule of mass $2.3 \times 10^{-28}\,kg$ travelling at $520\,m\,s^{-1}$. **Calculate** the total momentum of the system of the two particles before the collision (2 s.f.). (4 marks)

How is change in momentum calculated?

As you saw with "change" in earlier work, a change means final minus initial. The same is true of **change in momentum**:

change in momentum
the difference between the initial momentum and final momentum; a vector quantity

$$\text{change in momentum} = \text{final momentum} - \text{initial momentum}$$
$$\Delta p = p_f - p_i$$
$$\Delta(mv) = mv - mu$$

where u is the initial velocity and v is the final velocity. Recall that u comes before v in the alphabet, so u (initial) is before v (final) for velocities. Momentum is a vector quantity.

An object may change its momentum if affected by an external contact force, such as from a collision, or a field force, such as a magnetic or gravitational force. These effects can cause an object's velocity to change or both its speed and direction of movement to change. In either case, you must be very careful with the signs of the directions (e.g. +/–, east/west, and so on) when you calculate change in momentum.

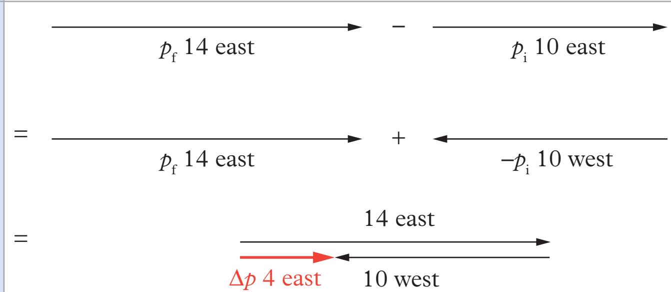
Velocity is changed but direction is not

The velocity of an object can change as it continues to travel in the same direction. For example, it could be struck by another object, or it could be affected by a field. It can speed up or slow down. The method for calculation is shown in Worked example 10.8C, along with the method that uses vector arrows.

Worked example 10.8C

Calculating change in momentum (same direction)

Calculate the change in momentum when an object of mass 2 kg travelling at 5 m s^{-1} east accelerates to 7 m s^{-1} east (1 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the change in momentum formula. The question is worth 3 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formula and gather any data required.	$\Delta p = p_f - p_i$ $p_i = m_i v_i$, $m_i = 2$ kg, $v_i = 5$ m s^{-1} east $p_f = m_f v_f$, $m_f = 2$ kg, $v_f = 7$ m s^{-1} east
Step 3: Substitute the known values into the formula and find the unknowns.	$p_i = 2 \times 5$ $= 10$ kg m s^{-1} $p_f = 2 \times 7$ $= 14$ kg m s^{-1} (1 mark)
Step 4: Calculate the change in momentum by subtracting the initial momentum from the final momentum. In this case, the direction is the same, so it is a simple subtraction.	$\Delta p = 14 - 10$ (1 mark for substitution) $= 4$ kg m s^{-1} east (1 mark for correct answer, including direction) Alternatively, if done in one step: $\Delta p = m(v - u)$ $= 2(7 - 5)$ $= 4$ kg m s^{-1} east (3 marks)
Vector method: When doing this using directional arrows for the two vectors, you have to change the subtraction to an addition. Change the direction of the initial momentum to the opposite (that is, from east to west), and add it to the final momentum by putting the vectors head to tail. You get the same answer.	

Your turn

An alpha particle of mass 6.6×10^{-27} kg travelling at 2.0×10^{5} m s^{-1} is accelerated to a speed of 3.0×10^{5} m s^{-1} in the same direction by a magnetic field. **Calculate** the change in momentum of the alpha particle including the direction of the change (2 s.f.). (3 marks)

Velocity and direction are both changed

Now, let us consider the case where the velocity changes to the opposite direction. The calculation is a bit more complicated so it is even more important to carefully map out the directions. A good example is when an incoming ball is struck by a bat and sent back where it came from, such as in tennis, baseball or cricket.

Worked example 10.8D

Calculating change in momentum (opposite direction)

A cricket ball of mass 160 g is travelling at 28.0 m s^{-1} when it is stuck by a bat that makes the ball go directly back the way it came at 25.5 m s^{-1}. **Calculate** the change in momentum, including the direction of the change (3 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the change in momentum formula. The question is worth 3 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the sign (+/–) for directions.	$\Delta p = p_f - p_i$ Initial direction = positive (+) $p_i = mu$, $m = 160\,\text{g}$, $u = +28.0\,\text{m s}^{-1}$ $p_f = mv$, $m = 160\,\text{g}$, $v = -25.5\,\text{m s}^{-1}$
Step 3: Substitute the known values into the formulas and find the unknowns. Convert mass to kg by dividing by 1,000.	$p_i = \frac{160}{1{,}000} \times (+28.0)$ $= +4.48\,\text{kg m s}^{-1}$ $p_f = \frac{160}{1{,}000} \times (-25.5)$ $= -4.08\,\text{kg m s}^{-1}$ (1 mark)
Step 4: Calculate the change in momentum by subtracting the initial momentum from the final momentum.	$\Delta p = -4.08 - (+4.48)$ (1 mark for substitution) $= -8.56\,\text{kg m s}^{-1}$ (1 mark) Alternatively, if done in one step: $\Delta p = m(v - u)$ $= 0.160(-25.5 - 28.0)$ $= -8.56\,\text{kg m s}^{-1}$ (3 marks)
Vector method: When doing this using directional arrows for the two vectors, you have to change the subtraction to an addition. Change the subtraction into an addition by reversing the arrow for the p_i value, then add the vectors head to tail. The resultant arrow points in the negative direction with a length that corresponds to the magnitude of the change in momentum.	$\Delta p = \underset{4.08}{\longleftarrow} - \underset{4.48}{\longrightarrow}$ $= \underset{4.08}{\longleftarrow} + \underset{4.48}{\longleftarrow}$ $= \underset{8.56}{\longleftarrow\!\!\!-\!\!\!-\!\!\!-}$

Your turn

A golf ball of mass 46 g is dropped from arm height and strikes the ground at 5.4 m s^{-1}. It rebounds at 4.4 m s^{-1}. **Calculate** the change in momentum including the direction of the change (2 s.f.). (3 marks)

What is impulse?

In 1688, Newton originally wrote his second law of motion (translated from Latin) as "the force on an object equals the rate of change in momentum":

$$\text{force} = \frac{\text{change in momentum}}{\text{time}}$$

$$F = \frac{mv - mu}{t}$$

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

Hence, the rate of change of momentum is equal to the external force causing the change. This can be rearranged and expressed as:

$$\Delta p = Ft$$

impulse
a vector quantity defined as the product of a force and the time interval over which the force acts; it is the change in momentum of an object during the time

The product Ft is called the **impulse** (Latin "pulsus" meaning "to beat" or "drive"). It is also a vector quantity. Impulse depends on the size of the force and for how long it is applied. The unit for impulse is newton second (N s), which is the same as kg m s^{-1}.

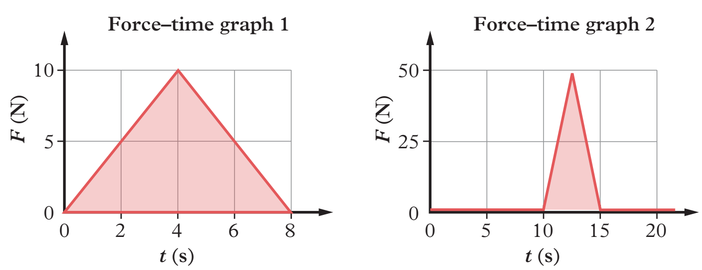
How do you use force–time graphs?

force–time graph
a graph that depicts the force acting on an object as a function of time, with the area under the curve being equal to the change in momentum (impulse)

It is useful to see how the force applied to an object changes during the course of an interaction, such as hitting a nail with a hammer or someone jumping in the air. Most situations involve forces that do not remain constant. We can use a **force–time graph** to show the force changes. The area under such a graph is $F \times t$, which is equal to impulse (Figure 3).

Study tip

The area under the curve depends on the shape of the curve. It might be worth reviewing the formulas for calculating the area of different shapes.



$Ft = \dfrac{10 \times 8}{2} = 40$ N s

$Ft = \dfrac{50 \times 5}{2} = 125$ N s

FIGURE 3 Force–time graphs allow impulse to be calculated.

Worked example 10.8E

Calculating impulse for a tennis ball being hit

Figure 4 shows how force varies with time as a stationary 57 g tennis ball is struck by a racquet (solid curved line). It is approximated to a more regular shape by the dotted line. Note: this dotted line would not be drawn for questions of this sort. It would be a part of the solution by the student.

Calculate (2 s.f.) the

a impulse (2 marks)

b final velocity of the ball. (2 marks)

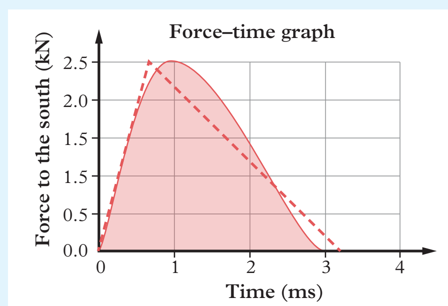


FIGURE 4 The force–time graph for a tennis ball during a serve

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to find the area under the curve and then use the change in momentum formula. Each question is worth 2 marks, so we must gather the correct information and complete the calculations.

Think	Do
Step 2: Select the correct formulas and gather any data required. The impulse is approximated by the dotted triangle in Figure 4, so recall the formula for the area of a triangle.	Δp = area under the curve $= \frac{1}{2} \times b \times h$ $b = 3.2\,\text{ms}$, $h = 2.5\,\text{kN}$ $\Delta p = Ft$, $Ft = mv - mu$ $m = 57\,\text{g}$, $u = 0$ since the ball starts at rest
Step 3: Substitute the known values into the formula and find the unknown. Remember to convert the units as required.	**a** $\Delta p = \frac{1}{2} \times \frac{3.2}{1000} \times (2.5 \times 1000)$ (1 mark) $= 4.375$ **b** $\Delta p = m(v - u)$ $4.375 = \frac{57}{1000} \times (v - 0)$ (1 mark) $v = 76.75$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures. Impulse is a vector quantity, so direction is required.	**a** 4.4 N s (south) (2 s.f.) (1 mark) **b** 77 m s^{-1} south (2 s.f.) (1 mark)

Your turn

The force delivered to a toy rocket during its flight is shown in Figure 5.

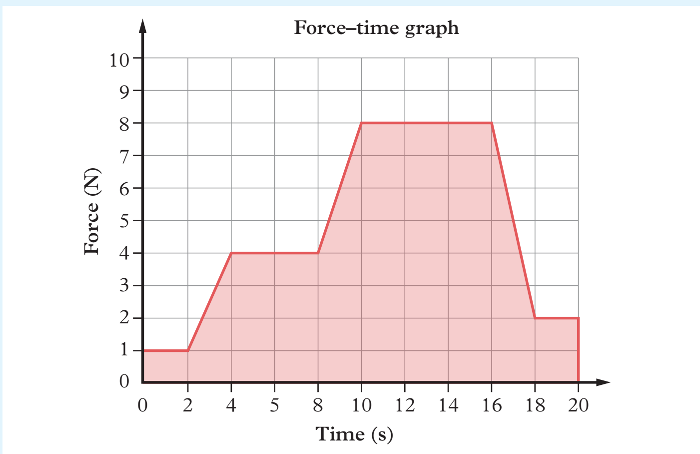


FIGURE 5 The force–time graph for a toy rocket during its flight

Calculate (2 s.f.) the

a impulse delivered in the first 8 seconds (2 marks)

b magnitude of the velocity at 8.0 s. (2 marks)

Study tip

You will often have to work out the area under a curve. Draw straight lines as in Figure 6 and try to have as much of the curve under the line as above it.

Study tip

If the question asks you for magnitude only, you do not need to indicate direction.

Real-world Physics

Using impulse to design better running shoes

When a runner's foot hits the ground, there is an upwards force that brings the foot to a gradual halt. The pull downwards by gravity is matched by the upwards normal force by the ground. This upwards force changes with the duration of the contact.

The change in momentum is the same no matter whether the time of contact is long or short, but the rate of change of momentum will affect the size of the force involved. This can be varied by the design of the shoe.

For a thick padded sole, the elapsed time is lengthened. This decreases the force necessary to produce the same change in momentum. By increasing the contact time, the force on the body is lessened. This decrease in the force on the body leads to less wear-and-tear on the body, leading to fewer injuries. The knees, for example, experience less impact and should stay in better condition throughout life.

However, excessive cushioning in a sole leads to heavier shoes, which makes running more difficult. The smaller force exerted on the body causes a less "explosive" power on the runner, which lowers speed. Many sprinters wear lightweight thin shoes, such as spikes or racing flats to reduce weight and increase the upwards force. Manufacturers take all these physics principles into account when designing running shoes.

FIGURE 6 Running shoes are designed with variable thicknesses of padding.

Apply your understanding

1 **Evaluate** the following claim about running shoes by referring to evidence described above: "The aim of shoe designers is to increase the time of contact so that the maximum force is reduced." (3 marks)

2 If a thin running shoe sole increases explosive power, **explain** why running barefoot with a zero thickness sole has drawbacks. (3 marks)

3 A study into the maximum vertical force experienced by runners reported that the well-cushioned Nike Air Pegasus (sprint running) generated a force of 1,530 N, compared to thin-soled Nike Waffle Racers (long-distance running) which generated a 1,920 N force. **Explain** which shoe had the longer contact time, assuming all other parameters are equal. (3 marks)

A

B

FIGURE 7 (A) Nike Air Pegasus runners have a thicker sole than (B) the Nike Waffle Racers.

Check your learning 10.8

Check your learning 10.8: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** momentum in terms of the motion of an alpha particle. (2 marks)

2 **Explain** change in momentum for a person bouncing on a trampoline. (3 marks)

3 **Explain** what a force–time graph measures in the context of a toy rocket taking off. (3 marks)

4 **Describe** impulse as it relates to a tennis ball being hit by a racquet. (2 marks)

5 **Calculate** the magnitude of the momentum of the following moving objects

a a 1,000 g bowling ball moving at 1.6 $m\,s^{-1}$ (2 marks)

b a 2.0 tonne car moving at 15 $m\,s^{-1}$ (2 marks)

c Earth at one point in its journey around the Sun (Earth's mass is 6×10^{24} kg and the average radius of its orbit is 1.5×10^{11} m). (4 marks)

6 A 900 kg car is travelling east at a velocity of 40 km h^{-1} when it is approached by a 290 kg motorbike travelling west at a velocity of 90 km h^{-1}. **Calculate** the total momentum of the system. (3 marks)

7 A proton of mass 1.67×10^{-27} kg is accelerated from 2×10^4 m s^{-1} to 9×10^5 m s^{-1}. **Calculate** the change in momentum. (2 marks)

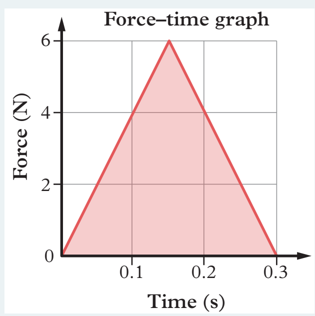
8 A force of 3 millinewton (3 mN) acts on an electron for 0.15 s. **Determine** the impulse imparted to the electron. (2 marks)

Analytical processes

9 A mass of 2.4 kg is moving at 6.0 m s^{-1} north.

- **a** **Determine** how long, and in what direction, a frictional force of 5.6 N must act to bring it to rest. (5 marks)
- **b** **Calculate** the impulse acting on the object. (3 marks)

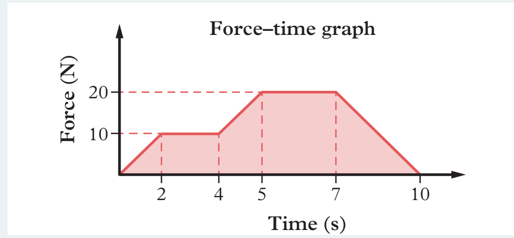
10 Consider this force–time graph for a tennis ball that is struck by a racquet.



Determine the

- **a** impulse given to the ball (3 marks)
- **b** change in momentum of the ball. (1 mark)

11 Consider this force–time graph for an object over 10 s.



- **a** **Calculate** the impulse imparted to the object over the whole 10 s. (3 marks)
- **b** **Determine** the greatest impulse given. (1 mark)

Lesson 10.9
Conservation of momentum

Key ideas

→ The law of conservation of momentum states that, for two objects colliding in an isolated system, the total momentum before and after the collision is equal.

→ Momentum is conserved in explosions and collisions.

What is the law of conservation of momentum?

Learning intentions and success criteria

When you throw a ball, shoot an arrow, or give someone a push, you tend to move backwards. Newton's third law of motion explains that the "third law pair"are equal and opposite forces.

As these opposing forces act for the same time, we can say that the change in momentum of object A is equal and opposite to the change in momentum of object B. In other words, if we add together the changes in momentum for both objects, we get zero.

isolated system
one that cannot exchange either matter or energy with its surroundings; also called a closed system

law of conservation of momentum
for two objects colliding in an isolated system, the total momentum before and after the collision is equal

Alternatively, we can say that for two objects colliding in an **isolated system**, the total momentum before and after the collision is equal. This is called the **law of conservation of momentum**. In an isolated system, the change in momentum is zero ($\Delta p = 0$):

$$p_{\text{before}} = p_{\text{after}}$$
$$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$$

By isolated system we mean one where nothing gets in or out; not energy, not matter, not even any radiation. It is like a little universe all to itself.

Examples of the concept and uses of the law of conservation of momentum are common in everyday life, but often they need pointing out to become obvious. The two most common interactions we can study are explosions and collisions.

What are explosions?

explosion
when a single object separates into two or more fragments

An **explosion** can be thought of as a single object separating into two or more fragments. The word "explode" was first used to mean "burst with destructive force" in the nineteenth century when a mathematical treatment of explosions became necessary.

Some familiar explosions are:
- a bomb blowing into fragments
- a bullet shot out of a gun
- water streaming out of a hose
- an alpha particle ejected out of a nucleus
- blood spurting from an artery.

FIGURE 1 Newton's cradle demonstrates the law of conservation of momentum.

FIGURE 2 A gas explosion. Gas and oxygen combine and the enormous heat generated causes products to fly apart in all directions with huge kinetic energy.

Consider a 10 kg bomb at rest that explodes into two fragments (Figure 3). If a 4 kg piece (m_1) travels west at 15 m s^{-1} (v_1), then the 6 kg piece (m_2) would have moved in the opposite direction (at a speed v_2). As there were no external unbalanced forces acting on the bomb (all forces were internal), we have a closed system and there would be no change in the total momentum of the system. This is the law of conservation of momentum.

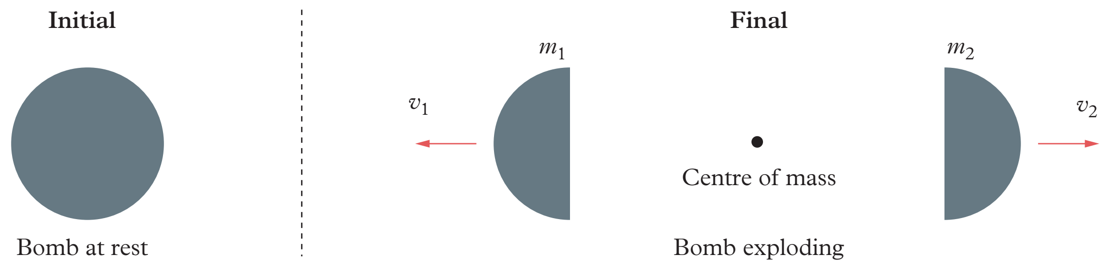


FIGURE 3 Bomb exploding away from the centre of mass. We can use the law of conservation of momentum formula to calculate the missing value, v_2, the speed at which the second fragment moves.

$$\begin{aligned} p_{\text{before}} &= p_{\text{after}} \\ \Sigma mv_{\text{before}} &= \Sigma mv_{\text{after}} \\ (m_1 + m_2)u &= m_1v_1 + m_2v_2 \\ 10 \times 0 &= (4 \times 15)+(6 \times v_2) \\ v_2 &= \frac{10 - 60}{6} \\ &= -8.3\,\text{m s}^{-1} \text{ or } -8\,\text{m s}^{-1}\ (1\text{ s.f.}) \end{aligned}$$

Worked example 10.9A

Calculating conservation of momentum in an explosion

A child on roller skates is travelling at 8.0 m s^{-1}. They have a mass of 60 kg and are carrying a schoolbag of mass 10 kg. They throw the bag directly forwards at 20 m s^{-1} relative to the ground. **Calculate** the child's velocity after the "explosion" (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the law of conservation of momentum. The question is worth 3 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the sign (+/–) for directions.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_1 = 60\,\text{kg}$, $m_2 = 10\,\text{kg}$, $u = 8.0\,\text{m s}^{-1}$, $v_1 = ?$, $v_2 = 20\,\text{m s}^{-1}$ Boy and bag moving in the positive (+) direction Bag thrown in the positive (+) direction
Step 3: Substitute the known values into the formula and find the unknowns.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $(m_1 + m_2)u = m_1v_1 + m_2v_2$ $(60 + 10) \times (+8.0) = (60 \times v_1)+(10 \times (+20))$ $(+560) = 60v_1 + 200$ $(+360) = 60v_1$ $v_1 = +6.0$ (2 marks)
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	$+6.0\,\text{m s}^{-1}$ (2 s.f.) (1 mark) The positive direction means that the child would continue to move forwards.

Your turn

A 10 kg meatball is sitting on a plate. Suddenly it explodes, breaking up into two pieces. One piece has a mass of 4.0 kg and travels to the right with a velocity of 21 m s^{-1}. **Calculate** the velocity of the other piece (2 s.f.). (3 marks)

Relationships such as this can be applied to all sorts of explosions, even radioactive decay in which a nucleus explodes into a daughter nucleus and a nuclear particle. In fact, that's how neutrinos were discovered. However, cases in which the bodies explode in a straight line (one dimension) are not that common. Explosions in two dimensions are not dealt with in this text.

What are collisions?

The Wolfe Creek Crater in Western Australia is a result of a meteorite collision with Earth about 300,000 years ago. The 100,000 tonne chunk of iron was travelling at about 15 km s^{-1} and would have exploded on impact with Earth and turned to vapour (along with huge quantities of the quartzite rock underneath).

collision
when two or more objects hit each other

In everyday language, a **collision** occurs when objects hit each other. This suits our purpose in physics too. Some familiar collisions are:

- a meteor crashing into Earth
- cars running into each other
- a billiard ball being struck by a cue
- gas molecules bouncing off each other.

FIGURE 4 Wolfe Creek Crater in Western Australia is the result of a meteorite collision with Earth. It has been known to the local Djaru people as Kandimalal for thousands of years.

Collisions can be grouped into two types and momentum is conserved in both cases:

elastic collision
a collision in which kinetic energy is conserved

inelastic collision
a collision in which total kinetic energy is not conserved

- **elastic collisions** in which kinetic energy is conserved; includes some collisions in which objects collide and bounce off each other (such as gas molecules or billiard balls)
- **inelastic collisions** in which kinetic energy is not conserved; includes collisions in which objects collide and remain bound to each other (such as a bullet in a target).

Elastic collisions

Consider a collision between two masses m_1 and m_2 with initial velocities u_1 and u_2, respectively (Figure 5).

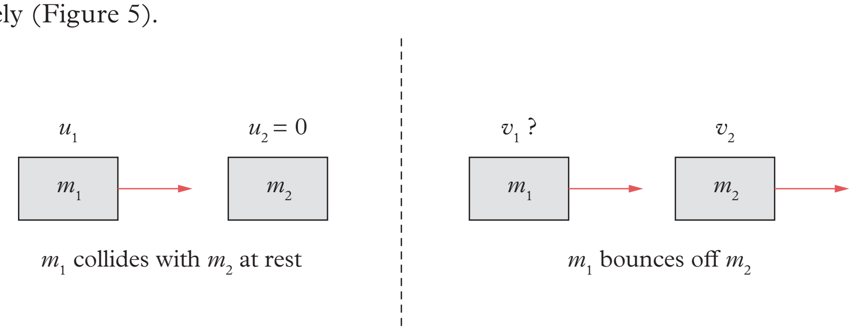


FIGURE 5 A collision between two masses showing before (left) and after (right)

For the law of conservation of momentum to hold, the total momentum before the collision must equal the total momentum after the collision:

$$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$$
$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

Worked example 10.9B

Calculating velocity after an elastic collision

Cart A with a mass of 2.0 kg travelling at 6.0 m s^{-1} collides with cart B of mass 0.40 kg travelling in the same direction at 2.0 m s^{-1}, as shown in Figure 6. After impact, the 2.0 kg cart (A) travels at 4.7 m s^{-1} in the same direction. **Calculate** the velocity of the 0.40 kg cart (B) after the collision (2 s.f.). (3 marks)

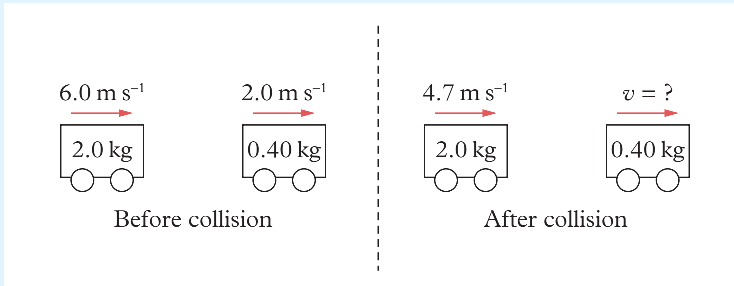


FIGURE 6 In this collision, the second cart bounces off the first cart.

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the law of conservation of momentum. The question involves an elastic collision since the objects remain separate after the collision. The question is worth 3 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the sign (+/–) for directions.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ m_1 = 2.0 kg, m_2 = 0.40 kg, u_1 = 6.0 m s^{-1}, u_2 = 2.0 m s^{-1}, v_1 = 4.7 m s^{-1}, v_2 = ? m s^{-1} Two carts initially move in the positive (+) direction.
Step 3: Substitute the known values into the formula and find the unknowns.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$ $(2.0 \times (+6.0)) \times (0.40 \times (+2.0)) = (2.0 \times (+4.7)) + (0.40 \times v_2)$ $12.0 + 0.80 = 9.4 + 0.40v_2$ $(+3.4) = 0.40v_2$ $v_2 = +8.5$ (1 mark for equation relating values, 1 mark for correct substitution
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	+8.5 m s^{-1} (2 s.f.) (1 mark for correct direction and magnitude) The positive direction means that the cart continues to move forwards.

Your turn

Carriage X of mass 0.150 kg moving right with a velocity of 1.2 m s^{-1} collides with a 0.30 kg carriage Y that is stationary on a track. Carriage Y moves at 0.8 m s^{-1} after the collision. **Calculate** the velocity of carriage X after the collision if the collision is perfectly elastic (2 s.f.). (3 marks)

Inelastic collisions

Inelastic collisions can be of two types: coupled and non-coupled.

Coupled

When objects stick together or are joined together, they are said to be coupled (Latin "copulare" meaning "to bond").

Some examples of coupled collisions are:

- an arrow sticking into its target
- two cars colliding and getting stuck together.

Non-coupled

Not all inelastic collisions involve coupling. They could be non-coupled, in which the objects bounce off each other (e.g. a tennis ball striking racquet strings).

When there is a loss of kinetic energy in a collision, whether it is coupled or non-coupled, the collision is said to be inelastic. The law of conservation of momentum still holds for all collisions – elastic or inelastic.

Worked example 10.9C

Calculating velocity after an inelastic collision

A supermarket trolley loaded with shopping has a mass of 60 kg. It rolls across the floor at 4.0 m s^{-1} and collides with an empty trolley of mass 25 kg, which was stationary. They become coupled (fastened) together and roll on as one. **Calculate** the magnitude of the velocity of the two trolleys when locked together (2 s.f.). (3 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to use the law of conservation of momentum. The question involves an inelastic collision since the objects are coupled after the collision. The question is worth 3 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the sign (+/–) for directions.	$\Sigma mv_{before} = \Sigma mv_{after}$ $m_1 = 60$ kg, $m_2 = 25$ kg, $u_1 = 4.0$ m s^{-1}, $u_2 = 0$ m s^{-1}, $v = ?$ Shopping trolley is initially moving in the positive (+) direction.
Step 3: Substitute the known values into the formula and find the unknowns.	$\Sigma mv_{before} = \Sigma mv_{after}$ (1 mark) $m_1u_1 + m_2u_2 = (m_1 + m_2)v$ $(60 \times (+4.0))+(25 \times 0) = (60 + 25)v$ (1 mark) $(+240) = 85v$ $v = +2.8$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures. You can sense check your answer: the final velocity should not be greater than the higher of the initial velocities. The question asks for magnitude only, so no need to state the direction.	2.8 m s^{-1} (2 s.f.) (1 mark)

Your turn

A toy freight train car of mass 50 kg moving at 5.0 m s^{-1} collides with a stationary empty car of mass 15 kg. After the collision, the cars couple together. **Calculate** the final velocity of the moving pair (2 s.f.). (3 marks)

Often questions will give you relative data – that is, the speed or mass of one object as a multiple of the other. Ultimately, it is just a matter of setting up an equation and cancelling out common physical quantities. You may encounter such questions on your external exam, so you need to practise! Let's look at Worked example 10.9D.

Worked example 10.9D

Determining velocity using relative quantities

A red object (R) and a blue object (B) of equal mass are both moving to the right. The red object is behind the blue one and the red object is moving $20\,\mathrm{m\,s^{-1}}$ faster. The objects eventually collide and stick together, and the combined object (C) has a velocity three times the original velocity of the blue object. **Determine** the final velocity of the combined object (C) (2 s.f.). (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to use the law of conservation of momentum. The question involves an inelastic collision since the objects are coupled after the collision. The question is worth 4 marks, so we must gather the correct information and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the sign (+/–) for directions. We have not been given the exact mass of R and B, so we can call the mass m. We also do not know the exact initial velocities of R and B, so we can call the initial velocity of B, u_B, and express the initial velocity of A, u_A, in terms of u_B. We also know the final velocity is three times the u_B.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_R = m_B = m$ $u_R = u_B + 20$, $v_C = 3u_B$ Right = positive (+) direction
Step 3: Substitute the known values into the formula and find the unknowns. You can factorise $2m$ out of the equation to find u_B.	$\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ (1 mark) $m_R u_R + m_B u_B = (m_R + m_B)v_C$ $(m \times (u_B + 20))+mu_B = 2m \times 3u_B$ (1 mark) $mu_B + 20m + mu_B = 2m3u_B$ $20m + 2mu_B = 2m3u_B$ $2m(10 + u_B) = 2m(3u_B)$ $10 + u_B = 3u_B$ $10 = 2u_B$ $u_B = 5$ (1 mark)
Step 4: Finalise your answer and make sure you have included the correct units and significant figures. Remember we need to find the final velocity ($v_C = 3u_B$).	$v_C = 3u_B$ $= 3 \times 5$ $= +15\,\mathrm{m\,s^{-1}}$ (2 s.f.) (1 mark) The positive direction means that the object C is moving to the right.

Your turn

Two objects X and Y are both moving to the right and are about to collide. Object Y is twice the mass of object X. Object Y starts in front of object X but is slower by $5\,\mathrm{m\,s^{-1}}$. On collision, X and Y become coupled and continue to move to the right at a combined speed of $20\,\mathrm{m\,s^{-1}}$. **Determine** the initial velocity of object Y (2 s.f.). (4 marks)

How are inelastic collisions used in practice?

One way of measuring bullet speeds is to make use of an inelastic collision. If an air gun pellet is shot into a soft absorbent target (such as a toilet roll) that is attached to a linear air track glider (very low friction), the glider moves away under the impact of the pellet. By measuring the time it takes the glider to move a specified distance (50 cm in Figure 7), the velocity of the glider can be determined. This data can be used to calculate the velocity of the pellet.

A device called a ballistic pendulum can be used for measuring the speed of high-speed bullets. This will be described in Module 13.

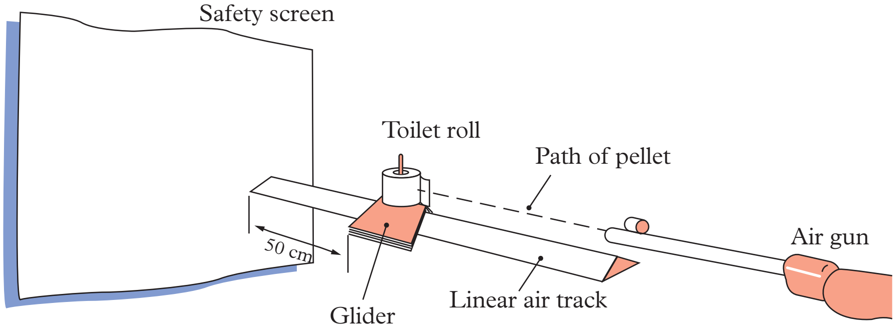


FIGURE 7 Measuring the velocity of an air-rifle pellet in the laboratory

Worked example 10.9E

Calculating velocity of bullets

When a 0.45 g air gun pellet is fired into a target attached to a glider on a frictionless linear air track, the glider moves 50 cm in 3.8 s. **Calculate** the magnitude of the velocity of the pellet (2 s.f.). The glider and target have a combined mass of 643 g. (4 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	“Calculate” means to determine or find a number or answer by using mathematical processes. We need to use the velocity formula and the law of conservation of momentum. The question involves an inelastic collision since the objects are coupled after the collision. It is worth 4 marks, so we must gather the correct information and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$\Sigma mv_{before} = \Sigma mv_{after}$ $m_{pellet} = 0.45\,\text{g}$, $m_{target} = 643\,\text{g}$, $u_{pellet} = ?$, $v_{target} = ?$ $v = \frac{s}{t}$ $s = 50\,\text{cm}$, $t = 3.8\,\text{s}$
Step 3: Calculate the glider velocity by substituting the known values into the formula and finding the unknowns. Remember to convert the units as required.	$v_{target} = \frac{\frac{50}{100}}{3.8}$ $= 0.132\,\text{m s}^{-1}$ (1 mark)
Step 4: Calculate the pellet velocity by substituting the known values into the formula and finding the unknowns. Remember to convert the units as required.	$\Sigma mv_{before} = \Sigma mv_{after}$ (1 mark) $m_{pellet} \times u_{pellet} = m_{target} \times v_{target}$ $\frac{0.45}{1{,}000} \times u_{pellet} = \frac{643}{1{,}000} \times 0.1316$ (1 mark) $u_{pellet} = 188.0$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures. The question asks for magnitude only so no need to state the direction.	$190\,\text{m s}^{-1}$ (2 s.f.) (1 mark)

Your turn

An 18 g arrow is fired into a foam target attached to a glider on a frictionless linear air track and becomes embedded (coupled). The glider moves 100.0 cm in 0.31 seconds. **Calculate** the magnitude of the velocity of the arrow (2 s.f.). The glider and foam target have a combined mass of 400.0 g. (4 marks)

Real-world physics

The physics of car safety

The safety of passengers in a car during a collision has drastically improved due to increased knowledge of forces and motion. One important notion is that passenger safety depends on how long it takes for you inside the moving car to stop. The more slowly this happens, the smaller the force needed and the smaller the potential damage. To reduce the force of an impact, we must increase the time it takes.

Such advances have led to the development of features such as seatbelts, crumple zones and air bags, most of which are based on the principle that the longer it takes for your body to come to rest, the smaller the force your body has to withstand. Although the change in momentum is usually the same no matter how you crash, it is better to suffer a small force for a long time than a large force for a short time.

Crumple zones

The main way car occupants are kept safe is by making the front and rear of cars collapsible. These "crumple zones" must not be too hard or too soft, and collapse progressively so that the time of the collision is prolonged. Before the mid-1950s, engineers believed that the stronger the structure, the safer the car. However, all the forces were transferred to the occupants – most of the time being fatal. The first crumple zones were implemented on vehicles in the mid-1950s.

FIGURE 8 In this head-on collision, the passengers would have experienced lower forces because of the crumple zones and airbags.

Air bags

Air bags increase the time taken for the occupant's head to decelerate from impact speed to zero. The inflated bag cushions the person's head and brings it to rest over a longer time (about 0.1 s).

Apply your understanding

1 **Explain** the physics principles of the crumple zone and air bags in terms of the rate of change of momentum. (3 marks)

2 A 1,400 kg VW Beetle sedan is travelling at 20 m s^{-1} and crashes into a power pole. The car comes to rest in 0.15 s. **Determine** the
   - **a** change in momentum (3 marks)
   - **b** force by the pole on the car. (2 marks)

3 A 3.300 tonne Landcruiser is filmed by traffic cameras crashing into a solid barrier. The crumple zone of the car is pushed back 0.9 m and the time (from the video footage) from the moment of impact to the car becoming stationary is 0.110 seconds. **Determine** the
   - **a** acceleration of the car during the crash (3 marks)
   - **b** impact speed (2 marks)
   - **c** change in momentum (2 marks)
   - **d** force of the impact. (2 marks)

Skill drill

Gathering secondary data for a research investigation

Science inquiry skills: Processing and analysing data (Lesson 1.7)

In the research investigation, you will analyse qualitative and quantitative data to identify relevant evidence. You will then use this evidence to describe trends, patterns and relationships and draw conclusions related to your research question.

Consider the following research question: To what extent are cars manufactured between 2020 and 2025 more likely to keep drivers safe in an accident compared with cars made between 1990 and 1995?

Practise your skills

1 **Select** two pieces of evidence that support or refute the question. **Identify** trends, patterns and relationships in the secondary data you have found. (3 marks)

2 **Explain** how this data allows you to make a justified response to your research question. (3 marks)

Skill drill

Evaluating the quality of evidence from a crumple zone experiment

Science inquiry skills: Evaluating evidence (Lesson 1.8)

Students performed an experiment to test the effectiveness of crumple zones in cars at different speeds. They let a cart roll down an incline of various heights and noted how much a 10 cm long aluminium foil cylinder placed end on was crushed on impact. The results show the final length of the cylinder (Table 1).

TABLE 1 Results of the crumple zone experiment

Height (cm)	Trial 1 (cm)	Trial 2 (cm)	Average (cm)
20	10	8	9
30	9	7	8
40	4	8	6

Practise your skills

1 **Identify** one limitation to their conclusion that “the amount of crush is proportional to the impact speed”. **Explain** your answer. (3 marks)

2 **Propose** how the uncertainty in the results for each height could be reduced. (2 marks)

3 **Propose** an extension that could improve the validity of the experiment. **Explain** your reasoning. (4 marks)

Check your learning 10.9

Check your learning 10.9: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** the meaning of momentum using the context of a ball bouncing on the floor. (3 marks)

2 **Describe** what is meant by the law of conservation of momentum, using an example. (2 marks)

3 **Describe** an example of

- **a** an elastic collision (1 mark)
- **b** an inelastic collision. (1 mark)

4 A girl of mass 50 kg is stationary on an ice rink. She throws a 1.0 kg parcel horizontally at 5.0 m s^{-1}. **Calculate** the velocity at which the girl moves. (3 marks)

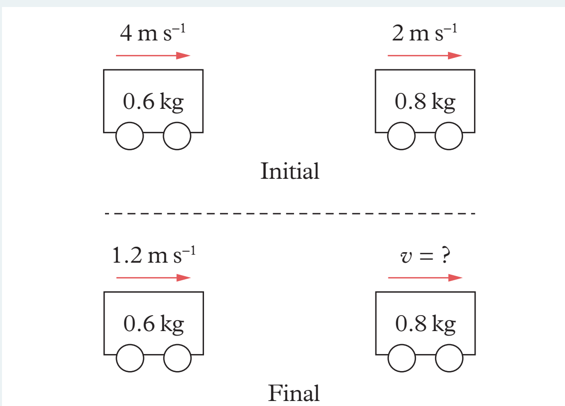
5 Two children at rest push off from each other in a swimming pool. The first child, with a mass of 50 kg, moves east at 1.5 m s^{-1}. The second child, who has a mass of 45 kg, moves to the west. **Calculate** the second child’s velocity. (3 marks)

6 Two lawn bowls, each with mass 300 g, collide. Initially, ball A is at rest and ball B is moving towards it with a speed of $2\,m\,s^{-1}$. After the balls collide, ball B comes to an immediate stop and ball A moves off. **Demonstrate** mathematically that the final velocity of ball A is $2\,m\,s^{-1}$. (3 marks)

Analytical processes

7 A jet flies at a speed of $355\,m\,s^{-1}$. The pilot fires a missile forwards at a speed of $750\,m\,s^{-1}$ relative to the ground. The respective masses of the jet and the missile are 6,000 kg and 60 kg. **Determine** the new speed of the jet immediately after the missile has been fired. (3 marks)

8 Two carts, one of mass 0.6 kg and the other of mass 0.8 kg, are moving to the right along a smooth horizontal surface with speeds of $4\,m\,s^{-1}$ and $2\,m\,s^{-1}$, respectively. After the collision, the 0.6 kg mass continues to travel to the right but with a speed of $1.2\,m\,s^{-1}$. **Determine** the speed of the 0.8 kg mass. (3 marks)



9 A very lightweight boat 24 m long with a mass of 30 kg lies still on a quiet pond. A 90 kg man walks from bow (front) to stern. **Determine** how far the boat moves relative to the pond. (2 marks)

Knowledge utilisation

10 A 0.41 g air gun pellet is fired into a target made up of a 170 g toilet roll attached to a glider of 350 g. The target slides 50 cm along a linear air track in 2.8 s.

- **a** **Calculate** the velocity of the pellet. (5 marks)
- **b** **Propose** what additional information you would need to calculate the recoil speed of the air gun. (1 mark)

11 Shooters who want to reduce the recoil of their rifles use a variety of anti-recoil devices. The simplest is to vent the exhaust gases out sideways instead of leaving them trapped in the barrel. One effective method involves drilling a hole in the rifle butt (the wooden shoulder piece) and inserting a rod of steel about 2 cm in diameter. Better still, inventive shooters use a length of steel water pipe filled with mercury and capped. **Propose** how this might help. (4 marks)

12 A lawyer emailed a physicist wanting to know what was meant when someone was "in an accident and suffered high g-forces". **Discuss** how you would explain this to the lawyer. (6 marks)

Practical

Lesson 10.10
Linear elastic collision between trolleys – conservation of momentum

Learning intentions and success criteria

Video demonstration

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

MODULE 10

Lesson 10.11
Review: Classical mechanics

Summary

10.1
- Forces can be contact or non-contact.
- When forces are balanced, there is no change in motion. However, when forces are unbalanced, there is a change in motion.
- Forces are vector quantities measured in the SI unit of newtons.
- A resultant force is the vector sum of all forces acting on an object.

10.2
- Newton's first law of motion states that an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force.

10.3
- Newton's second law of motion states that the acceleration of an object is in the direction of the net external force acting on it, proportional to the size of the force, and inversely proportional to its mass.

10.4
- Newton's third law of motion states that whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first.

10.5
- Gravitational forces dictate an object's weight.
- Normal force is the perpendicular force exerted on a body by a surface against which it is pressed.

10.6
- Friction is caused by adhesion forces between two objects in contact.
- Frictional forces oppose applied forces.
- Friction can be overcome by applying an opposite force that is larger than the frictional force.

10.7
- Terminal velocity is reached when a falling object stops accelerating.
- Drag force is the frictional force acting against an object moving through a fluid.

10.8
- Momentum is the product of mass and velocity.
- A change in momentum can involve a change in velocity alone or a change in velocity and direction.
- Impulse is the rate at which momentum changes.

10.9
- The law of conservation of momentum states that, for two objects colliding in an isolated system, the total momentum before and after the collision is equal.
- Momentum is conserved in explosions and collisions.

10.10
- Practical: Linear elastic collision between trolleys – conservation of momentum

Key formulas

Resultant (net) force	F_R (or F_{net}) $= \Sigma F$
Newton's second law	$a_{net} = \frac{F_{net}}{m}$
Newton's third law	$F_{AB} = -F_{BA}$
Relating mass to weight	$F_W = mg$
Momentum	$p = mv$
Change in momentum	$\Delta p = p_f - p_i$ or $\Delta(mv) = mv - mu$
Impulse	$Ft = mv - mu = \Delta p$
Law of conservation of momentum	$\Sigma mv_{before} = \Sigma mv_{after}$

Review questions 10.11A Multiple choice

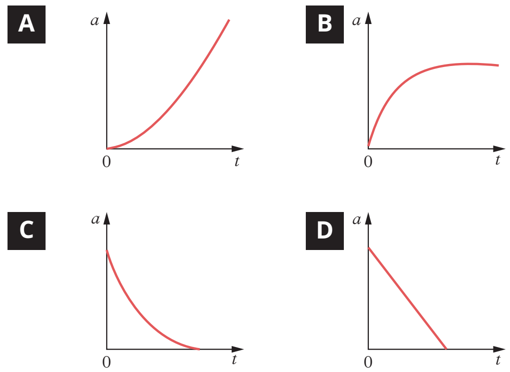
Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 A student is sitting on a chair. One force that is acting on the student is the pull of gravity. According to Newton's third law there must be another force acting, which is

- **A** the upwards push of the chair on the student.
- **B** the downwards force on the student.
- **C** the downwards push of the chair on Earth.
- **D** the upwards force on Earth.

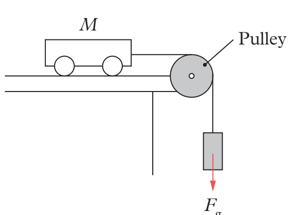
2 A ball, initially at rest, is dropped in the air from a great height. Air resistance is not negligible. Which of the following graphs best shows the variation with time, t, of the acceleration, a, of the ball?



3 Which of the following is a correct interpretation of Newton's second law of motion?

- **A** The momentum of a body is proportional to the force acting on it.
- **B** The change of momentum of a body is equal to the net external force acting on the body.
- **C** The momentum of a body is proportional to the net external force acting on the body.
- **D** A force acting on a body is proportional to the acceleration of the body.

4 A cart of mass M is on a horizontal frictionless table. The cart is connected to an object of weight F_g via a pulley. Which of the following is the acceleration of the cart?



- **A** $\frac{M + \frac{F_g}{g}}{F_g}$
- **B** $\frac{F_g}{M + \frac{F_g}{g}}$
- **C** $\frac{M_g}{F_g}$
- **D** zero

5 When a car's velocity is negative and its acceleration is negative, which of the following is happening to the car's motion?

- **A** The car slows down.
- **B** The car speeds up.
- **C** The car travels at constant speed.
- **D** The car remains at rest.

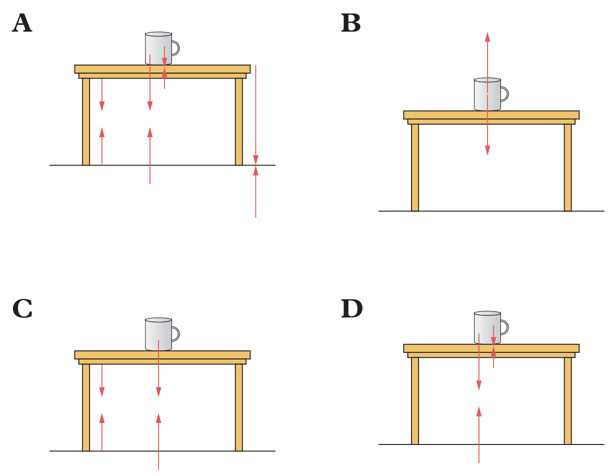
6 A 430 g soccer ball is kicked with 82 N of force, causing it to accelerate at 20 m s^{-2}. The magnitude of the force exerted by the soccer ball on the player is

- **A** 4.1 N.
- **B** 41 N.
- **C** 82 N.
- **D** 102 N.

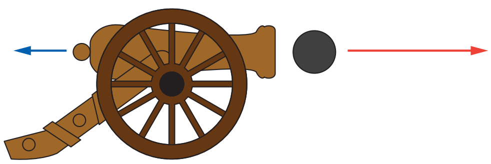
7 An 8 kg box is at rest on a bench and experiences a horizontal force of 36 N. A frictional force of 12 N is applied to the right. The acceleration of the box is

- **A** 1.5 m s^{-2} to the right.
- **B** 1.5 m s^{-2} to the left.
- **C** 3 m s^{-2} to the right.
- **D** 3 m s^{-2} to the left.

8 A mug is stationary on a table. Which of the following force diagrams correctly represents the forces acting between the table and Earth, and between the mug and the table?



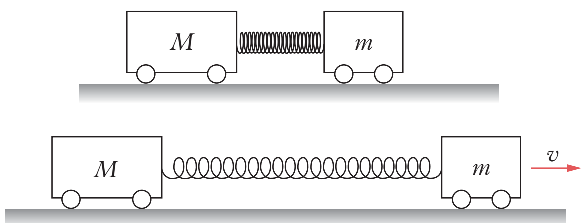
9 A cannon fires a cannonball with a momentum of 5,000 kg m s^{-1} to the right.



The momentum of the cannon after it fires the ball is

A 5,000 kg m s^{-1} to the right.
B 5,000 kg m s^{-1} to the left.
C zero.
D 2,500 kg m s^{-1} to the right.

10 Two carts of different mass m and M are connected by a spring. They are pushed together so that the spring is compressed.



After the carts are released, the cart of mass m moves with velocity v. The change in the momentum of mass M is

A mv. **B** $-mv$. **C** Mv. **D** $-Mv$.

11 An 80 kg diver jumps off a moving boat. The boat has a mass of 400 kg and moves at a constant velocity of 2 m s^{-1}. If the diver jumps with a velocity of 3 m s^{-1} in the opposite direction to the initial velocity of the boat, the velocity of the boat after the jump is

A 2 m s^{-1}. **B** 3 m s^{-1}.
C 4 m s^{-1}. **D** 6 m s^{-1}.

12 A 46 g golf ball at rest is hit with a golf club, which imparts a force of 8,000 N for a time of 0.0005 s. What is the final speed of the golf ball?

A 4 m s^{-1} **B** 87 m s^{-1}
C 184 m s^{-1} **D** 368 m s^{-1}

13 Which statement best describes the relationship between force, mass and acceleration?

A As mass doubles, acceleration also doubles when force applied is constant.
B As mass halves, force doubles when acceleration is also doubled.
C As force doubles, mass and acceleration each double proportionally.
D As mass halves, acceleration will double when force applied is constant.

14 Which statement describes why you feel a forwards jolt when a bus travelling at a constant velocity suddenly brakes?

A The force a body experiences is proportional to the acceleration of the body.
B An object will maintain its state of motion or rest unless acted upon by an external unbalanced force.
C Forces always occur in opposite and equal pairs.
D An object will accelerate in the direction in which the net external force is acting.

15 Stationary skateboarder A with a mass of 50 kg pushes stationary skateboarder B with a mass of 75 kg. After the push, skateboarder B moves with a velocity of 2 m s^{-1} to the right. The velocity of skateboarder A is

A 3 m s^{-1} to the left. **B** 2 m s^{-1} to the left.
C 1 m s^{-1} to the right. **D** 3 m s^{-1} to the right.

Review questions 10.11B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

16 **Explain** why you fall forwards when a moving bus comes to a halt, but you move backwards when it takes off again. (3 marks)

17 Suppose an object is travelling at constant velocity. **Explain** whether this means no forces are acting on it. (3 marks)

18 **Calculate** the resultant force when the following forces act on the same object.

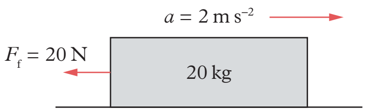
a 24 N north, 18 N south, 19 N north (1 mark)
b 6.5 N down, 9.2 N up and 7.4 N up (1 mark)

19 In a cathode ray tube, an electron starts from rest in the filament and experiences an unbalanced force of 8.0 femtonewtons over a distance of 20 mm. The prefix "femto" means 10^{-15}.

a **Calculate** the electron's acceleration. (2 marks)

b **Calculate** the electron's speed at the end of the 20 mm (starting from rest). (3 marks)

20 **Sketch** a free-body diagram showing the forces acting on the block shown and calculate their values. (4 marks)



21 **Explain** how the law of conservation of momentum applies to an inflated party balloon that is let go and whizzes around the room. (3 marks)

22 **Calculate** the momentum of a

a cricket ball of mass 160 g moving at 12.5 m s^{-1} east (2 marks)

b billiard ball of mass 200 g moving at 8.5 m s^{-1} N35°E (2 marks)

c 100 kg footballer moving with a velocity of 8 m s^{-1} north. (2 marks)

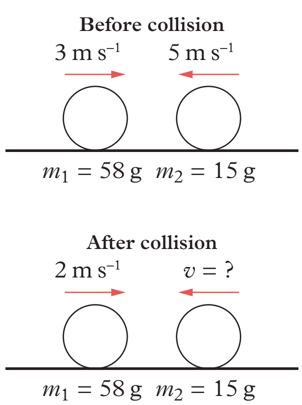
23 An alpha particle of mass 7×10^{-27} kg is accelerated from 5×10^{3} m s^{-1} to 2×10^{4} m s^{-1}. **Calculate** the change in momentum. (2 marks)

24 **Explain** how the conservation of momentum applies to a tennis ball bouncing up off the floor. (2 marks)

25 **Explain** whether impulse can ever be zero. (2 marks)

26 A skydiving company advertises that a person will experience 60 seconds of free fall if they jump from a height of 4,900 m. **Explain** what is meant by 'free fall' and how this links to terminal velocity. (3 marks)

27 A 58 g tennis ball collides with a 15 g bouncy ball and they rebound away from each other as shown.



Calculate the velocity of the bouncy ball after the collision. (3 marks)

Analytical processes

28 **Determine** what force is necessary to uniformly accelerate

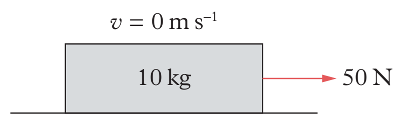
a a 6.4 kg mass at 2.4 m s^{-2} east (2 marks)

b a 0.16 kg mass from rest to 2 m s^{-1} in 3 s (4 marks)

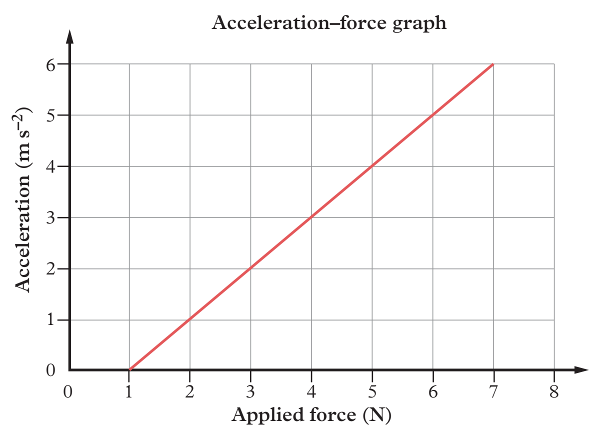
c an object weighing 25 N at 9.8 m s^{-2}. (4 marks)

29 A wooden box of bolts has a mass of 250 kg and requires a horizontal force of 2,100 N to slide it along a horizontal wooden surface at a constant speed. If the box was to be kept moving constantly at twice this speed, **determine** what force would be needed to maintain this constant speed. (3 marks)

30 A horizontal force of 50 N is applied to a 10 kg box resting on a horizontal surface. The box is not moving. **Determine** the force of friction. (1 mark)



31 An acceleration–force graph is produced for an experiment with a loaded cart pulled by rubber bands.



a **Explain** what the intercept of the graph with the force axis measures. (2 marks)

b **Determine** what acceleration an applied force of 2.5 N would produce. (1 mark)

c **Determine** what net force would produce an acceleration of 2.0 m s^{-2} and what applied force this is equal to. (2 marks)

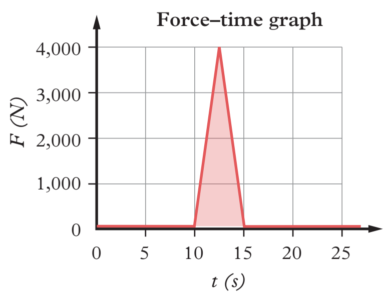
d **Calculate** the mass of the loaded cart. (2 marks)

32 A bicycle and rider have a combined mass of 65 kg. When travelling at 5.0 m s^{-1} on a level road, the cyclist ceases to pedal and comes to rest in 255 m. **Determine** what frictional forces must have been acting on the cyclist. (4 marks)

33 A rubber ball of mass 0.7 kg is dropped and strikes the floor with an initial velocity of 5 m s^{-1}. It bounces back with a final velocity of 3 m s^{-1}. **Determine** the change in the momentum of the rubber ball caused by the floor. (2 marks)

34 A car of mass 2,200 kg accelerates from rest at 3 m s^{-2} for 10 s. **Determine** the impulse imparted to the car. (4 marks)

35 A ball of mass 180 g is struck by a bat moving in the opposite direction. The force acting on the ball is as shown in the graph.



If the ball was initially moving at 10.1 m s^{-1} south, **determine** the

a impulse (2 marks)

b final velocity of the ball. (3 marks)

36 An object of mass 5.0 kg moving with a velocity of 10 m s^{-1} strikes another of mass 3 kg at rest. The two masses continue in motion together. **Determine** their common velocity. (3 marks)

37 An archer fires an arrow of mass 96 g with a velocity of 120 m s^{-1} at a target of mass 1,500 g hanging by a long piece of string from a tall tree. If the arrow becomes embedded in the target, **determine** the velocity with which the target moves. (3 marks)

38 Two masses of 4 kg and 3 kg respectively are travelling east along a frictionless surface with respective speeds of 12 m s^{-1} and 5 m s^{-1}. If the 3 kg mass continues to move east with a speed of 9 m s^{-1} after the collision, **determine** the speed of the 4 kg mass. (3 marks)

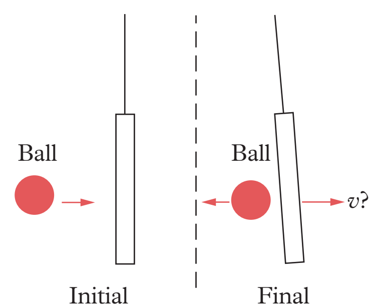
39 A basketball has a velocity of 15 m s^{-1} downwards just before it hits the ground and rebounds with a velocity of 15 m s^{-1} upwards. **Describe** the changes in the momentum of the basketball as it bounces off the ground. (3 marks)

40 A railway truck of mass 4,000 kg moving with a speed of 3.6 m s^{-1} collides with a stationary truck of mass 2,400 kg. The two trucks become coupled together. **Determine** their common speed. (3 marks)

41 A bullet of mass 20 g travelling horizontally to the right at 700 m s^{-1} strikes a stationary wooden block of mass 2.0 kg resting on a smooth horizontal surface. The bullet goes through the block and comes out on the other side at 200 m s^{-1}. **Determine** the speed of the block after the bullet has come out the other side. (3 marks)

42 A ball of mass 50 g moving horizontally at a speed of 40 cm s^{-1} strikes a suspended plate of mass 1,000 g and rebounds from it with a speed of 25 cm s^{-1} as shown.

Determine the speed with which the plate begins to move. (3 marks)



Knowledge utilisation

43 During an experiment, a frictionless trolley was subjected to a single force whose magnitude could be varied. Assume the friction was negligible. The acceleration from various forces was measured and the results tabled as shown in the table.

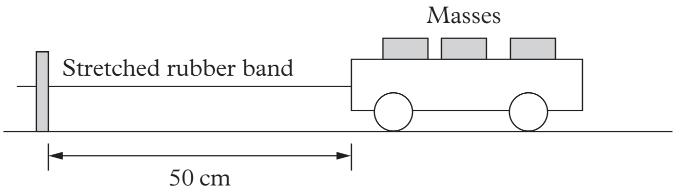
Force, F (N)	5	10	15	20	25
Acceleration, a (m s^{-2})	1.5	3.0	4.5	6.0	7.5

a **Sketch** a graph of the results. (3 marks)

b **Determine** the mass of the trolley. (2 marks)

c **Propose** how the shape of the graph would have changed if friction was present. (2 marks)

44 An experiment was conducted to find the relationship between force, mass and acceleration. A stretched rubber band was used to provide constant force on a trolley to which different masses were added. The trolley was released from rest and timed to move 50.0 cm.



A student made the following notes: "When the trolley had no masses on it, it took 2.00 s. With 300 g added it took 2.40 s, and with 900 g added it took 2.60 s. I measured the mass of the trolley by itself and it was 700 g."

a **Construct** a data table to show the results. (3 marks)

b **Calculate** the acceleration for each trial and add them to the table. (3 marks)

c **Sketch** a graph of total mass (horizontal axis) versus acceleration. (2 marks)

d **Identify** the relationship suggested by this graph. (2 marks)

e Use Newton's second law of motion to **calculate** the force provided by the rubber band in each case and add this information to the table. (3 marks)

Data drill

Collision of trolleys

A student conducted an experiment that investigated conservation of momentum. They used two trolleys of varying weights and collided them, recording the initial and final velocity using a camera and video analysis software. They then manually calculated the initial momentum, the final momentum and the change in momentum. The collision did not couple the trolleys together. Table 1 shows the results.

TABLE 1 Results of trolley collision experiment

Trial	m_A (kg)	m_B (kg)	u_A (m s^{-1})	u_B (m s^{-1})	v_A (m s^{-1})	v_B (m s^{-1})	p_i (kg m s^{-1})	p_f (kg m s^{-1})	Δp (kg m s^{-1})
1	0.600	0.600	0.650	0	0.000	0.585	0.390	0.351	–0.039
2	0.600	1.600	1.165	0	–0.267	0.468	0.699	0.589	–0.110
3	1.600	0.600	0.863	0	–0.167	2.472			
4	0.600	2.100	0.745	0	–0.346	0.285	0.447	0.391	–0.056

Apply understanding

1 **Determine** the change in momentum for trial 3. (3 marks)

2 **Explain** the meaning of the negative sign for change in momentum. (1 mark)

Analyse data

3 **Identify** which object was moving before the collision, A or B. (1 mark)

4 **Identify** which of the four trials had the greatest change in momentum as a percentage of the initial momentum. (2 marks)

Interpret evidence

5 **Draw a conclusion** about whether momentum was conserved in these collisions. **Justify** your answer. (2 marks)

6 **Propose** an improvement to the experiment that is logically derived from the analysis of evidence. **Justify** your answer. (2 marks)

Module 10 checklist: Classical mechanics

Quizlet: Revise key terms online to test your understanding

MODULE 11 Energy

Introduction

In simple terms, energy is the capacity to do work. The word “energy” stems from the Greek “en” meaning “in”, and “ergos” meaning “work”. But this doesn’t give us a good understanding of the idea of energy and work. Physicists only developed a better understanding of these concepts 100 years after Newton’s death. Today, these ideas are considered fundamental to the processes of nature.

If you leave a torch turned on, its batteries will run out of energy. But has the energy gone forever? Where did it go? These are fundamental questions when it comes to energy. As you learnt earlier, energy is not lost – it just gets transferred from one place to another or transformed into another form of energy. This is called the law of conservation of energy. The universe seems to have a finite amount of energy that is continually being rearranged.

Prior knowledge

Prior knowledge quiz Check your understanding of energy before you start.

Subject matter

Science understanding

- → Describe the concepts of mechanical work, kinetic energy and gravitational potential energy.
- → Solve problems involving work done by a force using $W = \Delta E$ and $W = Fs$.
- → Solve problems involving kinetic energy and gravitational potential energy using $E_k = \frac{1}{2}mv^2$ and $\Delta E_p = mg\Delta h$.
- → Analyse the area under a force–displacement graph using geometric methods.
- → Interpret energy–time graphs.
- → Discuss the differences between elastic and inelastic collisions.
- → Solve problems involving elastic collisions and inelastic collisions (including explosions) using $\Sigma\frac{1}{2}mv^2_{\text{before}} = \Sigma\frac{1}{2}mv^2_{\text{after}}$.

Science as a human endeavour

- → Appreciate the significant contributions of scientists such as Isaac Newton and Émilie du Châtelet.

Source: *Physics 2025 v1.1 General Senior Syllabus* © State of Queensland (QCAA) 2024

Lesson 11.1
Forms of energy

Key ideas

→ Mechanical energy includes kinetic energy and gravitational potential energy.
→ Work is done on an object when energy is transferred to it. Work is done by an object when energy is transferred from it.
→ The law of conservation of energy states that the total energy of an isolated system remains constant over time.

Learning intentions and success criteria

potential energy
the energy stored in an object due to its position relative to another object to which it is attracted by the force of gravity (symbol: E_p; SI unit: joule; unit symbol: J)

mechanical energy
the sum of potential energy and kinetic energy of an object; the energy associated with its motion and position

What are the different forms of energy?

Have you ever competed in a "stair challenge" in which you are timed to run up the stairs of a high-rise building? The Q1 on the Gold Coast is one of the highest buildings in the world and the record for the 77 floors is just under 7 minutes. Lots of people get half-way up and say "I ran out of energy". Actually, they didn't. They just couldn't convert their internal energy into gravitational and kinetic energy fast enough.

There are many forms of energy and most of things you do in daily life involve energy conversions. However, words such as light, thermal, electromagnetic, sound, mechanical, nuclear and chemical energy do not provide a systematic way of organising the different forms of energy. Physicists decided it was most useful to classify energy using the following two categories:

- Kinetic energy. Bodies that are moving have kinetic energy (E_k); examples include, a flying bird, a shooting star, a moving locomotive, a rollercoaster in motion, a speeding bullet, the wind, running water, and a person running up the stairs.
- **Potential energy**. Two common forms are gravitational potential energy and elastic potential energy. Bodies that can do work because of their position have gravitational potential energy (E_p); for example, water in a reservoir, weights lifted off the ground, a rollercoaster at the top of a rise, and you at the top of a high-rise building.

Kinetic and gravitational potential energy are both forms of **mechanical energy**. In classical mechanics, chemical, thermal, nuclear and electromagnetic energy are forms of internal energy (U). They are to do with the random vibrations or motions of electrons, protons, neutrons, atoms and molecules within an object. We will deal only with mechanical energy in this module. In Unit 4 you will see that light can be modelled as electromagnetic waves or as particles (photons) with kinetic energy.

FIGURE 1 At the Wivenhoe Dam power station in Queensland, water is pumped from the lower reservoir (Wivenhoe Dam) up to the higher reservoir (Splityard Creek Dam), thus increasing the gravitational potential of the water.

What happens to energy during work?

Energy can be used to do work, such as when the water in a reservoir is used to turn a turbine (Figure 1). The reverse is also true: when work is done, it can increase the energy of an object. For example, we can do work to pump water from a lake to a high reservoir. The stored water has higher energy because of its height and can later be used to drive electric generators and produce electrical energy. When energy is transferred to an object, we say work is done on the object. When energy is transferred away from an object, we say that work is done by the object. Consider a falling weight attached to a string over a pulley that pulls a block along a horizontal surface. We can make statements about the work done from two different perspectives. This is summarised in Table 1.

TABLE 1 Work and the transfer of energy

Work	Energy	Example	Direction of transfer
Done on the object (the block)	Transferred to an object	Work is done by the falling weight on the block of wood (the object).	$E_p \rightarrow E_k$
Done by the object (the falling weight)	Transferred from an object	Work is done by the falling weight (the object) on the block of wood.	$E_k \rightarrow E_p$

The law of conservation of energy

Recall that the law of conservation of energy states that energy cannot be created or destroyed, just transformed from one form to another. Another way of saying this is that the total energy of an isolated system remains constant (conserved) over time.

When work is done on an object, whether it is pumping water up to a dam, pulling a block of wood across a desk or firing protons at a nucleus, the object gains energy. We can say energy is transferred to the object in the process of work being done. An equation called the work–energy equation states that the change in energy (E) of the object is equal to the work done (W), in line with the law of conservation of energy. This energy may be kinetic, potential or both combined.

$$W = \Delta E$$

Check your learning 11.1

Check your learning 11.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Identify** the types of energy that are considered to be mechanical energy. (1 mark)

2 **Describe** two differences between kinetic energy and gravitational potential energy. (2 marks)

Analytical processes

3 A compressed spring has a lot of energy and can do work. **Deduce** whether its energy is in the form of potential or kinetic energy, and **explain** your answer. (2 marks)

4 **Categorise** the energy in a stretched rubber band as kinetic or potential energy and whether it is macroscopic or microscopic. (2 marks)

Knowledge utilisation

5 When bodies interact, the energy of one may increase at the expense of another. However, we can't intercept the energy and bottle it. **Evaluate** the claim: "Energy is not a thing; it is a property of a system." (2 marks)

6 A book rests on a shelf and is measured to have 5 J of gravitational potential energy. If 10 J of work is done to raise it to a higher shelf, **determine** the change in energy of the book. (1 mark)

7 In an experiment similar to Joule's paddlewheel "mechanical equivalent of heat experiment" (Unit 1), a 10 kg mass was allowed to fall through a vertical height of 10 m. Assume an idealised case in which the change in gravitational potential energy was transformed into heat in 0.400 kg of water. **Determine** the change in temperature of the water. The specific heat capacity of water is 4,180 kJ kg^{-1} K^{-1}. (3 marks)

Lesson 11.2
Work done by a force

Key ideas

→ Work has been done when the applied force causes a change in displacement in the direction of the force.

→ The area under a force–displacement graph is equal to the work done.

Learning intentions and success criteria

Study tip

For this unit, the direction of motion and the applied force will be in a line. In Unit 3, we will look at forces at an angle to the direction of motion.

Study tip

Work has the unit newton metre (N m) as it is the product of *F* × *s*. Alternatively, it can have the unit joule (J), as it is equivalent to energy according to the law of conservation of energy.

What is work?

When you are told you should work harder at school, what exactly is meant by "work? Are you doing any work if you are reading a book? We need to define work to use it in physics. Work is a mathematical concept linked to energy. Just talking about simple energy transfers and transformations is one way of presenting this difficult idea, but it makes energy seem like an invisible, intangible substance that can flow from place to place (which it is not).

For example, Figure 1 shows a person trying to push a desk across the floor. The desk with mass m is moved from rest a distance s across the floor by an applied force F_A against the frictional force F_f. It acquires a velocity v. Remember, when we need to specify force or displacement or many other quantities as vectors, they are shown with an arrow above the symbol ($\vec{F}$, $\vec{s}$). Scalar quantity symbols do not have the arrow above them. Energy and work are not vector quantities as they have no direction that could be specified.

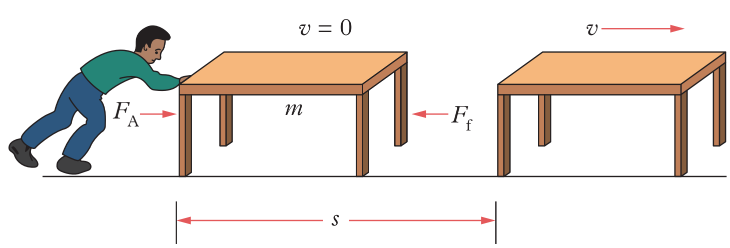


FIGURE 1 Doing work to shift a desk means applying a force over a certain distance.

If you tried to push a desk across the floor and it didn't move, you might say you did a lot of work on the desk. But to a physicist, if the desk didn't move, then no work was done. If you did move the desk, then the work done would depend on how hard you pushed and the distance the desk moved. Work is therefore defined as the product of the force and the distance moved in the direction of an applied force. It is a scalar quantity, and yet it is the product of a vector and a scalar quantity. For instance, if you applied a horizontal force F and shifted the desk through a horizontal distance s:

$$\text{Work} = \text{force} \times \text{displacement}$$

$$W = Fs$$

where force F is in newtons (N) and displacement s is in metres (m).

When work involves the transfer of energy to or from an object by the action of a force over a distance, we distinguish it from other forms of work by calling it **mechanical work**.

mechanical work the transfer of energy to or from an object by the action of a force over a distance; $W = \Delta E$ and $W = Fs$

Worked example 11.2A

Calculating work done on an object

Calculate the work done when a constant horizontal net force of 3 N is used to push a book a distance of 2 m along a desk. Express your answer to the nearest whole number. (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the work formula. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Note that the direction of the force and the motion of the object are in a line (both horizontal along the desk).	$W = Fs$ $F = 3\text{N}$, $s = 2\text{m}$, $W = ?$
Step 3: Substitute the known values into the formula and find the unknown.	$W = 3 \times 2$ (1 mark) $= 6$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures (or in this case, rounded to the nearest whole number). Work is scalar so no direction needs to be specified.	6 J or 6 N m (1 mark)

Your turn

It takes a constant vertical force of 30 N for a person to raise a 3.0 kg container of milk 80 cm from the floor to the benchtop. **Calculate** the work done on the object by the person doing the lifting. Express your answer to the nearest whole number. (2 marks)

Doing no work in class

According to our definition of work, you are not doing any work on a book (in a scientific sense) if you hold it in your outstretched arm for a long period of time. Although you get tired, no work is done on the book. You will feel tired because your muscles are using energy and burning up fuel. As the muscle fibres relax and contract to keep your arm still, you are using energy – but this energy is not being transferred to the book. Because of this, no work has been done on the book. However, there is a change in the internal energy of your body as internal motions and reactions occur.

The same is true for a helicopter hovering in a stationary position above the ground. These motions never result in any measurable displacement and therefore never do any work (in the way "work" is used in the physics sense).

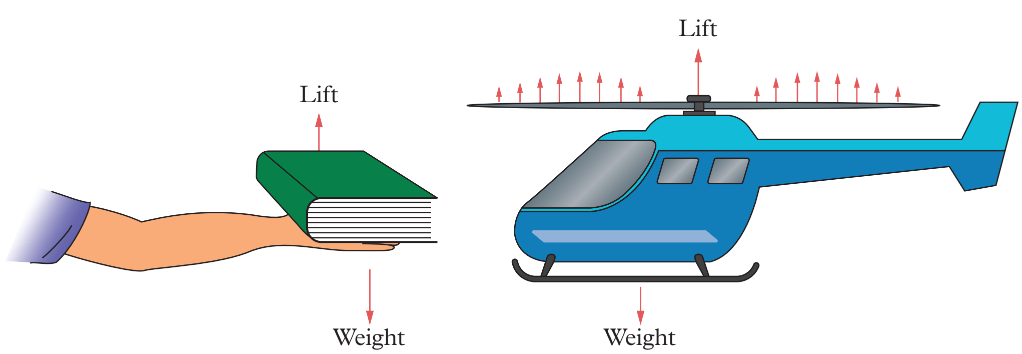


FIGURE 2 No work is done on the book or the helicopter if there is no movement.

How are force–displacement graphs used to calculate work done?

force–displacement graph
a graph depicting the force acting on an object as a function of displacement, with the area under the curve representing work done

constant force
one that has the same magnitude and direction for the duration of an interaction; also known as uniform force

variable force
one that has a change in magnitude or direction during an interaction; also known as non-uniform force

We can use **force–displacement graphs** to depict the work done when a force moves an object. The simplest case is for a **constant force**; for example, pushing a desk across a room. A more complicated case is when the force is **variable** – such as pushing the desk over tiles, and then carpet and so on. We will be considering both uniform (constant) and non-uniform (variable) forces.

Constant and variable forces

In Figure 3A, a constant horizontal force of 150 N is applied to an object that shifts the object a horizontal distance of 100 m. The work done is simply the product of $F \times s$, which is the shaded area under the line of a force–displacement graph (15,000 J). If the force does not remain constant but varies (Figure 3B), the work is still determined by calculating the shaded area (13,000 J).

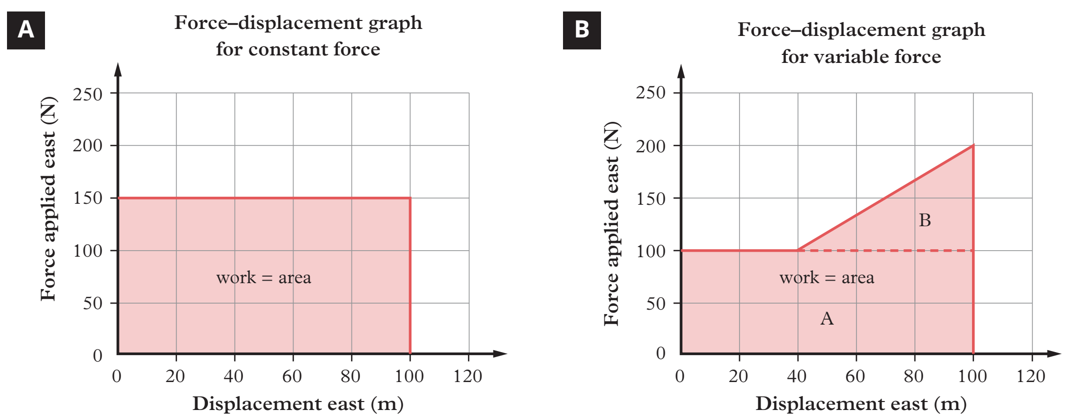


FIGURE 3 Work done is the area under a force–displacement graph. (A) Area = 150 × 100 = 15,000 J; (B) Area = area of rectangle A + area of triangle B = $(100 \times 100) + \frac{1}{2}(60 \times 100)$ = 13,000 J.

Constant force calculations

When calculating the work done in lifting an object vertically, the force applied will be equal to the object's weight ($F_W = mg$). This is assuming it is lifted at a constant speed. If the speed is varied, then Newton's second law formula ($F = ma$) would be applied. We can use these formulas to calculate the work done in lifting an object, such as lifting a 15 kg schoolbag at constant speed from the floor to a port rack 1.2 m off the ground.

$$F_W = mg$$
$$= 15 \times 9.8$$
$$= 147\,\text{N (weight of the bag)}$$
$$W = Fs$$
$$= 147 \times 1.2$$
$$= 176\,\text{J}$$

A Mars bar provides you with 1,235,000 J of energy. This is equivalent to lifting your bag 7,000 times to burn off the energy. Luckily your body uses up a lot more energy in lifting a bag than just the amount needed to overcome gravitational forces.

FIGURE 4 A Mars bar gives you 1,235,000 J of energy.

Variable forces – linear

The graph in Figure 3B shows a constant force at the start and a varying force later. But there are circumstances in which the force varies in a linear manner, such as with stretching a spring or bending a plastic ruler. Figure 5 shows the change in length of a spring (in mm, horizontal axis) as masses are added to it (in N, vertical axis).

The work done is the product of force times displacement, which is the area under the line. In this case, the work done is calculated as:

$$
\begin{aligned}
W &= Fs \\
&= \frac{1}{2} \times b \times h \\
&= \frac{1}{2} \times \left(\frac{100}{1000} \times 20\right) \\
&= 1.0\,\text{J}
\end{aligned}
$$

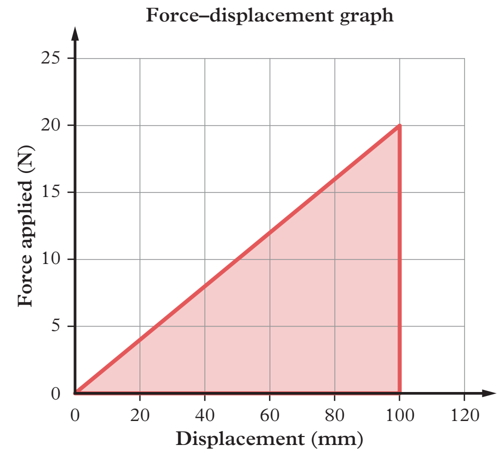


FIGURE 5 The change in length of a spring (horizontal axis) as masses are added to it shows a linear relationship. Work done is the area under the graph line (the shaded triangle).

Variable forces – non-linear

Some forces get stronger or weaker as an object moves, but in a non-linear way. For example, with the opposite poles of two magnets facing each other, the force is very strong. To pull them further apart, work has to be done but the force required becomes smaller as the distance increases. Work still has to be done as this happens. We can see this in Figure 6. The force is measured and plotted as a solid line in the graph.

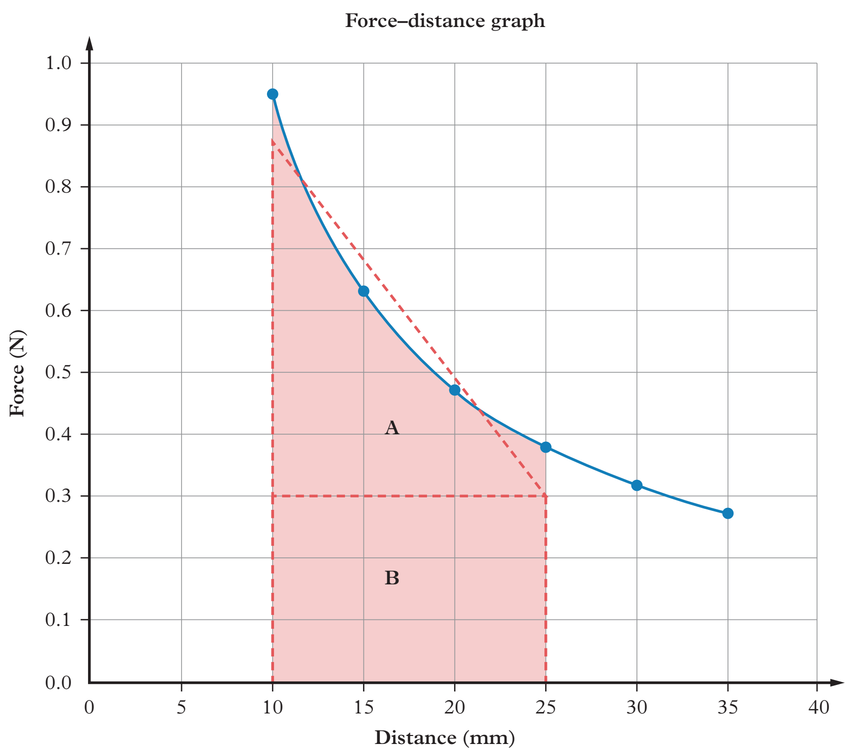


FIGURE 6 The change in distance between the two magnets as work is done to separate them shows a non-linear relationship.

The work done to separate the magnets from 10 mm to 25 mm is the area under the curve (shading), but it is difficult to work this out. We draw a line through the curve to make a triangle (A). With care, we can make the shaded area above the line equal to the unshaded area under the line. The area under the curve is now just the area of triangle A. The distance is in millimetres, so we need to multiply it by 10^{-3} to convert it to metres:

$$\begin{aligned}
\text{Area (A)} &= \frac{1}{2} \times b \times h \\
&= \frac{1}{2} \times ((25 - 10)\times 10^{-3})\times(0.88 - 0.30) \\
&= 4.35 \times 10^{-3}\,\text{N m} \\
\text{Area (B)} &= l \times w \\
&= ((25 - 10)\times 10^{-3})\times 0.30 \\
&= 4.5 \times 10^{-3}\,\text{N m}
\end{aligned}$$

$$\text{Total area (A + B)} = 8.85 \times 10^{-3}\,\text{N m (J)}$$

Check your learning 11.2

Check your learning 11.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Recall** the relationship between the area under a force–displacement graph and the work done. (2 marks)

2 **Explain** if you are doing any work when you push hard against a rock, but it doesn't move. (2 marks)

3 **Calculate** the amount of work done in the following.

a Pulling a bag of dog food 3.5 m along a table by applying a 25 N horizontal force (2 marks)

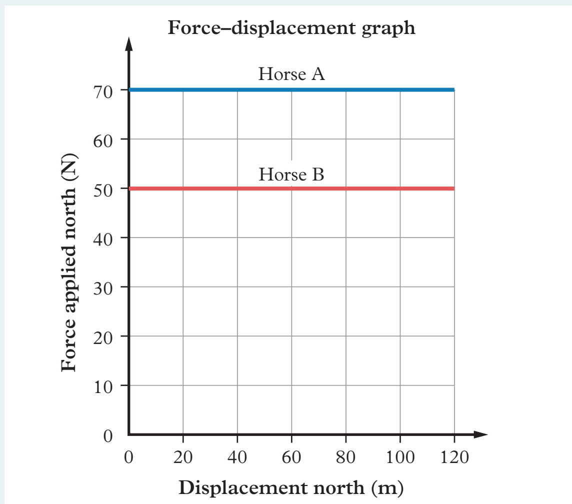
b Lifting a 20 kg bag of dog food at constant speed on to a table 85 cm off the ground (2 marks)

c Pumping 200 kg of water at a constant flow rate into a tank 25 m high (2 marks)

4 A team of two horses is pulling a loaded cart in a northerly direction along a horizontal road at constant speed. The force–displacement graph is shown in the figure.

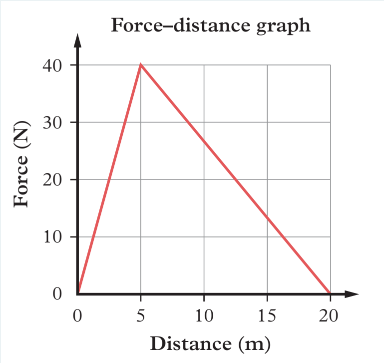
a **Calculate** the work done by each horse. (4 marks)

b **Calculate** the total work done on the cart. (2 marks)

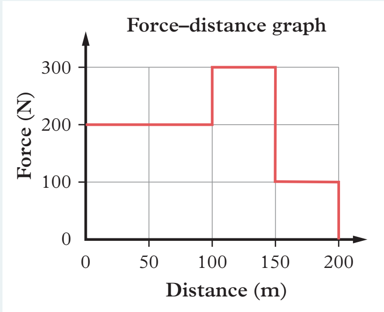


5 The figures show different forces acting on different objects. **Calculate** the work done in each case. (6 marks)

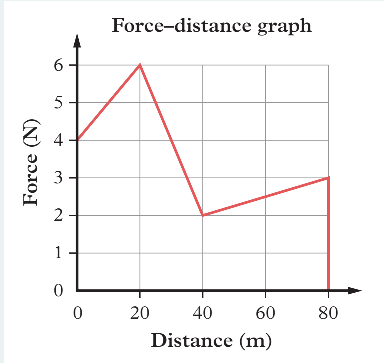
a



b



c



6 **Construct** a force–displacement graph of a schoolbag of mass 10 kg being raised vertically at constant speed to a height of 2.0 m. (4 marks)

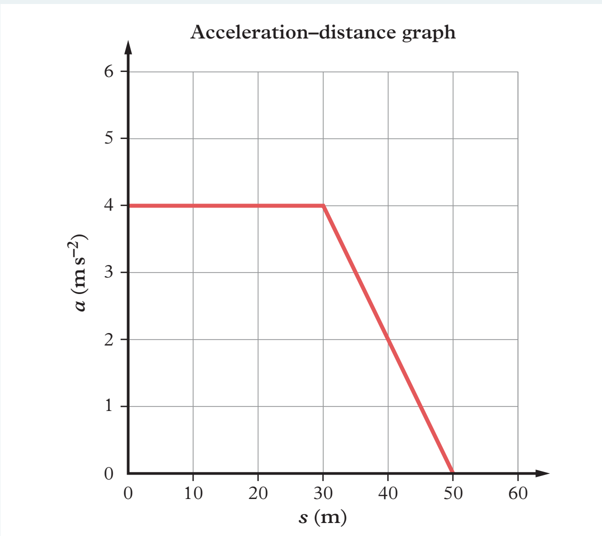
Analytical processes

7 A 200 kg piano is lowered by a rope out of a third-floor window.

a **Calculate** how much work is done in lowering the piano a distance of 9 m to the ground at constant speed. (2 marks)

b **Decide** whether work was done on or by the piano in this process. (1 mark)

8 The graph in the figure shows how an object has accelerated as it travels along a road a distance *s*. Note that it is an acceleration–distance graph.



a If the mass of the object is 4 kg, **determine** how much work is done by the 50 m mark. (2 marks)

b **Construct** a force–distance graph of the motion. (2 marks)

9 **Evaluate** the following claim: "The area under a force–displacement graph is a measure of the change of energy of an object." (2 marks)

Lesson 11.3
Solving problems: E_k and E_p

Key ideas

→ The kinetic and gravitational potential energy involved in work can be calculated.
→ Mechanical energy is conserved through transformations between E_k and E_p.
→ Energy–time graphs show how E_k and E_p change over time.

Learning intentions and success criteria

How is kinetic energy calculated?

A bowling ball at rest on the floor has no energy of motion, but when it rolls along the floor it is said to have energy of motion. Recall that energy due to the motion of an object is called kinetic energy (Greek "kinema" = "motion").

To determine an equation for kinetic energy, we will bring together concepts you have already learnt. Imagine a hockey puck moving on a frictionless surface such as an air table.

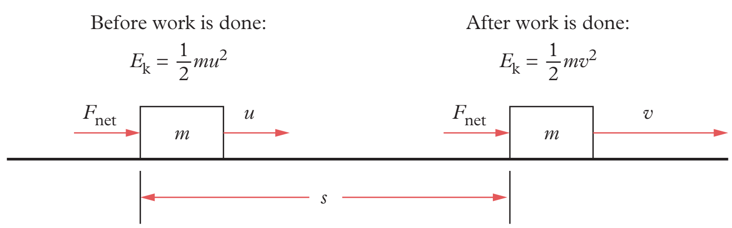


FIGURE 1 Motion of a hockey puck on an air table

If an unbalanced force F_{net} is applied to the puck for a period of time t, the force produces accelerated motion and the object goes from an initial velocity u to a final velocity v. This can be expressed as:

$$v^2 = u^2 + 2as \text{ or } a = \frac{v^2 - u^2}{2s}$$

By letting $F = ma$, the work done in accelerating the puck is given by:

$$\begin{aligned} W &= Fs \\ &= mas \\ &= m \times \left(\frac{v^2 - u^2}{2s}\right) \times s \\ &= \frac{1}{2}mv^2 - \frac{1}{2}mu^2 \end{aligned}$$

This represents the change kinetic energy, or work done:

$$W = \Delta E_k$$

Hence, if an object starts from rest, its final kinetic energy is given by:

$$E_k = \frac{1}{2}mv^2$$

Study tip

Kinetic energy (E_k) is a scalar quantity and does not require direction.

Worked example 11.3A

Calculating kinetic energy of a sliding object

Calculate the kinetic energy of a 6.0 kg bowling ball sliding at 5.0 m s^{-1} (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the kinetic energy formula. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$E_k = \frac{1}{2}mv^2$ $m = 6.0\,\text{kg}$, $v = 5.0\,\text{m s}^{-1}$
Step 3: Substitute the known values into the formula and find the unknown.	$E_k = \frac{1}{2} \times 6.0 \times 5.0^2$ (1 mark) $= 75$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures. Kinetic energy is scalar so no direction needs to be specified.	75 J (2 s.f.) (1 mark)

Your turn

Calculate the kinetic energy of an oxygen molecule of mass 5.31×10^{-26} kg moving at $440\,\text{m s}^{-1}$ (2 s.f.). (2 marks)

Worked example 11.3B

Calculating work done on a sliding object

A 520 kg rocket sled at rest is propelled along the ice by an engine developing a constant thrust of 12,000 N over a distance of 40 m. Assuming all of the work goes into motion, **calculate** (2 s.f.)

a the work done by the engine on the sled after 40 m (2 marks)

b the velocity of the sled after 40 m (using the kinetic energy formula). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the work and kinetic energy formulas. Each question is worth 2 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$W = Fs$ $F = 12{,}000\,\text{N}$, $s = 40\,\text{m}$ $E_k = \frac{1}{2}mv^2$ $m = 520\,\text{kg}$, $v = ?$
Step 3: Substitute the known values into the formulas and find the unknowns.	**a** $W = 12{,}000 \times 40$ (1 mark) $= 480{,}000$ **b** Work is converted to kinetic energy, so $W = E_k$. $480{,}000 = \frac{1}{2} \times 520 \times v^2$ (1 mark) $v^2 = 1846.15$ $v = \sqrt{1846.15}$ $= 42.967$
Step 4: Finalise your answers and make sure you have included the correct units and significant figures.	**a** 480,000 J (2 s.f.) (1 mark) **b** $43\,\text{m s}^{-1}$ (2 s.f.) (1 mark)

Your turn

A 600 g cart is placed on a horizontal bench and connected to a hanging mass by a string over a pulley. The hanging mass provides a constant 2.5 N force. **Calculate** (2 s.f.)

a the work done on the cart as it moves 50 cm across the bench (2 marks)

b the velocity of the cart across the bench after it has moved 50 cm from rest. (2 marks)

How is gravitational potential energy calculated?

When you lift something off the floor and put it on a desk, you are applying a force to the object and displacing it – you are doing work on it. If work is done on it, it gains energy. Actually, it is not so much the object that gains energy – it is the system made up of the object and Earth that gains energy.

Vertical movement

When you lift something, you increase the separation distance between that object and Earth. It is this system, this gravitational field, that gains energy. We look at gravitational fields in more detail in Unit 3. For now, it is simpler to say the object itself has gained energy.

FIGURE 2 Lifting weights off the ground increases their gravitational potential energy. The weightlifter applies a force to separate Earth and the weights from each other.

If the object is lifted at constant speed, it is not gaining kinetic energy but instead gaining energy of position. This is called gravitational potential energy (Latin "potens" = "capable", meaning capable of doing work). Gravitational potential energy has the symbol E_p.

The work done is a measure of the change in gravitational potential energy. If the object is lifted at constant speed, then the force applied equals its weight ($F_W = mg$). The vertical distance through which it is moved is its change in height, Δh. The change in gravitational potential energy is the force applied multiplied by the vertical distance through which the object is moved.

$$\Delta E_p = mg\Delta h$$

For example, a 5 kg ball raised 20 m (Δh) will have work done on it or a change in its potential energy equivalent to $5 \times 9.8 \times 20 = 980$ J. We assume that an object on the ground has zero E_p, so the E_p of the ball is 980 J. We say that objects raised off the ground gain E_p and objects falling lose E_p.

Worked example 11.3C

Calculating work done by lifting an object

Calculate the change in gravitational potential energy of a 20 kg box of groceries lifted 0.75 m to a benchtop (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the gravitational potential energy formula. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$\Delta E_p = mg\Delta h$ $m = 20\,\text{kg}$, $g = 9.8\,\text{m s}^{-2}$, $\Delta h = 0.75\,\text{m}$
Step 3: Substitute the known values into the formulas and find the unknowns.	$\Delta E_p = 20 \times 9.8 \times 0.75$ (1 mark) $= 147$
Step 4: Finalise your answers and make sure you have included the correct units and significant figures. Note that it is actually the system of the box and Earth that has increased its gravitational potential energy by 150 J.	150 J (2 s.f.) (1 mark)

Your turn

A 70 kg person takes a lift from the ground floor to the 90th floor of a high-rise building 150 m up. **Calculate** the change in gravitational potential energy (2 s.f.). (2 marks)

Sideways movement

In many cases, the object is not lifted vertically, but is dragged, rolled or taken up an inclined ramp. The distance travelled is greater than if it was lifted vertically, but it is just the vertical distance that affects the gravitational potential energy. The sideways component of any motion has no effect. Here is a simple example. More complex situations will be discussed in Unit 3.

Worked example 11.3D

Calculating work done by rolling an object up an incline

A 35 kg barrel of cider is rolled up a 5.0 m long plank, which makes a 30° angle to the ground. **Calculate** the gravitational potential energy of the barrel at the top (Figure 3) (2 s.f.). (3 marks)

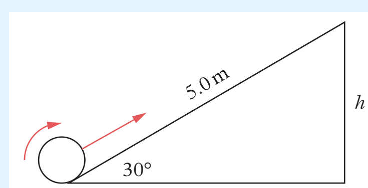


FIGURE 3 Barrel being rolled up an incline

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply SOHCAHTOA and the gravitational potential energy formula. The question is worth 3 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.

Think	Do
Step 2: Select the correct formulas and gather any data required. We have the hypotenuse (H) and want to find the opposite (O), so the relevant ratio is SOH.	$\Delta E_p = mg\Delta h$ $m = 35\,kg, g = 9.8\,m\,s^{-2}, \Delta h = ?$ $\sin\theta = \frac{O}{H}$ $O = h, H = 5.0\,m, \theta = 30°$
Step 3: Substitute the known values into the formula to find the height of the incline.	$\sin 30° = \frac{h}{5.0}$ $h = 5.0 \sin 30°$ $= 2.5\,m$ (1 mark)
Step 4: Substitute the known values into the formula to find the change in gravitational potential energy.	$\Delta E_p = 35 \times 9.8 \times 2.5$ $= 857.5$ (1 mark)
Step 5: Finalise your answers and make sure you have included the correct units and significant figures. It doesn't matter how the barrel was raised the 2.5 m; it could have been rolled up an incline 10 m long and the gravitational potential energy would be the same.	860 J (2 s.f.) (1 mark)

Your turn

A car of mass 1,550 kg is driven 250 m up a road that has a slope of 20° to the horizontal. **Calculate** the change in gravitational potential energy (2 s.f.). (3 marks)

The formula $\Delta E_p = mg\Delta h$ will only be true over distances for which the gravitational force remains constant. When you get too far away from Earth's surface, this relationship does not hold, as g becomes less than $9.8\,m\,s^{-2}$.

How is mechanical energy conserved?

Mechanical energy was earlier described as including both kinetic and potential energy. The total mechanical energy of a system can be defined as the sum of kinetic and potential energy. Within an isolated system, this mechanical energy is conserved.

When a ball is thrown upwards in the air, it starts with a high kinetic energy. At the top of its travel, when it stops moving, it has none. The kinetic energy has been transformed into the gravitational potential energy of the ball (and Earth).

Figure 4 depicts how the E_p and E_k change as the ball falls in the second part of its motion. This is also shown more specifically in Table 1. Note that the total energy is constant at 1,000 J.

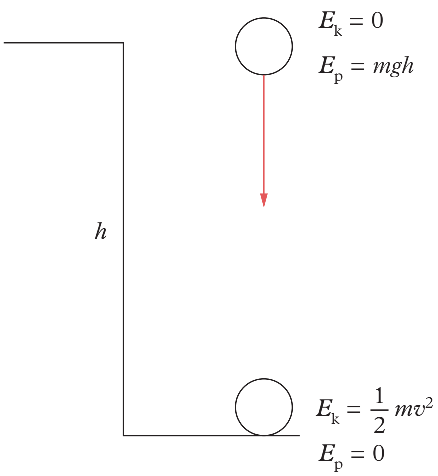


FIGURE 4 A ball loses E_p and gains E_k as it falls.

TABLE 1 E_p and E_k of the ball at different heights as it falls

Height (m)	Potential energy, mgh (J)	Kinetic energy, $\frac{1}{2}mv^2$ (J)	Total $E_p + E_k$ (J)	Velocity ($m\,s^{-1}$)
100	1,000	0	1,000	0
75	750	250	1,000	22
50	500	500	1,000	32
25	250	750	1,000	39
0	0	1,000	1,000	45

Real-world physics

The work of Émilie du Châtelet

In the 1780s, Newton argued that conservation of momentum was the crucial principle of mechanics. He was formulating principles about the conservation of energy as well, but the concept of energy was not well defined at that stage. One person who cleared this up was Émilie du Châtelet, a French scientist.

At the age of 32, while translating Newton's works into French, du Châtelet saw some ambiguities in Newton's ideas about energy and its relationship to momentum. Newton had said that energy was proportional to mv, but du Châtelet carried out experiments by dropping lead balls into clay and found that energy was actually proportional to mv^2. In this way, she corrected and completed many of Newton's hypotheses and, in doing so, helped France play an important role in Europe's scientific revolution.

FIGURE 5 Émilie du Châtelet

Apply your understanding

1 **Identify** the current name for the physical quantity Newton equated to $m \times v$. (1 mark)
2 A 500 g ball of lead strikes a lump of clay at a speed of 6 m s^{-1}. **Compare** the magnitudes of the quantities given by $m \times v$ and $m \times v^2$. (3 marks)
3 **Propose** what quantity du Châtelet would have measured in terms of the clay. **Explain** how this measurement would be related to energy. (3 marks)

Skill drill

Investigating the relationship between E_p and other parameters

Science inquiry skills: Processing and analysing data (Lesson 1.7)

Students set up an experiment to investigate conservation of mechanical energy. They used a ramp, raised at one end to a height, h, and allowed a frictionless cart to move freely down it. They measured the velocity of the cart at the bottom. Their results are shown in Table 1.

TABLE 1 Data obtained from the conservation experiment

Height, h (cm)	Gravitational potential energy, E_p (J × 10^{-3})	Velocity (m s^{-1})	Velocity squared (m s^{-1})^2
5.0	147	0.99	0.98
10.0	294	1.40	1.96
15.0	441	1.71	2.94
20.0		1.98	3.92

Practise your skills

1 **Calculate** the gravitational potential energy for a height of 20.0 cm. (2 marks)
2 **Determine** whether there is a directly proportional relationship between the height and either velocity or velocity squared. Justify your answer. (2 marks)
3 **Draw a conclusion** about the transformation of gravitational potential energy to kinetic energy. (1 mark)

How can you observe energy transformations in real life?

In the modern day, we can find many examples of physics principles at amusement parks. There we can witness Newton's laws in action, the conservation of energy and momentum, centripetal forces, rotation and weightlessness.

The rollercoaster is a good example of conservation of mechanical energy (Figure 6). At the start, electrical energy is used to drag the carriages to a great height (point A), giving them high gravitational potential energy. At the point of release, the kinetic energy is almost zero. As the carriages roll down the tracks, E_p is converted to E_k and the carriages accelerate (point B). At the next hill, some of the E_k is converted back to E_p, but some is transferred to thermal energy (by friction) and sound, and the carriages rise (point D), but never as high as at the start.

If there was no energy transfer to the structure, then mechanical energy would be conserved and the sum of E_p and E_k would be constant. However, there is always some loss and the rollercoaster designers take this into account. The energy losses become quite small on rainy days because frictional losses are reduced and unsafe high speeds result. In these cases, the rollercoaster has to be closed.

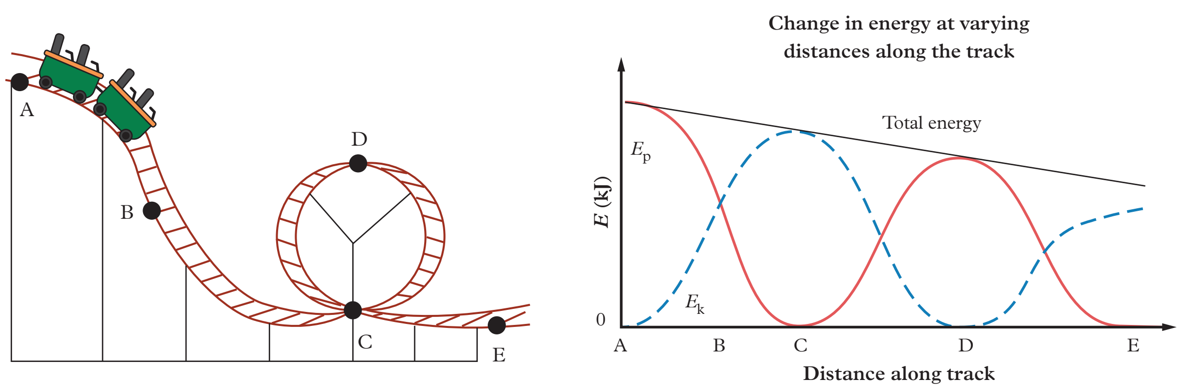


FIGURE 6 Rollercoaster ride and an energy graph

Challenge

Rollercoasters

A rollercoaster is made up of carriages A, B and C. The three carriages enter a loop (Figure 7). Out of positions 1, 2, 3 and 4 on the loop, **determine** which position will give the greatest speed for

a carriage A (1 mark)
b carriage B (1 mark)
c carriage C. (1 mark)

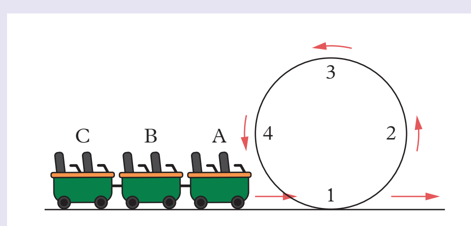


FIGURE 7 Four stages around a rollercoaster loop

What can be interpreted from energy–time graphs?

energy–time graph
a graph that depicts the kinetic and potential energy of an object as a function of time

It is useful to be able to interpret meaning from **energy–time graphs**. The graphs in Figures 8 and 9 show the changes in kinetic and gravitational potential energy with time as a ball is dropped from 1 m high onto a hard, flat, horizontal surface.

Figure 8 is a theoretical energy–time graph for a ball of 100 g (0.100 kg) raised to 1.0 m high. It has 0.98 J of E_p and zero E_k. As it falls, the E_p drops and the E_k rises by an equal amount. After striking the surface where both E_k and E_p are both zero (the energy has been transferred to **elastic potential energy**), the ball rebounds and the E_k starts off with a high value, then decreases. The graph in Figure 9 is a real-world version of the theoretical graph. Note that the energy input is about 0.97 J (at the start of the dashed line) and the energy output is 0.77 J (at the end of the dashed line). The efficiency, $\eta = \frac{0.77}{0.97} \times 100 = 80\%$.

elastic potential energy
potential energy stored as a result of deformation of an elastic object, such as the stretching of a spring

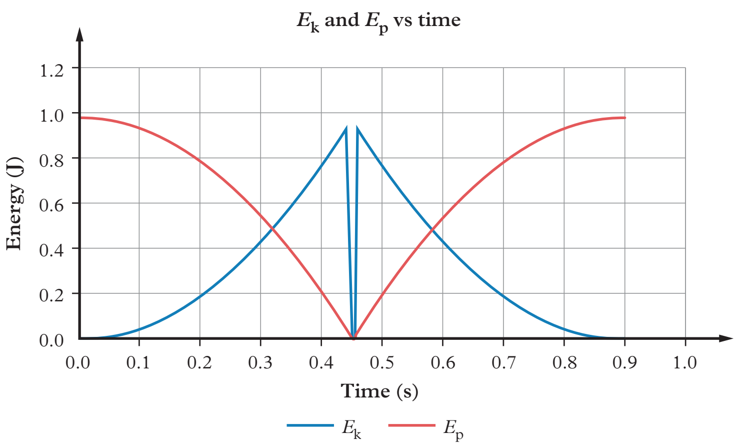


FIGURE 8 Theoretical energy–time graph for a ball bouncing off a horizontal surface

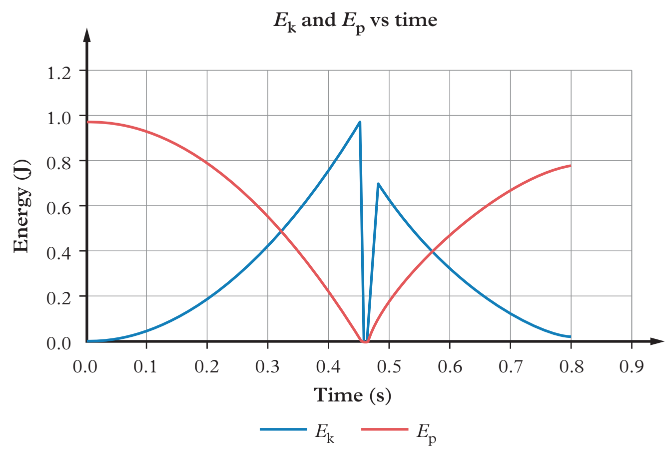


FIGURE 9 "Real-world" energy–time graph for a ball bouncing off a horizontal surface. Note that some energy is "lost" (probably transformed to heat) in the collision.

Check your learning 11.3

Check your learning 11.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 A ball dropped from a height of 100 cm bounces back to a height of 60 cm.

a **Calculate** the percentage of its original E_p that the ball has at the 60 cm mark. (2 marks)

b **Identify** the efficiency of the process. (1 mark)

c **Explain** where the rest of the energy has gone. (1 mark)

2 Use conservation of mechanical energy principles to **calculate** the impact speed of a 65 kg diver who dives off a platform 8.5 m above the water. (2 marks)

3 Champion weightlifter Leonid Taranenko lifted 266 kg in a clean and jerk to a height of 2.4 m.

a **Calculate** how much work he did in the lift. (2 marks)

b **Calculate** the impact speed when he dropped the weight onto the mat from this height. (2 marks)

Analytical processes

4 When a ball bounces off the floor, it has no E_p or E_k at its moment of impact. **Propose** where the energy has gone. (1 mark)

5 A stroller can be pushed up a ramp 10 m long to get to a height of 1.0 m. **Consider** why doing the same work to push a stroller up a 5 m ramp to get to the same height of 1.0 m is so much harder. (2 marks)

6 Consider the theoretical energy–time graph in Figure 8.

a **Determine** for how long the ball was stationary. (1 mark)

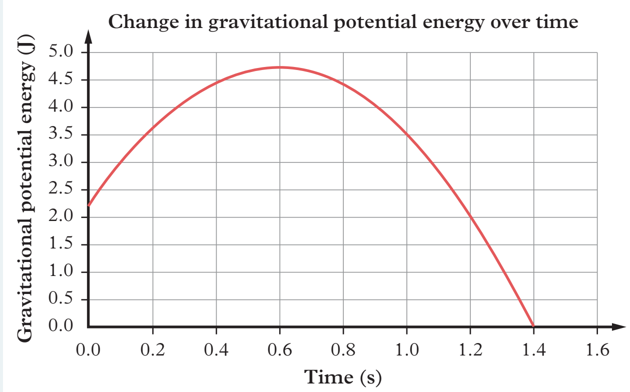
b **Calculate** how much energy was converted to elastic potential energy during the stationary period. (2 marks)

Now consider the ball in Figure 9.

c **Describe** its motion and explain how you interpreted this from the graph. (7 marks)

d **Explain** how momentum is conserved in this collision. (Hint: think of the motion of the hard horizontal surface.) (2 marks)

7 An object of mass 150 g is thrown vertically from shoulder height, then allowed to bounce elastically on the ground. A graph of the object's gravitational potential energy over time is shown.



Determine the velocity of the object on impact with the ground (2 s.f.). (3 marks)

Lesson 11.4
Energy changes and collisions

Key ideas

→ In elastic collisions, kinetic energy and momentum are conserved.

→ In inelastic collisions, momentum is conserved but kinetic energy is not.

How does kinetic energy change in elastic collisions?

Learning intentions and success criteria

Remember from Module 10 that collisions can be either elastic or inelastic. For elastic collisions, the total amount of kinetic energy before the collision is the same as the total kinetic energy after the collision:

$$E_k\text{(before)} = E_k\text{(after)}$$
$$\Sigma\frac{1}{2}mv^2{}_{\text{before}} = \Sigma\frac{1}{2}mv^2{}_{\text{after}}$$

A collision between steel ball bearings is also approximately elastic. Consider the case of colliding balls in Newton's cradle (Figure 1).

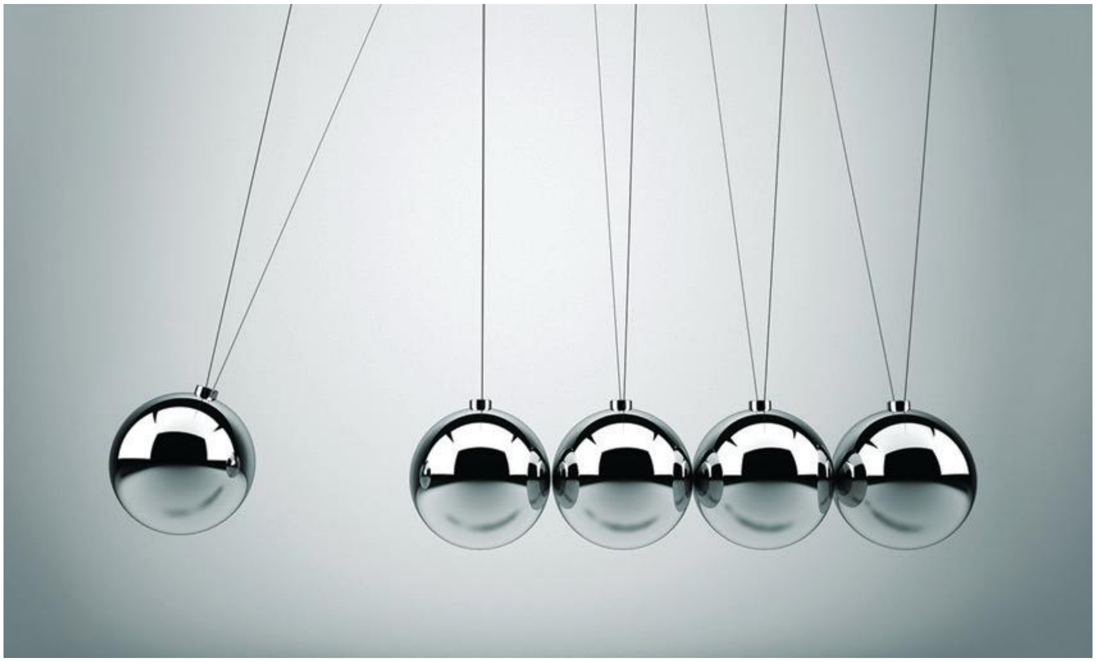


FIGURE 1 Newton's cradle

The ball on the left has kinetic energy as it approaches the stationary balls. It collides, and the energy is passed along as one ball collides with the next. At the right, the end ball rises to the same height as the first ball was released from. Because it rises to the same height, we say the collision was elastic and no energy was lost. In reality, some energy would be lost and the heights get lower and lower with time, but it is almost perfectly elastic.

Let's consider the law of conservation of mechanical energy in the collision of two steel balls, a and b (Figure 2).

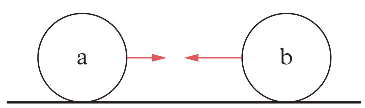


FIGURE 2 Two rigid balls colliding head-on is an elastic collision.

Assuming it is an elastic collision:

$$\Sigma\frac{1}{2}mv^2{}_{\text{before}} = \Sigma\frac{1}{2}mv^2{}_{\text{after}}$$

$$\frac{1}{2}m_a u_a^2 + \frac{1}{2}m_b u_b^2 = \frac{1}{2}m_a v_a^2 + \frac{1}{2}m_b v_b^2$$

How do you solve elastic collision problems?

Sometimes, we are given the details of a collision and need to apply this relationship – for example, to see if it is an elastic collision or not. To determine this, we need to see if kinetic energy is conserved in the collision. If it is conserved, then it is elastic. Momentum is always conserved, regardless of whether the collision is elastic or inelastic.

Conservation of energy and momentum problems

With some collision problems, you need to use conservation of momentum and conservation of kinetic energy to achieve a solution.

Worked example 11.4A

Determining whether a collision is elastic

A 3 kg steel ball moving east at 4 m s^{-1} collides with a stationary 1 kg ball. After the collision, the 3 kg mass moves east at 2 m s^{-1} and the 1 kg mass moves east at 6 m s^{-1} (Figure 3).

a **Determine** whether this collision is elastic. (3 marks)

b **Prove** that momentum is conserved. (3 marks)

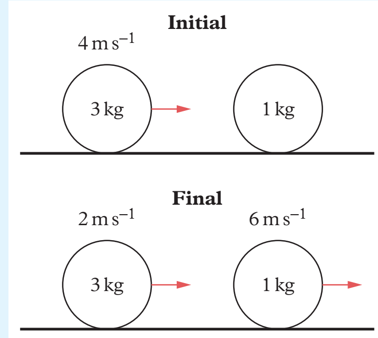


FIGURE 3 Is this collision elastic?

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Determine" means to establish after a calculation. "Prove" means to use a sequence of steps to obtain the required result in a formal way. We need to use the elastic collisions and momentum formulas. The questions are worth 3 marks each, so we must gather the correct information and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$\Sigma\frac{1}{2}mv^2{}_{\text{before}} = \Sigma\frac{1}{2}mv^2{}_{\text{after}}$ $\frac{1}{2}m_a u_a{}^2 + \frac{1}{2}m_b u_b{}^2 = \frac{1}{2}m_a v_a{}^2 + \frac{1}{2}m_b v_b{}^2$ $\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_a u_a + m_b u_b = m_a v_a + m_b v_b$ Before: $m_a = 3$ kg, $u_a = 4$ m s^{-1}, $m_b = 1$ kg, $u_b = 0$ m s^{-1} After: $m_a = 3$ kg, $v_a = 2$ m s^{-1}, $m_b = 1$ kg, $v_b = 6$ m s^{-1}
Step 3: Substitute the known values into the formula and find the kinetic energies.	**a** $E_k(\text{before}) = \left(\frac{1}{2} \times 3 \times 4^2\right) + \left(\frac{1}{2} \times 1 \times 0^2\right)$ $= 24$ J (1 mark) $E_k(\text{after}) = \left(\frac{1}{2} \times 3 \times 2^2\right) + \left(\frac{1}{2} \times 1 \times 6^2\right)$ $= 24$ J (1 mark)
Step 4: Finalise your answer by comparing the final and initial energies.	The final kinetic energy is the same as the initial; therefore, the collision is elastic. (1 mark)
Step 5: Substitute the known values into the formula and find the momenta.	**b** $p_i = (3 \times (+4)) + (1 \times 0)$ $= +12$ kg m s^{-1} (1 mark) $p_f = (3 \times (+2)) + (1 \times (+6))$ $= +12$ kg m s^{-1} (1 mark)
Step 6: Finalise your answer by comparing the final and initial momenta.	The initial and final momentum values are equal and directions are the same (+) so momentum is conserved. (1 mark)

Your turn

A collision occurs between a 3,000 kg truck moving at 20 m s^{-1} and a stationary 1,000 kg car. After the collision, the truck is moving at 10 m s^{-1} and the car at 30 m s^{-1}, both in the same direction.

a **Determine** whether the collision is elastic. (3 marks)

b **Prove** that momentum is conserved. (3 marks)

In Worked example 11.4B in which objects A and B collided head-on, the velocities of the objects swapped. This is true of linear elastic collisions between objects of equal mass. It is sometimes called the pool player's result.

Worked example 11.4B

Calculating final velocities for an elastic collision

Object A of mass 1.0 kg moving at 3.0 m s^{-1} to the right collides elastically head-on with object B of mass 1.0 kg and moving at 2 m s^{-1} to the left. **Determine** the final velocity of each object (2 s.f.). (8 marks)

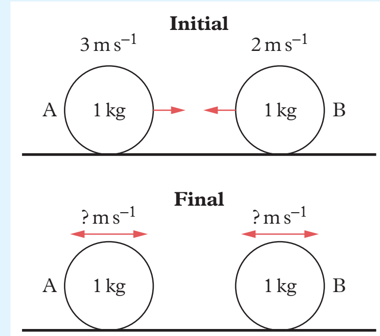


FIGURE 4 What is the final velocity of each object after the collision?

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to use the elastic collisions and momentum formulas. The question is worth 8 marks, so we must gather the correct information and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$\Sigma\frac{1}{2}mv^2{}_{\text{before}} = \Sigma\frac{1}{2}mv^2{}_{\text{after}}$ $\frac{1}{2}m_Au_A{}^2 + \frac{1}{2}m_Bu_B{}^2 = \frac{1}{2}m_Av_A{}^2 + \frac{1}{2}m_Bv_B{}^2$ $\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_Au_A + m_Bu_B = m_Av_A + m_Bv_B$ Before: $m_A = 1$ kg, $u_A = 3$ m s^{-1}, $m_B = 1$ kg, $u_B = -2$ m s^{-1} After: $m_A = 1$ kg, $v_A = ?$ m s^{-1}, $m_B = 1$ kg, $v_B = ?$ m s^{-1}
Step 3: Substitute the known values into the formula and find the momenta. Substitute and simplify so that v_A is the subject of the equation. We will call this [Equation 1].	$p_{\text{before}} = p_{\text{after}}$ $\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_Au_A + m_Bu_B = m_Av_A + m_Bv_B$ $1 \times 3 + 1 \times (-2) = 1 \times v_A + 1 \times v_B$ $3 - 2 = v_A + v_B$ $1 = v_A + v_B$ (1 mark for formula; 1 mark for rearrangement)
Step 4: Substitute the known values into the formula and find the kinetic energies.	$E_k(\text{before}) = E_k(\text{after})$ $\Sigma\frac{1}{2}mv^2{}_{\text{before}} = \Sigma\frac{1}{2}mv^2{}_{\text{after}}$ $\frac{1}{2}m_Au_A{}^2 + \frac{1}{2}m_Bu_B{}^2 = \frac{1}{2}m_Av_A{}^2 + \frac{1}{2}m_Bv_B{}^2$ $\frac{1}{2} \times 1 \times 3^2 \times \frac{1}{2} \times 1 \times (-2)^2 = \frac{1}{2} \times 1 \times v_A{}^2 \times \frac{1}{2} 1 \times v_B{}^2$ (1 mark for substitution)
Step 5: Multiply both sides by 2 to cancel out the $\frac{1}{2}$. We will call this [Equation 2].	$9 + 4 = v_A{}^2 + v_B{}^2$ $13 = v_A{}^2 + v_B{}^2$ $v_A{}^2 = 13 - v_B{}^2$ (1 mark for rearrangement)
Step 6: Substitute in the relationship for v_A found earlier [Equation 1] into [Equation 2]. Solve both equations simultaneously by eliminating the term v_A.	$v_A{}^2 = (1 - v_B)^2 = 1 - 2v_B + v_B{}^2$ and $v_A{}^2 = 13 - v_B{}^2$ $1 - 2v_B + v_B{}^2 = 13 - v_B{}^2$ (1 mark) $2v_B{}^2 - 2v_B - 12 = 0$ (1 mark)

Think	Do
Step 7: Using the quadratic formula or factorising into $(v_B - 3)(v_B + 2) = 0$ gives two solutions for v_B.	$v_B = 3\,\text{m s}^{-1}$ and $-2\,\text{m s}^{-1}$
Step 8: The second of these solutions is the case where the velocities are the same as the initial. In other words, no collision took place – they were on parallel but separate tracks. The first solution is where a collision took place.	$3\,\text{m s}^{-1}$ (positive value means to the right)
Step 9: Substitute this into the equation $v_A = 1 - v_B$ and solve for v_A. Check that units are correct and to correct number of significant figures, and that direction is shown. Summarise to make the answer clear.	$v_A = 1 - v_B$ $v_A = 1 - 3 = -2\,\text{m s}^{-1}$ $v_A = -2.0\,\text{m s}^{-1}$ (to the left) (1 mark) $v_B = +\,3.0\,\text{m s}^{-1}$ (to the right) (1 mark)

Your turn

A 3 kg steel ball moving at $8\,\text{m s}^{-1}$ collides elastically with a stationary steel ball of mass 2 kg. After the collision, both balls move in the same direction. **Determine** the velocity of each ball (2 s.f.). (8 marks)

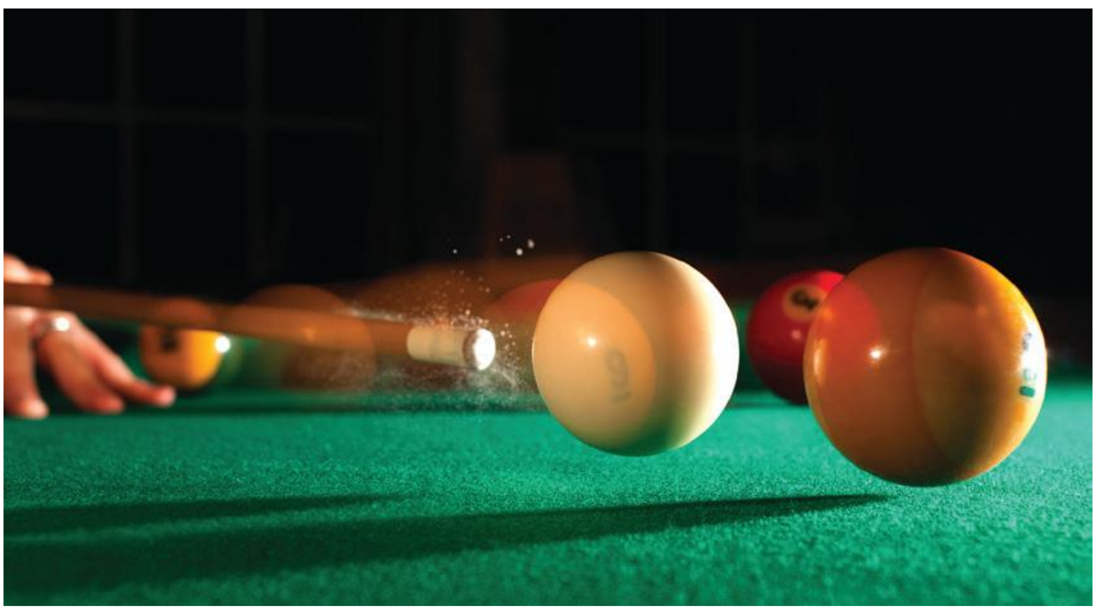


FIGURE 5 When a billiard ball has an elastic collision with another ball of equal size, they swap velocities. This is sometimes called the pool player's result.

What do the energy–time graphs for elastic collisions look like?

The energy–time graph is also useful here. Here are the results of classroom experiments using collision carts as shown in Figure 6.

In this case the two carts are of equal mass. Figure 7 shows the changes in E_k when a moving cart collides elastically with a stationary one of the same mass. Notice that the line remains at 1.0 J for the first 2.5 seconds as the moving cart approaches the stationary one.

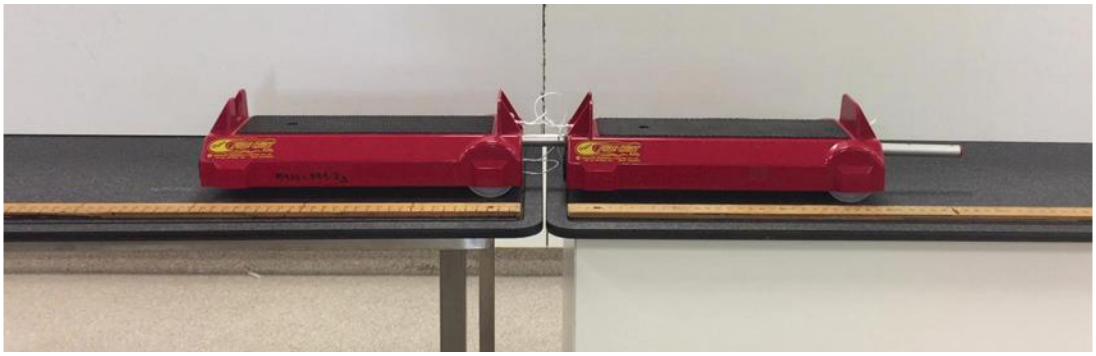


FIGURE 6 Collision carts are used for conservation experiments in linear motion.

When they meet (at 2.6 s), the spring between them is compressed and the E_k reduces as the cart slows. At maximum compression of the spring, the E_k is zero as it has all been transferred to the spring as elastic potential energy. Then, the second cart takes off as the spring expands and transfers its potential energy to the trolley and its E_k increases. The E_k of the first cart remains at zero as it stays in place. Because it is an elastic collision, the total kinetic energy at the end of the collision is the same as at the beginning.

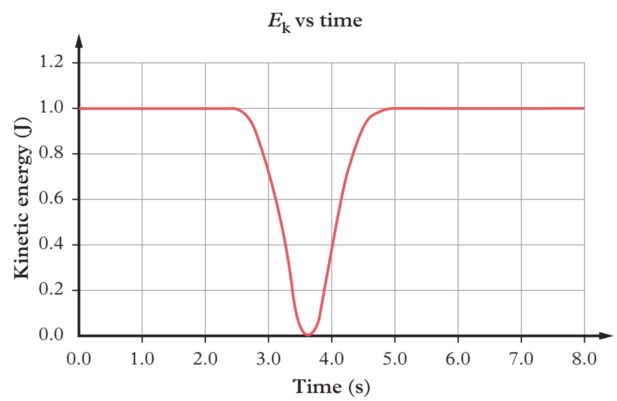


FIGURE 7 Energy–time graph for an elastic collision

How does kinetic energy change in inelastic collisions?

In an inelastic collision, kinetic energy is said to be "lost". However, it is not really lost; the missing kinetic energy is transformed to other types of energy such as thermal energy and sound. Most collisions in the real world are inelastic collisions.

An inelastic collision is one in which the total kinetic energy is not conserved:

$$\Sigma\frac{1}{2}mv^2{}_{\text{before}} \neq \Sigma\frac{1}{2}mv^2{}_{\text{after}}$$

Remember, momentum is always conserved.

Figure 8 shows the same collision as above but this time the carts become coupled and experience an inelastic collision. This is a real-life graph generated by video analysis of a collision between laboratory collision carts. Notice that the line remains at 1.0 J for the first 2 seconds, similar to the graph for an elastic collision. The carts then collide and the energy is shared through the combined mass over a period of about 1 second as one slows down and the other speeds up to match. They move off coupled with about 0.4 J of kinetic energy. The theoretical final velocity based on the conservation of momentum is 0.5 m s^{-1} but some energy is inevitably lost – in this case, about 0.6 J, mostly as heat. The temperature rise of about 0.001°C for this system is unnoticeable.

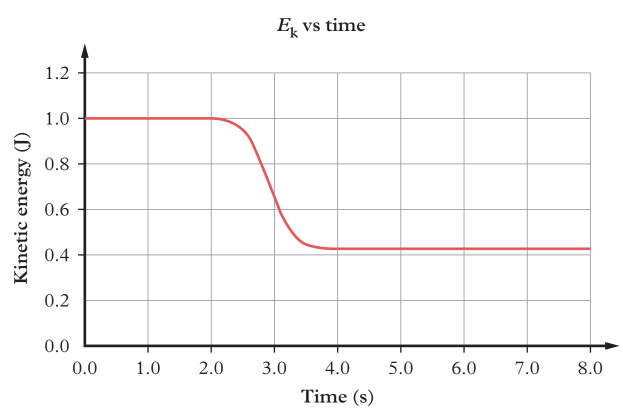


FIGURE 8 Energy–time graph for an inelastic collision

FIGURE 9 A tennis ball undergoes an inelastic collision with a tennis racquet. Different spots on the racquet provide different levels of bounce (kinetic energy changes).

How do you solve inelastic collision problems?

When different balls are dropped onto a concrete floor, they bounce to different heights. A perfectly elastic collision would see the ball returning to its original height. A superball is about 90% elastic, a golf ball about 60% and a lump of putty is perfectly inelastic.

Although there is always some bounce associated with a collision, in this lesson, for the sake of simplicity, we will deal with collisions that are almost totally inelastic.

Worked example 11.4C

Determining whether a collision is inelastic

A body of mass 6 kg travelling east at 4 m s^{-1} strikes a 2 kg mass at rest. After the collision they remain coupled and the mass moves east at 3 m s^{-1}.

a **Determine** whether the collision is inelastic. (3 marks)

b **Prove** that momentum is conserved. (3 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocations to determine what the questions are asking you to do.	"Determine" means to establish after a calculation. "Prove" means to use a sequence of steps to obtain the required result in a formal way. We need to use the inelastic collisions and momentum formulas. The questions are worth 3 marks each, so we must gather the correct information and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	**a** $\Sigma\frac{1}{2}mv^2{}_{\text{before}} \neq \Sigma\frac{1}{2}mv^2{}_{\text{after}}$ $\frac{1}{2}m_A u_A{}^2 + \frac{1}{2}m_B u_B{}^2 \neq \frac{1}{2}(m_A + m_B)v^2$ $\Sigma mv_{\text{before}} = \Sigma mv_{\text{after}}$ $m_A u_A + m_B u_B = (m_A + m_B)v$ Before: $m_A = 6\,\text{kg}$, $u_A = 4\,\text{m s}^{-1}$, $m_B = 2\,\text{kg}$, $u_B = 0\,\text{m s}^{-1}$ After: $m_A = 6\,\text{kg}$, $m_B = 4\,\text{kg}$, $v = 3\,\text{m s}^{-1}$
Step 3: Substitute the known values into the formula and find the kinetic energies.	$E_k(\text{before}) = \left(\frac{1}{2} \times 6 \times 4^2\right) + \left(\frac{1}{2} \times 2 \times 0^2\right)$ $= 48\,\text{J}$ (1 mark) $E_k(\text{after}) = \frac{1}{2} \times (6 + 2) \times 3^2$ $= 36\,\text{J}$ (1 mark)
Step 4: Finalise your answer by comparing the final and initial energies.	The final kinetic energy is smaller than the initial; therefore, the collision is inelastic. (1 mark)
Step 5: Substitute the known values into the formula and find the momenta.	**b** $p_i = (6 \times (+4)) + (2 \times 0)$ $= +24\,\text{kg m s}^{-1}$ (1 mark) $p_f = (6 + 2) \times (+3)$ $= +24\,\text{kg m s}^{-1}$ (1 mark)
Step 6: Finalise your answer by comparing the final and initial momenta.	The initial and final momentum values are equal and directions are the same (+) so momentum is conserved. (1 mark)

Your turn

A toy freight train car of mass 50 kg collides with a stationary empty car of mass 15 kg while moving at 5.0 m s^{-1}. At the collision the cars couple together.

a **Calculate** the velocity of the coupled pair using conservation of momentum principles (2 s.f.). (2 marks)

b **Determine** whether the collision is elastic or inelastic. Show your working. (3 marks)

Explosions

An explosion is an example of an inelastic collision. As such, momentum is conserved and kinetic energy changes.

Consider an example in which a 10 kg bomb at rest explodes into two fragments: a 4 kg piece (m_1) that moves west at 15 m s^{-1} (v_1), and a 6 kg piece (m_2) that moves east at an unknown speed (v_2). We can calculate this speed using conservation of momentum:

$$\Sigma p_{\text{before}} = \Sigma p_{\text{after}}$$
$$(m_1 + m_2)u = m_1 v_1 + m_2 v_2$$
$$10 \times 0 = 4 \times 15 + 6 \times v_2$$
$$v_2 = -10\,\text{m s}^{-1} \quad \text{(the negative sign means east)}$$

However, consider the kinetic energy before and after the explosion:

Before: $\Sigma \frac{1}{2} m v^2_{\text{before}} = \frac{1}{2}(m_1 + m_2)u^2 = \frac{1}{2}(10) \times 0 = 0\,\text{J}$

After: $\Sigma \frac{1}{2} m v^2_{\text{after}} = \frac{1}{2} m_1 {v_1}^2 + \frac{1}{2} m_2 {v_2}^2 = \frac{1}{2} \times 4 \times 15^2 + \frac{1}{2} \times 6 \times (-10)^2 = 450 + 300 = 750\,\text{J}$

$0\,\text{J} \neq 750\,\text{J}$, so kinetic energy is not conserved.

Only the conservation of momentum law can be applied to the motion of objects before and after an explosion. Kinetic energy is never conserved in an explosion.

Study tip

Kinetic energy is not conserved in an explosion, so you cannot use conservation of kinetic energy principles to solve explosion questions. However, momentum is conserved in all interactions (explosions and collisions), so you should use conservation of momentum principles.

Check your learning 11.4

Check your learning 11.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** the difference between an elastic and an inelastic collision in terms of conservation of momentum and of kinetic energy. (2 marks)

2 **Recall** whether colliding steel balls are considered to have elastic or inelastic collisions. (1 mark)

3 **Explain** the statement "collisions between gas molecules are elastic collisions". **Describe** the consequences if these collisions were inelastic. (2 marks)

4 Two objects of equal mass collide head-on in an elastic collision.

  a **Describe** what happens to their velocities. (1 mark)

  b **Explain** why this situation is sometimes called the pool player's result. (2 marks)

5 Consider a pool ball (A) that strikes another pool ball (B) initially at rest. Ball A comes to a halt and ball B moves away.

  a **Construct** a graph showing total kinetic energy on the vertical axis and time of the horizontal axis for Ball A undergoing an elastic collision with Ball B. (2 marks)

  b **Construct** a similar graph for a collision that is inelastic. (2 marks)

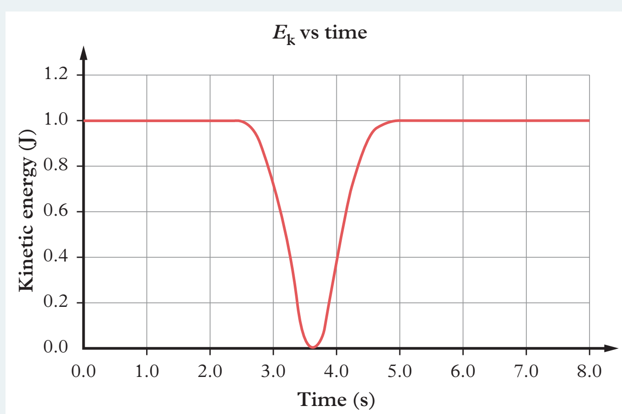
6 A brick of mass 2.5 kg is lifted to a height of 2.5 m above the ground by a bricklayer. **Calculate** the

  a E_p acquired by the brick (2 marks)

  b work done by the bricklayer in lifting it. (1 mark)

Analytical processes

7 The graph shows the changes in E_k when a moving cart collides elastically with a stationary one of the same mass.



a **Sketch** the graph in your workbook and add the elastic potential energy as time goes by. (3 marks)

b **Construct** a line showing the total energy ($E_k + E_p$) of the cart with time. (1 mark)

c **Determine** how this graph would change if the mass of the incoming cart was twice that of the stationary cart. (2 marks)

d **Sketch** and **explain** how the graph would change if, instead of the collision being elastic, the original two carts became coupled. (2 marks)

8 **Consider** a collision between two balls, each of mass 300 g. Ball 2 is at rest and ball 1 is moving towards it with a speed of $2\,m\,s^{-1}$. After the balls collide elastically, ball 1 comes to an immediate stop and ball 2 moves off.

a **Calculate** the speed of ball 2. (2 marks)

b Show that momentum is conserved. (3 marks)

9 Imagine a game of marbles. A child rolls a blue marble of mass 100 g along the ground at a speed of $3\,m\,s^{-1}$, to the right towards the red marble (mass 50 g) initially at rest. After the marbles collide elastically, the blue marble is moving at $1\,m\,s^{-1}$ to the right. **Determine** the final speed of the red marble. (4 marks)

10 Ball A of mass 0.20 kg, moving with a speed of $1.75\,m\,s^{-1}$, approaches a stationary ball B of mass 0.15 kg, and collides head-on. After the collision, ball B travels at $2.0\,m\,s^{-1}$ in the same direction.

a **Calculate** the speed of ball A after the collision. (3 marks)

b **Determine** if the collision was elastic. (5 marks)

MODULE 11

Lesson 11.5
Review: Energy

Summary

11.1
- Mechanical energy includes kinetic energy and gravitational potential energy.
- Work is done on an object when energy is transferred to it. Work is done by an object when energy is transferred from it.
- The law of conservation of energy states that the total energy of an isolated system remains constant over time.

11.2
- Work has been done when the applied force causes a change in displacement in the direction of the force.
- The area under a force–displacement graph is equal to the work done.

11.3
- The kinetic and gravitational potential energy involved in work can be calculated.
- Mechanical energy is conserved through transformations between E_k and E_p.
- Energy–time graphs show how E_k and E_p change over time.

11.4
- In elastic collisions, kinetic energy and momentum are conserved.
- In inelastic collisions, momentum is conserved but kinetic energy is not.

Key formulas

Work	$W = \Delta E$ and $W = Fs$
Kinetic energy	$E_k = \frac{1}{2}mv^2$
Change in gravitational potential energy	$\Delta E_p = mg\Delta h$
Elastic collision	$\Sigma\frac{1}{2}mv^2_{before} = \Sigma\frac{1}{2}mv^2_{after}$
Inelastic collision	$\Sigma\frac{1}{2}mv^2_{before} \neq \Sigma\frac{1}{2}mv^2_{after}$

Review questions 11.5A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 A lift (elevator) is operated by an electric motor. It moves between the 10th floor and the 2nd floor at constant speed. One main energy transformation during this journey is

A gravitational potential energy → kinetic energy.

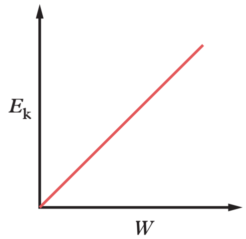
B electrical energy → kinetic energy.

C kinetic energy → thermal energy.

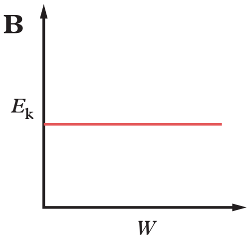
D electrical energy → thermal energy.

2 A constant force acts on a mass that is initially at rest. Which of the following graphs best shows how the kinetic energy, E_k, of the mass changes with the work, W, done on the mass? Friction is negligible.

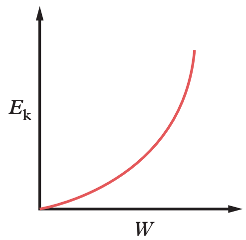
A



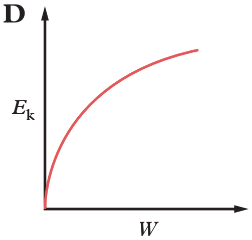
B



C



D



3 Work is described as the

A product of mass and velocity.

B product of force and distance moved in the direction of the force.

C rate of change of force.

D rate of change of work.

4 A pump can extract 100 kg of water per minute from a well 10 m deep. What is the rate at which work is done by the pump in $J\,s^{-1}$?

A $\frac{t}{mgh}$

B $\frac{mgh}{t}$

C $\frac{mg}{t}$

D $mgh \times t$

5 A truck driver slams on the brakes of a truck moving with a velocity v. As a result of his action, the truck stops after travelling a distance d. If the driver had been travelling with twice the velocity, the stopping distance compared to the distance in the first trial would be

A two times greater.

B four times greater.

C half as much.

D one-quarter as much.

6 What is the force required to do 80 J of work to move an object 10 m across a level surface?

A 8 N

B 10 N

C 80 N

D 800 N

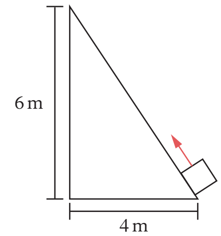
7 A 20 kg box is pushed up a ramp.
How much work must be done to move the box to the top of the ramp?

A 120 J

B 784 J

C 1,176 J

D 1,411.2 J



8 A 3 kg block of ice is sliding across a frozen lake. A frictional force of 2.5 N acts on the block of ice, causing it to come to rest after 18 m. The work done to stop the block of ice is

A 30 J.

B 45 J.

C 54 J.

D 135 J.

9 Which of the following statements about kinetic energy is correct?

A Kinetic energy is always conserved in an inelastic collision.

B Kinetic energy is always conserved in an elastic collision.

C Kinetic energy is always equal to the potential energy.

D Kinetic energy is always conserved in an explosion.

10 In which of the following scenarios is zero net work done?

A A box is pushed across a frictionless surface.

B A child pulls a toy cart along the grass quickly, causing it to accelerate.

C A barrel is pushed up a frictionless inclined plane.

D A box is pulled across a rough bench at a constant speed.

Review questions 11.5B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

11 **Define** these terms: kinetic energy, gravitational potential energy, law of conservation of energy, and mechanical work. (4 marks)

12 **Calculate** the gravitational potential energy of a 50 kg bag of cement lifted 1.4 m from the ground to a mixer bowl. (2 marks)

13 **Calculate** the kinetic energy of a 120 kg object that is moving with a speed of 15 m s^{-1}. (2 marks)

14 **Calculate** the kinetic energy of a 60 g air-hockey puck sliding at 8.0 m s^{-1}. (2 marks)

15 An arrow of mass 75 g is fired directly upwards at a speed of 60 m s^{-1}.

a **Calculate** the E_p at its highest point. (2 marks)

b **Calculate** how high this highest point is. (3 marks)

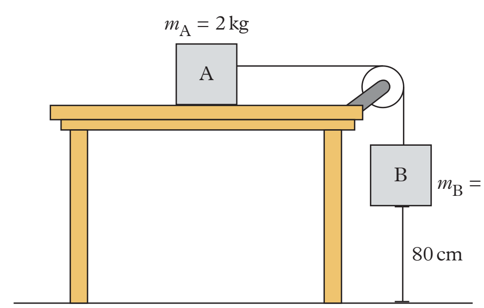
16 A glass ball (ball A) of mass 100 g is rolled to the right along the ground at 3 m s^{-1} towards a stationary ball (ball B) of mass 50 g. After they collide elastically, both balls are moving. **Calculate** the final velocity of each ball. (9 marks)

17 Car A of mass 1,500 kg is moving at a speed of 10 m s^{-1} to the left and collides inelastically with car B at rest, and they remain coupled. Car B has a mass of 1,200 kg.

a **Calculate** the velocity of the resulting mass. (3 marks)

b If the combined mass rolls 2.6 m before coming to a halt, **calculate** the force that must be acting to stop it moving. (3 marks)

18 Two boxes, A and B, are connected in a pulley system.



The system is released from rest and box B falls 80 cm to reach the ground. Assuming the table is frictionless, **calculate** the kinetic energy of box B just before it hits the ground. (4 marks)

19 **Explain** why a collision in which the objects become coupled is always an inelastic collision. (3 marks)

20 An object has a kinetic energy of 250 J and a mass of 17 kg. **Determine** the speed of the object. (2 marks)

21 **Determine** the impact speed of a 2 kg rock dropped off a cliff 8.5 m above the water (using conservation of mechanical energy principles). (2 marks)

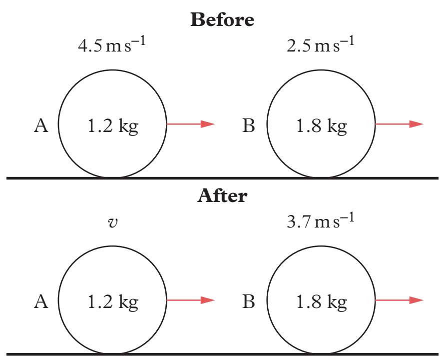
Analytical processes

22 An archer does 250 J of work to pull back a 50 g arrow. **Determine** the initial speed of the arrow when it is released. (2 marks)

23 A motorcycle (A) of mass 200 kg is travelling east at a speed of $85\,\text{km}\,\text{h}^{-1}$ and undergoes a high-speed collision with another motorcycle (B) of mass 190 kg travelling west at $130\,\text{km}\,\text{h}^{-1}$. The motorcycles collide inelastically and become tangled.

- **a** **Calculate** the velocity at which the entangled motorcycles will continue to travel. (3 marks)
- **b** A frictional force of 1,450 N causes the motorcycles to come to a stop. **Determine** what distance the entangled motorcycles will travel before stopping. (4 marks)

24 A 1.2 kg ball (ball A) collides with a 1.8 kg ball (ball B).

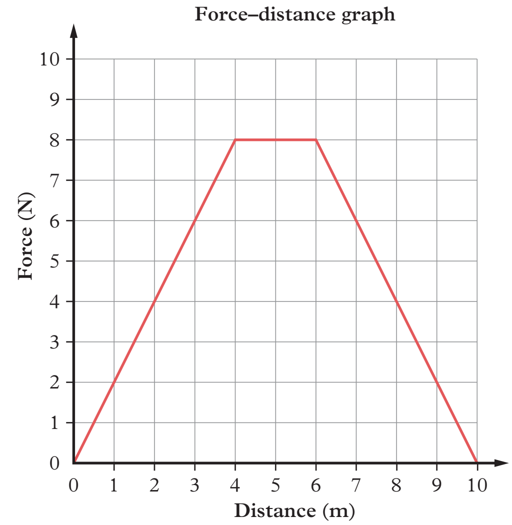


- **a** **Calculate** the final velocity of ball A. (3 marks)
- **b** **Deduce** whether the collision is elastic or inelastic. **Justify** your choice. (3 marks)

25 A motor uses 950 J of energy to raise a 50 kg box to a height of 1.2 m. **Determine** the percentage efficiency of the motor. (3 marks)

26 A car is pulling a loaded trailer in an easterly direction along a horizontal road at a constant speed. A force–distance graph is shown.

Determine the work done by the car. (2 marks)



27 A body of mass 10 kg is travelling east at $4\,\text{m}\,\text{s}^{-1}$ and strikes a 3 kg mass at rest. After the collision, the bodies remain coupled and the mass moves east at $3\,\text{m}\,\text{s}^{-1}$. **Deduce** mathematically whether the collision is elastic or inelastic. Show your working. (5 marks)

28 An object has a kinetic energy of 250 J and a mass of 17 kg. **Determine** the speed of the object. (3 marks)

29 It takes a horizontal force of 75 N to pull a 20 kg box across the floor at constant speed.

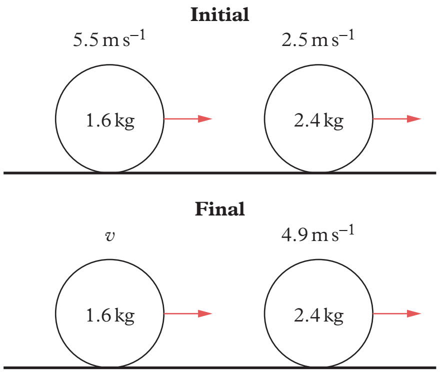
- **a** **Calculate** how much work is done in moving the box 3.0 m. (2 marks)
- **b** If instead there was no friction, **determine** what acceleration this box would experience. (2 marks)

30 A basketball with a mass of 2.2 kg falls off a 50 m-high window ledge. **Determine** its gravitational energy after 2.0 seconds have elapsed. (4 marks)

31 A ball of mass 0.70 kg is kicked straight up. **Determine** its gravitational potential energy at its highest point, 6.5 m off the ground. (3 marks)

32 A student is asked to carry a 15 kg carton of books from the ground floor to the first floor. **Deduce** and **explain** which way uses less energy: to walk up the stairs slowly or to run up. (2 marks)

33 A 1.6 kg ball collides with a 2.4 kg ball. After the collision, the balls continue to travel.



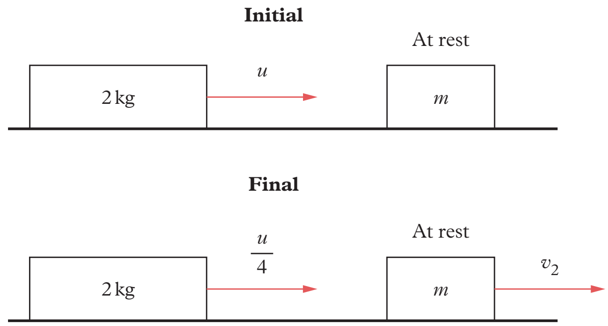
- **a** **Calculate** the velocity v. (2 marks)
- **b** **Determine** whether the collision is elastic or inelastic. **Explain** your reasoning. (5 marks)
- **c** The collision is now repeated except that the 2.4 kg ball now has a velocity of $2.5\,m\,s^{-1}$ in the opposite direction. If the collision is elastic, **determine** the velocity of both balls after the collision. (Warning, this will require the use of simultaneous equations linking both momentum and kinetic energy.) (5 marks)

34 Two inflatable boats (X and Y) are at rest in a swimming pool and are 1.5 m apart. A boy of mass 60 kg jumps from boat X into boat Y at a speed of $1.0\,m\,s^{-1}$. The boats move away from each other. The mass of boat X = 50 kg, mass of boat Y = 40 kg and mass of boy = 60 kg.

- **a** **Calculate** the velocity of boat X after the boy jumps. (2 marks)
- **b** **Calculate** the velocity of boat Y just after he lands in it. (2 marks)
- **c** Given that friction between each boat and the water is 3.0 N, **determine** how far apart the boats will be when they come to rest. (5 marks)

35 A 0.63 kg ball is thrown straight up into the air with an initial speed of $14\,m\,s^{-1}$ and reaches a maximum height of 8.1 m before falling back down again. Assuming that the only forces acting on the ball are the ball's weight and air drag, **deduce** the work done on the ball during the ascent by the air drag. (5 marks)

36 A body of mass 2.0 kg makes an elastic collision with another body at rest and continues to move in the same direction but with one-fourth of its original speed. **Determine** the mass of the struck body. (7 marks)



37 A London Underground train consisting of a locomotive and 30 carriages with a total mass of 320 tonnes and travelling at $28\,km\,h^{-1}$ is slowed by travelling up a slight incline to the horizontal platform. If the train is raised vertically by 1.2 m over a distance of 300 m, **determine** the speed of the train at the top of the incline (assuming no braking takes place). (5 marks)

Knowledge utilisation

38 A motor consumes 60 J of electrical energy per second but converts this to only 18 J of mechanical energy per second. **Propose** where the remaining 42 J is going. (1 mark)

39 When two lumps of clay hit each other head-on, they form a big lump. **Propose** where the kinetic energy goes. (1 mark)

40 Two billiard balls, each with a mass of 150 g, collide head-on in an elastic collision. Ball 1 was travelling right at a speed of $2\,m\,s^{-1}$ and ball 2 was travelling left at a speed of $1.5\,m\,s^{-1}$. After the collision, ball 1 travels in the reverse direction at a velocity of $1.5\,m\,s^{-1}$.

- **a** **Calculate** the velocity of ball 2. (2 marks)
- **b** **Justify** the conclusion that the collision was elastic. (5 marks)

41 A 4 kg block moving to the right at $6.0\,m\,s^{-1}$ undergoes an elastic head-on collision with a 2.0 kg block moving to the right at $3.0\,m\,s^{-1}$. Using both conservation of momentum and conservation of energy principles, **determine** the velocity of each of the blocks after the collision. (6 marks)

42 An artillery shell of mass 30 kg has a velocity of $250\,m\,s^{-1}$ vertically upwards. The shell explodes into two pieces. Immediately after the explosion, a fragment of mass 10 kg has a velocity of $120\,m\,s^{-1}$ straight downwards. **Determine** how high above the point of the explosion the larger fragment rises. (6 marks)

Data drill

Conservation of mechanical energy

A student released a marble from different starting heights and recorded the final height reached in a U-shaped tube called a "rollercoaster". The research question was:

"How does the efficiency of mechanical energy transfers vary with initial gravitational potential energy?"

The student calculated the potential energy at the start and end of each event (Table 1).

TABLE 1 Data from marble rollercoaster experiment

Initial drop height (cm)	Final height reached (cm)	Potential energy at start (J)	Potential energy at end (J)	Efficiency (%)
20.0	17.5	0.27	0.24	88.9
40.0	34.2	0.55	0.47	Question 3
60.0	52.3	0.82	Question 2	87.2
80.0	Question 1	1.10	0.94	85.4

Apply understanding

1 **Calculate** the final height reached for the 80.0 cm trial. (1 mark)
2 **Calculate** the potential energy at the end for the 60.0 cm trial. (1 mark)
3 **Calculate** the percentage efficiency for the 40.0 cm trial. Note: "efficiency" is defined as work (out) divided by work (in). (1 mark)

Analyse data

4 **Compare** the efficiency with the initial drop height to identify any patterns in the data. (2 marks)

Interpret evidence

5 **Draw a conclusion** related to the research question and **justify** your answer. (2 marks)
6 **Determine** whether the design of the experiment is appropriate to gather sufficient and relevant data. (2 marks)

Module 11 checklist: Energy

Quizlet: Revise key terms online to test your understanding

UNIT 2

Topic 1 review

Multiple choice

(1 mark each)

1 Which of the following is a vector quantity?

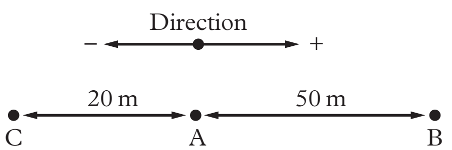
A Distance

B Speed

C Force

D Mass

2 A person starts a journey at position A, travels to position B and finishes at position C.
The direction to the right is positive.



For the journey, the distance travelled, and the displacement, in order are

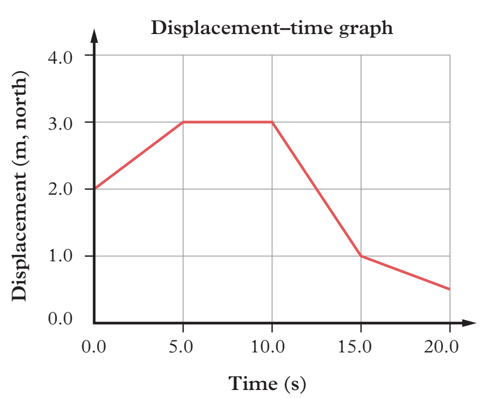
A 70 m, –20 m.

B 120 m, 20 m.

C 120 m, –20 m.

D 120 m, –120 m.

3 The graph shows the motion of a dog.



During which interval does the dog have the fastest speed?

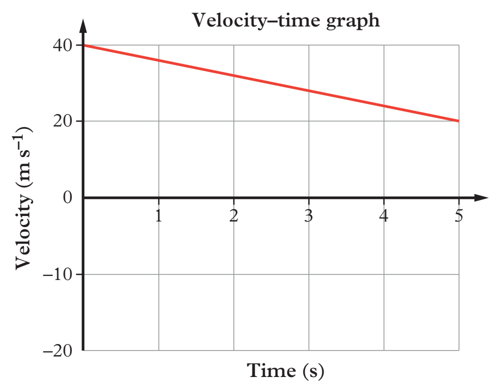
A 0.0–5.0 s

B 5.0–10.0 s

C 10.0–15.0 s

D 15.0–20.0 s

4 The graph is a velocity–time graph for the motion of an object.



The acceleration and distance covered in the 5 seconds is

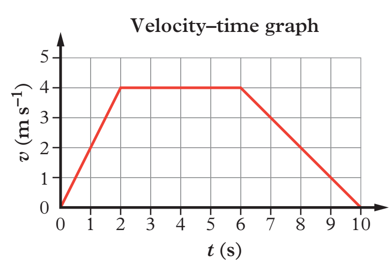
A $-8\,m\,s^{-2}$, 100 m.

B $-4\,m\,s^{-2}$, 150 m.

C $-8\,m\,s^{-2}$, 50 m.

D $4\,m\,s^{-2}$, 50 m.

5 The velocity of a go-cart as a function of time is shown in the graph. The distance it has travelled in the 10 seconds is



A 28 m. **B** 32 m.

C 36 m. **D** 40 m.

6 An object moves to the right 10.0 m from the starting point in a time of 1.0 s. It then moves 20 m to the left in a time of a further 3.0 s. The average speed and average velocity of the object for this period is

A $2.5\,m\,s^{-1}$, $2.5\,m\,s^{-1}$ right.

B $16.7\,m\,s^{-1}$, $6.7\,m\,s^{-1}$ left.

C $7.5\,m\,s^{-1}$, $2.5\,m\,s^{-1}$ left.

D $7.5\,m\,s^{-1}$, $7.5\,m\,s^{-1}$ left.

7 The initial velocity of an object is $2\,\mathrm{m\,s^{-1}}$, so the distance covered by it in time t and acceleration of $9.8\,\mathrm{m\,s^{-2}}$ would be

A $4.9t^2$.

B $9.8t^2$.

C $4.9t^2 + 2t$.

D $9.8t^2 + 2t$.

8 A ball tossed vertically upwards rises, reaches its highest point and then falls back to its starting point. During this time the acceleration of the ball is always

A in the direction of motion.

B directed downwards.

C opposite its velocity.

D directed upwards.

9 A rock is dropped off a cliff 125 m high. Its final velocity when it strikes the ground is

A $5.1\,\mathrm{m\,s^{-1}}$. **B** $24.7\,\mathrm{m\,s^{-1}}$.

C $25.5\,\mathrm{m\,s^{-1}}$. **D** $49.5\,\mathrm{m\,s^{-1}}$.

10 Two forces are acting on a 5.00 kg mass. One of the forces is 5.0 N south and the other is 15.0 N north. The magnitude of the acceleration of the mass is

A $2\,\mathrm{m\,s^{-2}}$ north.

B $2\,\mathrm{m\,s^{-2}}$ south.

C $4\,\mathrm{m\,s^{-2}}$ north.

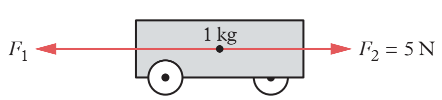
D $4\,\mathrm{m\,s^{-2}}$ south.

11 A 4 kg ball of clay moving at $5\,\mathrm{m\,s^{-1}}$ slams into a 2 kg ball of clay at rest and the two balls stick together after collision. The speed of the combined ball is

A $2.5\,\mathrm{m\,s^{-1}}$. **B** $3.3\,\mathrm{m\,s^{-1}}$.

C $4.1\,\mathrm{m\,s^{-1}}$. **D** $5.0\,\mathrm{m\,s^{-1}}$.

12 The diagram shows the horizontal force vectors acting on a collision trolley.



Which of the following is most likely to be true about this situation?

A The trolley is accelerating at $10\,\mathrm{m\,s^{-2}}$ to the left.

B The trolley is accelerating at $5\,\mathrm{m\,s^{-2}}$ to the left.

C The vector sum of the forces is 15 N.

D F_1 could be the frictional force.

13 A ball is projected into the air with 200 J of kinetic energy that is transformed to gravitational potential energy at the top of its trajectory. When the ball returns to its original level after encountering air resistance, its kinetic energy is

A less than 200 J but not 0 J.

B more than 200 J.

C 200 J.

D 0 J.

14 Two identical trolleys, each of mass m and speed v, travel towards each other on a frictionless surface and in the absence of air resistance.

The trolleys undergo a head-on elastic collision. Which statement correctly describes the trolleys after the collision?

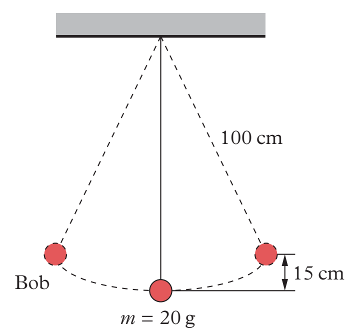
A Each trolley has zero momentum.

B Each trolley has zero kinetic energy.

C The total momentum of the trolleys is $2mv$.

D The total kinetic energy of the trolleys is mv^2.

15 A simple pendulum consists of a 20 g brass bob tied to a 100 cm length of string and supported at the top by a rigid clamp. The bob is pulled sideways until it is at a vertical height of 15 cm from its rest position. It is allowed to oscillate freely. What is the velocity of the bob at the bottom of its travel?



A $1.21\,\mathrm{m\,s^{-1}}$

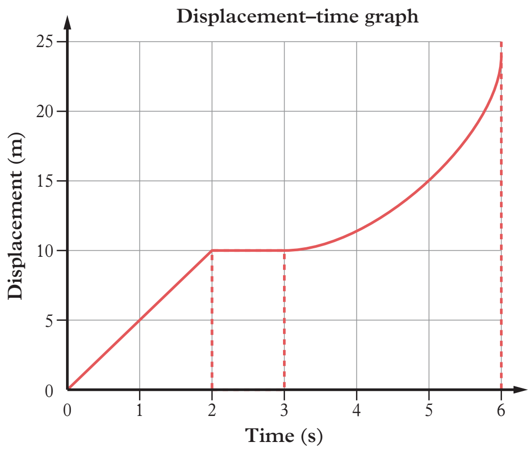
B $1.71\,\mathrm{m\,s^{-1}}$

C $2.94\,\mathrm{m\,s^{-1}}$

D $17.1\,\mathrm{m\,s^{-1}}$

Short response

16 A radio-controlled car is being driven in a straight line along a flat path. Its displacement at each second is shown on the graph.

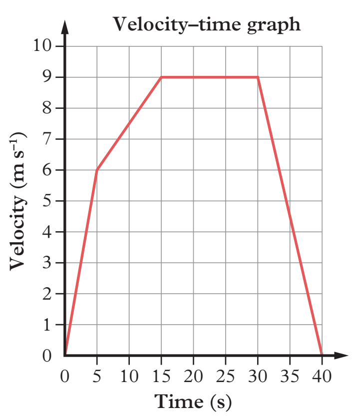


a **Determine** its acceleration during the first 2 seconds. (1 mark)

b **Determine** the instantaneous velocity at the 5 second mark (2 s.f.). (2 marks)

c **Explain** whether, at the 2 second mark, the distance travelled was the same as the displacement. (2 marks)

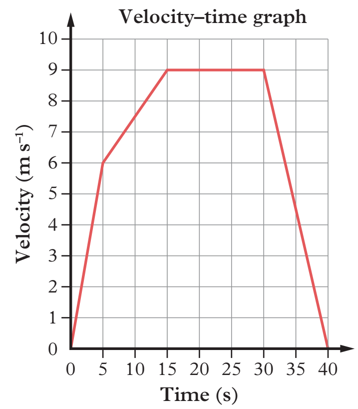
17 A person takes their dog for a walk from home. The graph shows how their distance from home changes with time.



a **Determine** which part of the graph, A, B, C or D, shows them walking the fastest. **Justify** your answer. (3 marks)

b During the walk, both the speed and the velocity of the person and the dog change. **Explain** how velocity is different from speed. (2 marks)

18 A cyclist is travelling along a straight level road as shown in the graph. The mass of the cyclist and the bicycle is 70 kg.

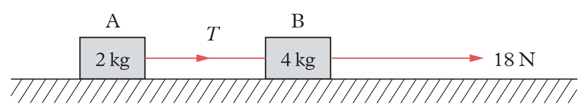


a The cyclist accelerates at $1.2\ m\ s^{-2}$ for 5 seconds. **Calculate** the resultant force needed to produce this acceleration. (2 marks)

b **Determine** the distance travelled by the cyclist in the 40 seconds. (2 marks)

c **Identify** the time period when the cyclist had the greatest acceleration. **Justify** your answer by referring to the graph. (2 marks)

19 Two blocks of masses 2 kg (A) and 4 kg (B) respectively rest on a smooth horizontal surface and are connected by a taut string of negligible mass. A force of 18 N is applied to the 4 kg mass as shown in the figure.

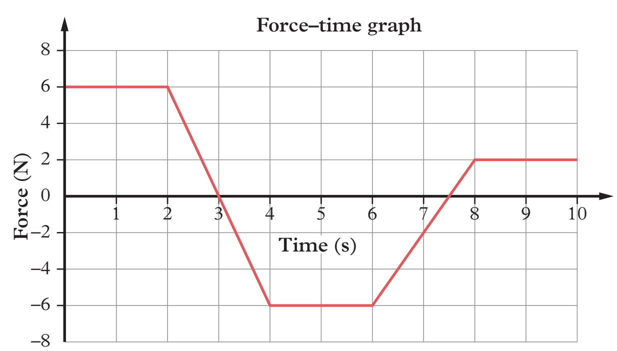


Calculate the

a acceleration of the system (2 s.f.) (2 marks)

b tension in the string between the blocks (2 s.f.). (2 marks)

20 The net force on an 8.0 kg object was plotted as a function of time over a period of 10 seconds.



a **Calculate** the magnitude of the acceleration of the object from 4 s to 6 s (2 s.f.). (2 marks)

b **Determine** the change in velocity from 2 s to 4 s (2 s.f.). (2 marks)

c **Determine** the impulse delivered to the object over the 10 s period (2 s.f.). (3 marks)

21 A ball is thrown vertically upwards at $30\,\mathrm{m\,s^{-1}}$. **Calculate**

a its maximum height (2 s.f.) (3 marks)

b the time taken to reach this height (2 s.f.) (2 marks)

c the time from being launched to arriving back at its starting position (2 s.f.). (2 marks)

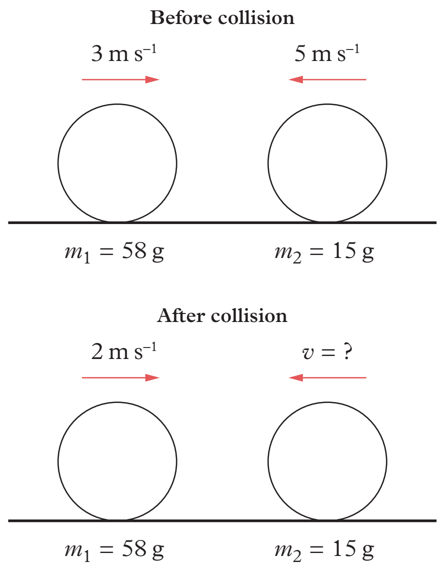
22 **Calculate** the magnitude of the momentum of the following moving objects.

a A 1.5 tonne car moving at $15\,\mathrm{m\,s^{-1}}$ (1 tonne = 1,000 kg) (2 s.f.) (2 marks)

b Earth in its journey around the Sun (Earth's average radius of orbit is 1.5×10^{11} m and its mass is 5.97×10^{24} kg) (2 s.f.) (4 marks)

23 A basketball of mass 0.625 kg has a velocity of $15\,\mathrm{m\,s^{-1}}$ downwards just before it hits the ground and rebounds with a velocity of $14\,\mathrm{m\,s^{-1}}$ upwards. **Calculate** the change in the momentum of the basketball during this interaction (2 s.f.). (3 marks)

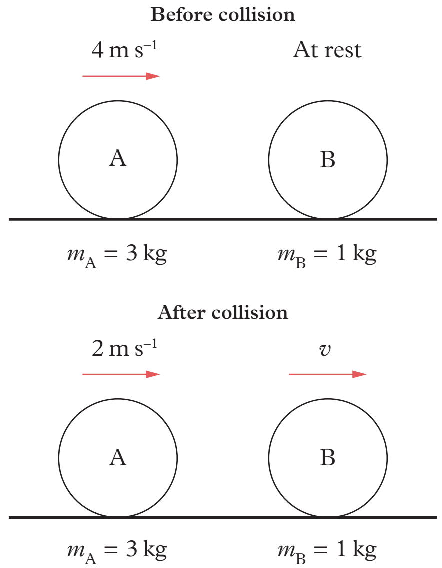
24 A 58 g tennis ball collides with a 15 g bouncy ball and afterwards they move as shown in the figure.



a **Calculate** the velocity of the bouncy ball after the collision (2 s.f.). (3 marks)

b **Determine** whether or not the collision was elastic (2 s.f.). Show your working. (3 marks)

25 A 3 kg steel ball (A) is moving to the right at a speed of $4\,\mathrm{m\,s^{-1}}$ and collides with a 1 kg stationary ball (B). After the collision, ball A has slowed to $2\,\mathrm{m\,s^{-1}}$ to the right and ball B has been pushed forwards at a speed of v. **Determine** whether or not the collision was elastic. **Justify** your conclusion. (7 marks)



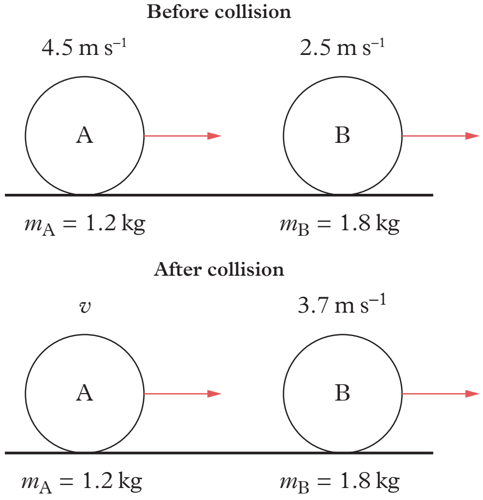
26 An archer does 250 J of work to pull back a 50 g arrow. **Determine** the initial speed of the arrow when it is released (2 s.f.). (2 marks)

27 A motorcycle (A) of mass 200 kg is travelling east at a speed of $85.0\,\mathrm{km\,h^{-1}}$ and undergoes a high-speed collision with another motorcycle (B) of mass 190 kg travelling west at $130\,\mathrm{km\,h^{-1}}$. The motorcycles collide inelastically and become tangled.

a **Calculate** the velocity the tangled motorcycles will continue to travel at (3 s.f.). (3 marks)

b A frictional force of 1450 N is applied to cause the motorcycles to come to a stop. **Determine** the distance the entangled motorcycles will travel before stopping (3 s.f.). (4 marks)

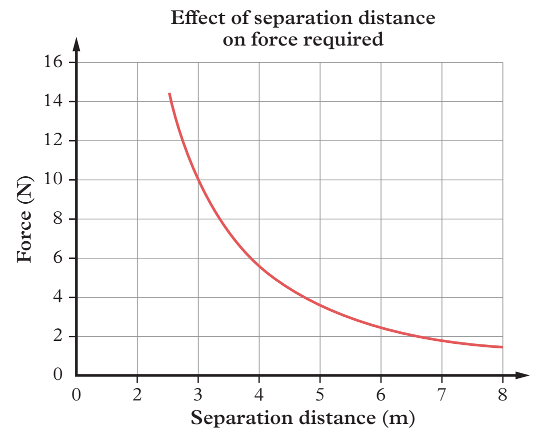
28 A 1.2 kg ball collides with a 1.8 kg ball as shown.



a **Calculate** the final velocity of ball A (2 s.f.). (3 marks)

b **Deduce** whether the collision is elastic or inelastic. **Justify** your answer. (3 marks)

29 An electrically charged object, Q, is gradually separated from an oppositely charged object, P, that is fixed in place. The force required is recorded as a function of the distance. The objects each have a mass of 2.0 g. A graph of the results is shown.



a **Calculate** the work done in moving charge Q from 3 cm to 5 cm. (3 marks)

b Charge Q is released when it is at 5 cm and it moves freely back towards P. **Calculate** the velocity of Q when it passes the 3 cm point. (3 marks)

TOTAL MARKS

/92

MODULE 12 Waves

Introduction

When you stand in the surf at the beach, the waves roll in and lift you up. Your potential energy increases and this energy has to come from somewhere. Waves carry energy, and this energy can be related to movement up or down, as well as in the direction of travel. Because of the energy waves carry, the motion of ocean waves has become one of the latest – and renewable – sources for generating electricity.

Consider the energy carried by a tsunami – a giant wave produced in the ocean after a volcano or earthquake. Tsunamis often cause more destruction and damage than the event that created them. Areas that are affected frequently by tsunamis, including Japan and Hawaii, go to great efforts to detect the source of earthquakes by measuring wave velocities. This allows governments to estimate the time of a tsunami's arrival so that people can be warned and can evacuate.

Prior knowledge

Prior knowledge quiz

Check your understanding of the properties of waves before you start.

Subject matter

Science understanding

- → Describe the transfer of energy through waves.
- → Describe the concept of mechanical waves.
- → Compare transverse waves and longitudinal waves.
- → Describe examples of transverse and longitudinal waves, such as sound, seismic waves and vibrations of stringed instruments.
- → Describe the concepts of compression, rarefaction, crest, trough, displacement, amplitude, period, frequency, wavelength and velocity and identify them on graphical and visual representations of a wave.
- → Analyse the amplitude, period, frequency and wavelength from graphs of transverse and longitudinal waves.
- → Solve problems involving the period, frequency, wavelength, and velocity of a wave using $v = f\lambda$ and $f = \frac{1}{T}$.

→ Describe the concepts of reflection, refraction, diffraction and superposition.
→ Explain phenomena related to reflection and refraction using the wave model of light.
→ Describe the reflection and refraction of a wave at a boundary between two media.
→ Explain constructive interference and destructive interference of two simple waves.
→ Determine the resultant amplitude of two simple waves interacting using the principle of superposition.
→ Explain the formation of standing waves in terms of superposition with reference to constructive and destructive interference, and nodes and antinodes.

Science as a human endeavour

→ Appreciate that knowledge of different types of waves, and their motion through the ocean and the continents, allows prediction of the possible extent of damage or the timing of a tsunami.

Science inquiry

→ Investigate the behaviour of both longitudinal waves and transverse waves on springs in relation to reflection from fixed and free ends and transmission/reflection at a medium boundary.

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Practicals

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Lesson 12.4 Longitudinal and transverse waves on springs

Lesson 12.1
Mechanical model of waves

Key ideas

- → Mechanical waves transfer energy through a medium.
- → The amplitude of a wave indicates its energy.
- → In transverse waves, particles move perpendicular to the direction of propagation, whereas in longitudinal waves, they move parallel to the direction of propagation.

Learning intentions and success criteria

What is a mechanical wave?

A wave is a disturbance in a medium that propagates through the medium. Waves are classified according to how they transfer energy. If a **medium** (a substance such as air or water) is required for the transfer of energy, then the waves are called **mechanical waves**. If no medium is required and the waves can travel through a vacuum, then the waves are called **electromagnetic waves**. This module and Module 13 "Sound" will only discuss mechanical waves. Module 14 "Light" deals with electromagnetic waves.

FIGURE 1 A circular wave is formed when a rock (or water droplets in this case) is dropped into water.

medium
an elastic substance such as air or water that allows for the transfer of energy in the form of a mechanical wave

mechanical wave
wave that requires a medium for the transfer of energy

electromagnetic wave
wave that does not require a medium for transmission and travels at the speed of light in a vacuum; includes long wavelength radio waves through to short wavelength gamma rays (called the electromagnetic spectrum)

What is an "elastic" medium?

We talk about mechanical waves travelling in a "medium". But what makes a medium suitable for transmitting waves is that it must be "elastic". The substance should be able to change shape as the wave passes through, but then bounce back to its original position afterwards. You can think of it as if the particles of the medium are connected by elastic bands that get stretched by neighbouring particles as the disturbance passes through, but then snap back to their home position as the wave leaves.

Picture a still pool of water. When a stone is dropped in, a circular wave is seen to radiate outwards from the point where the stone enters the water. In this case, the water is the medium for the wave. But other substances are elastic. Gases and liquids seem obvious, but solids such as metals, stone and bone are also elastic.

How do waves form?

disturbance
a displacement from the equilibrium position of a vibrating system

equilibrium position
the natural or resting position assumed by a medium if no disturbance is travelling through it

wave height
the vertical distance of a wave from the crest to the trough; equal to twice the amplitude

amplitude
the distance of a point in a wave from the rest position (equilibrium position) to the crest position, which is half the vertical distance from a trough to a crest

displacement
(for wave motion) the distance between a particle's position and the equilibrium position

To create a wave, you must create a **disturbance** in an undisturbed (still) medium. This provides the energy for the wave to form. When a stone is thrown into a pond, some of the kinetic energy of the stone is transferred to the water wave. The wave will continue to move outwards from the point of the disturbance until it runs out of energy.

If there were no waves in the ocean on one particular day, the water would be in its **equilibrium position** (from the Latin meaning "equal balance") – the crests and troughs cancel out and appear flat. The **wave height** is the bottom of the trough to the top of a crest.

After a disturbance, the energy of a wave can be seen by analysing its height, or **amplitude** (Latin "amplus" = "large, abundant"). Amplitude is the maximum **displacement** of a point on the wave from rest in the equilibrium position. Amplitude is shown as *A* in Figure 2.

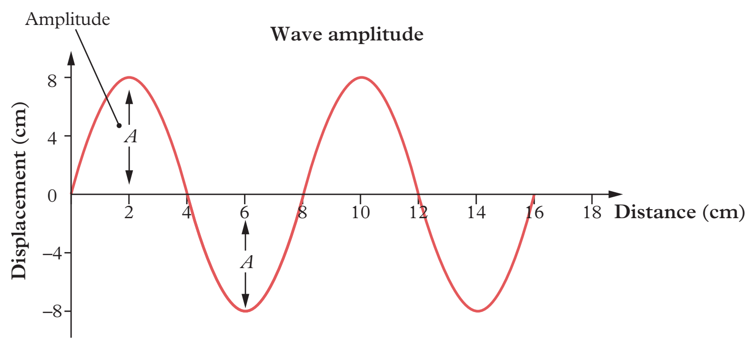


FIGURE 2 The amplitude of a wave is the maximum displacement of a point on the wave from the equilibrium position. For this wave, the amplitude is 8 m.

For example, a surfer in the ocean will move up and down as a wave passes, but they will return to their original (equilibrium) position once the wave has passed (Figure 3). The water also returns to its original position. It is an elastic medium.

FIGURE 3 A surfboard rider moves up and down as a wave passes.

dissipate
to lose energy (and hence, for a wave, amplitude) over time

The amplitude of a large water wave might be over 5 m. In fact, the Queensland record is a wave height of 12.0 m or an amplitude of 6.0 m recorded in 2004 off the Sunshine Coast during a cyclone. This amplitude suggests that the wave would have large amounts of energy. The larger the amplitude, the more energy the wave possesses. If the wave energy gets transformed into heat and sound, it **dissipates** and the amplitude of the wave decreases until the equilibrium position is reached.

How are waves propagated?

pulse
single disturbance produced in a medium by a source

A single disturbance produced in a medium by a source, such as a flicking rope, is called a **pulse** (Latin "pulsus" = "beating"). If a continuous set of pulses is produced by a source, with a constant time interval between the generation of each pulse, the result is a wave.

When children hold the ends of a skipping rope and flick it, a wave (or pulse) moves from the flicked end to the other. This energy can be felt by a child at the other end of the rope. The energy and the pulse move along the rope without the particles that make up the rope moving towards the receiver. The direction of energy flow is called the **direction of propagation**. Propagation comes from the idea of something being created from an earlier version of itself. In the case of waves, each disturbance creates or propagates the next disturbance, so energy gets passed down the line. Waves can be categorised as transverse or longitudinal, depending on the way the particles in the path of the wave move relative to the direction of propagation.

direction of propagation
the direction of energy flow for a wave

Transverse waves

Water waves and rope waves are a particular type of wave. As seen in Figure 3, the water (and the surfer) move upwards as the wave passes. The particles that make up the water move at right angles to the direction in which the wave is travelling. This is the same for the rope wave. The rope moves upwards as the pulse passes and then goes back to its original position (Figure 4).

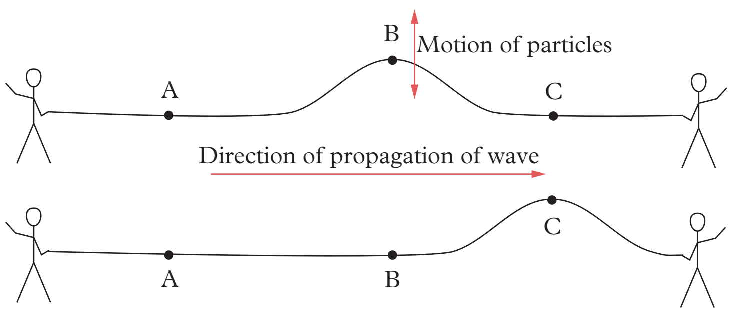


FIGURE 4 The parts of a rope move up and down as waves pass.

Waves that move in this manner are called **transverse waves**. Transverse comes from the Latin "transvertere," meaning "to turn across". Each point of the wave oscillates perpendicularly to the direction in which the wave is travelling; that is, perpendicular to the direction of propagation of the wave or energy transfer.

Examples of transverse waves include waves in water, ropes, hoses and springs. Notice the direction of motion of the particles of a spring as a transverse wave passes (Figure 6).

transverse wave
for a mechanical wave, the direction of oscillation of particles is perpendicular to the direction of energy transfer

FIGURE 5 Radio waves are also an example of transverse waves.

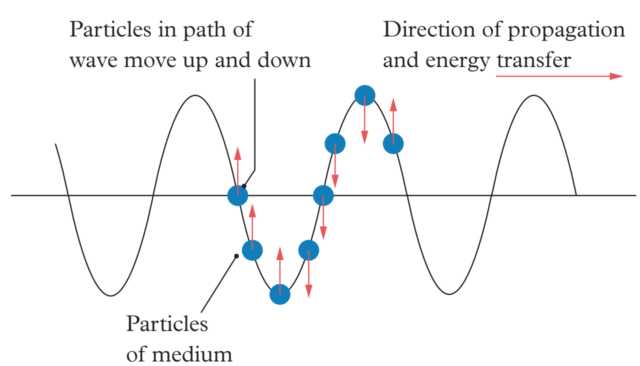


FIGURE 6 In a transverse mechanical wave, the particles move at right angles to the direction of propagation of the wave. The direction of individual particles is given by the arrows.

Waves of electromagnetic radiation (e.g. light, radio waves and television waves) are also transverse even if they are not mechanical waves. Their electric and magnetic fields oscillate in planes that are perpendicular to the direction of propagation of the wave. This will be explored more in Module 14.

Longitudinal waves

longitudinal wave a wave for which the direction of oscillation of particles is parallel to the direction of energy transfer

compression a region in a longitudinal wave where the particles are forced closer together in the direction of propagation; where they are closest together

rarefaction a region in a longitudinal wave where the particles are furthest apart

Another type of wave is a compression or **longitudinal wave**. Examples of these can be created in springs by compressing a part of a spring and then letting it go so the compression travels down the spring. In a longitudinal wave, the particles oscillate in the same direction as the pulse is moving. This creates **compressions** and **rarefactions**.

The following diagrams show the difference between transverse waves (Figure 7A) and longitudinal waves (Figure 7B).

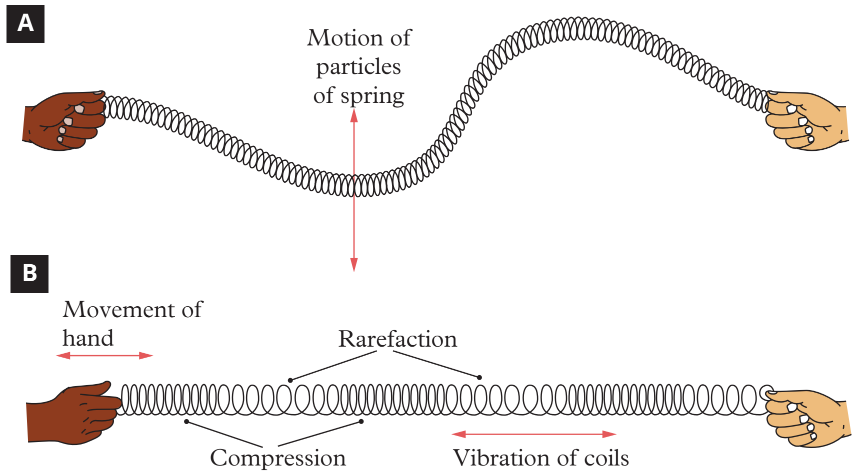


FIGURE 7 (A) Transverse waves; (B) longitudinal waves

The main characteristics of the two wave types are summarised in Table 1.

TABLE 1 Summary of main characteristics of the two types of mechanical waves

Characteristic	Transverse (mechanical)	Longitudinal
Is a medium needed for propagation?	yes	yes
Direction of particle movement relative to direction of propagation	perpendicular	parallel
Example	water, springs, strings	slinky, sound

Check your learning 12.1

Check your learning 12.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the term "mechanical wave" and distinguish a mechanical wave from an electromagnetic wave. (2 marks)

2 **Explain** what is meant by amplitude in the context of a water wave. (2 marks)

3 **Describe** the concept of equilibrium in relation to a wave passing along a stretched spring. (2 marks)

4 **Recall** the characteristic of a medium that enables it to transmit a mechanical wave. (1 mark)

5 **Describe** the transfer of energy through waves. (3 marks)

Analytical processes

6 Using an example, **compare** longitudinal and transverse mechanical waves. (3 marks)

7 **Contrast** compression and rarefaction. (2 marks)

8 If the energy in a longitudinal wave travels from south to north, **determine** the direction in which the particles of the medium would be vibrating. (1 mark)

Knowledge utilisation

9 **Devise** a method to demonstrate experimentally that energy is carried by a wave. (2 marks)

10 **Evaluate** the following statement: "Waves transmit energy and momentum." (3 marks)

Lesson 12.2
Characteristics of waves

Key ideas

→ Waves are characterised by their amplitude, wavelength, crests, troughs and phases.
→ Frequency is the number of waves passing through a point per second.
→ Period is the time taken for a full wave cycle to occur.
→ The velocity of a wave is the product of wavelength and frequency.

What are the features of waves?

As you saw in the previous lesson, the pattern of movement of waves over time is represented visually using **waveform diagrams**. We have already looked at amplitude, but there are a range of other features we can use to describe waves. Let us take a close look at the waveform diagram of a transverse wave (Figure 1).

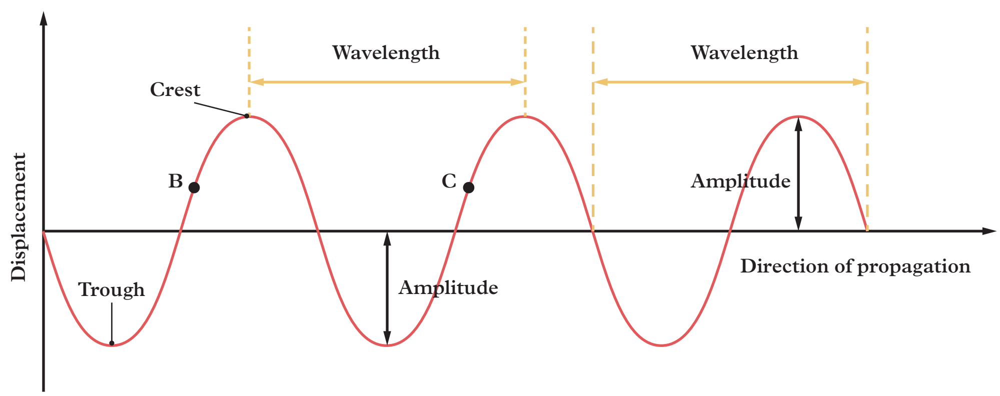


FIGURE 1 A waveform diagram a transverse wave at a moment in time

When particles of a wave have the same motion – that is, are at the same amplitude and are moving at the same velocity – they are said to be in **phase**. **Wavelength** (λ) is the minimum distance between two points in phase. This is the distance between corresponding points on successive waves. For example, in Figure 1, the wavelength is the distance between two consecutive **crests** (highest points) or two successive **troughs** (lowest points). Similarly, the wavelength is the distance between points B and C; these two points are not crests or troughs, but they are in phase as they are at the same distance from the equilibrium position and are moving in the same direction at the same time. One cycle from the equilibrium position to the wave crest/trough and then back to equilibrium is one **oscillation**.

It is a little harder to see and measure the various characteristics of the wavelength of a longitudinal wave as shown in Figure 2. Figure 2A shows the alternating compressions and rarefactions in a spring at a moment in time. The amplitude A is shown in Figure 2B as the maximum distance particle P in the medium will move from its equilibrium as the wave passes. The wavelength, as shown in Figure 2C, is the distance between the middle of adjacent compressions or adjacent rarefactions. The symbol λ is the Greek "L" (lambda) and is used for length.

Learning intentions and success criteria

waveform diagram
a graph that shows displacement (amplitude) of a wave at a moment in time

phase
the position of a particle at a point in time on a waveform cycle; particles in phase have the same motion (velocity, amplitude and direction of movement) at that time

wavelength
the minimum distance between two points on the wave in phase

crest
the highest part or point of a wave; the point of maximum positive displacement

trough
the lowest part or point of a wave; the point of maximum negative displacement

oscillation
the back and forth repetitive motion of an object through a central equilibrium point

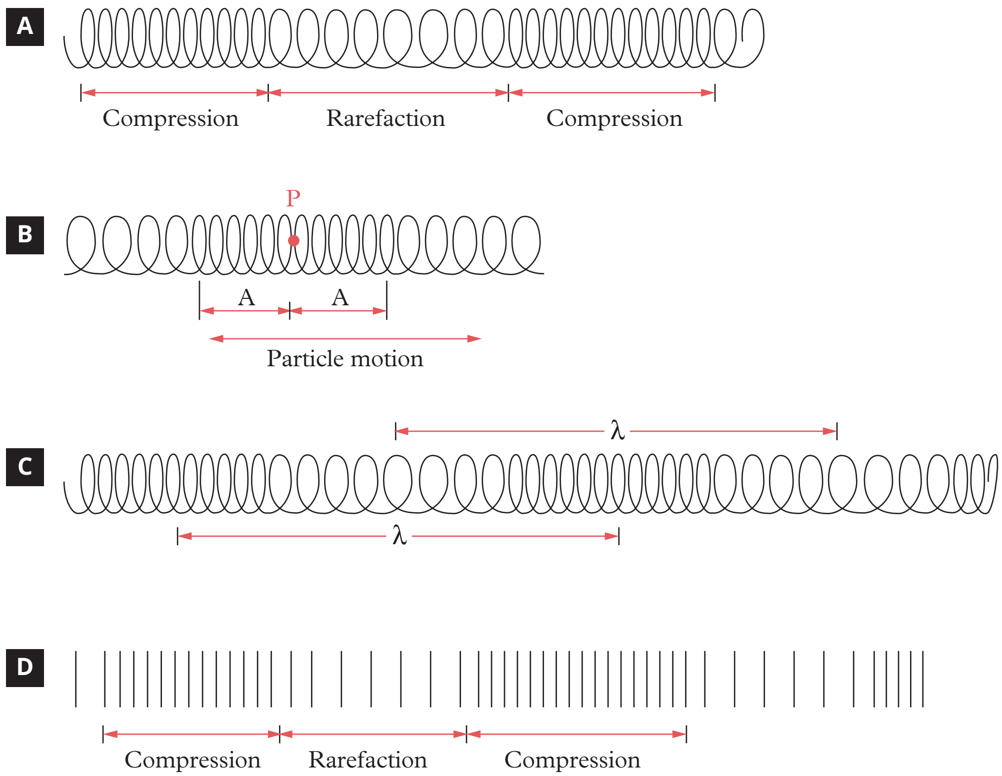


FIGURE 2 Wave characteristics of a longitudinal wave at a moment in time

What is frequency?

frequency
the number of oscillations of a wave source per unit of time; when time is in seconds, the unit is hertz (Hz)

The **frequency** (f) of a wave is the number of waves passing a given point per second, or the number of waves created by the source per second. The unit for frequency is waves per second, or cycles per second (cps or s^{-1}), or the modern unit of hertz (Hz). This is named after German physicist Heinrich Hertz (1857–1894), who discovered a technique for transmitting and receiving radio waves in the 1880s. A hertz is one cycle per second.

For example, if four crests pass a point in 1 s, then the frequency is 4 Hz. Ocean waves near the shore are in the order of 0.1 Hz. Sound waves that humans can hear have frequencies in the range of 20Hz to 20,000 Hz. The frequency of visible light waves is between 4×10^{14} Hz and 8×10^{14} Hz.

What is a period?

period
the length of time one cycle or one event takes to occur; the length of time taken for one wavelength to pass a given point

The **period** (T) of a wave is the time it takes for one full wave to pass a given point (i.e. one complete cycle). If the frequency of a wave is 10 Hz, then 10 waves pass per second. It will then take $\frac{1}{10}$ second for one wave to pass. The period of the wave is $\frac{1}{10}$ second when the frequency is 10 Hz. Therefore:

$$\text{Period} = \frac{1}{\text{frequency}}$$

$$T = \frac{1}{f} \text{ or } f = \frac{1}{T}$$

“Period” is from the Greek “periodos” meaning “recurrence”.

What is the velocity of a wave?

The velocity of a wave is measured using the distance the wave travels in a certain time. If the time for one wave to pass is the period, T, and the distance travelled in this time is one wavelength, then the velocity is given by:

$$v = \frac{\lambda \text{ (distance = wavelength)}}{T \text{ (time = period)}}$$
$$= \frac{1}{T} \times \lambda$$
$$= f\lambda$$

Note that we have replaced $\frac{1}{T}$ by f.

This is known as the **wave equation**, where v is the velocity of the wave in m s^{-1}, λ is the wavelength of the wave in m, and f is the frequency of the wave in Hz. The wave equation applies to all wave forms: mechanical and electromagnetic.

wave equation
a formula that relates the velocity of wave propagation through a medium to the frequency and wavelength of the disturbance; $v = f\lambda$

Worked example 12.2A

Calculating the velocity of waves

An observer sitting on the shore counts the waves and finds there are 6 waves per minute hitting the shore. They measure the distance between consecutive crests to be 10 m. **Calculate** the velocity of the waves (1 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the wave equation. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$v = f\lambda$ $\lambda = 10\text{ m}, f = ?$
Step 3: Find the frequency in waves per second.	$f = \frac{6}{60\text{ s}}$ $= 0.1\text{ Hz}$ (1 mark)
Step 4: Substitute the known values into the formula and find the unknown.	$v = 0.1 \times 10$ $= 1$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	1 m s^{-1} (1 s.f.) (1 mark)

Your turn

Ocean waves were measured to be travelling at 4 m s^{-1} and successive crests were 5 m apart. **Calculate** the number of wave crests that will pass by a moored boat in one minute. **Express** your answer to the nearest whole number. (2 marks)

How do you represent wave motion using graphs?

Wave motion can be represented graphically in two ways: displacement–distance graphs and displacement–time graphs.

Displacement–distance graphs ("snapshot")

Displacement–distance graphs (sometimes referred to as "snapshots") represent the position of all parts of a wave at a certain moment in time (Figure 3). It is like taking a photo of a wave

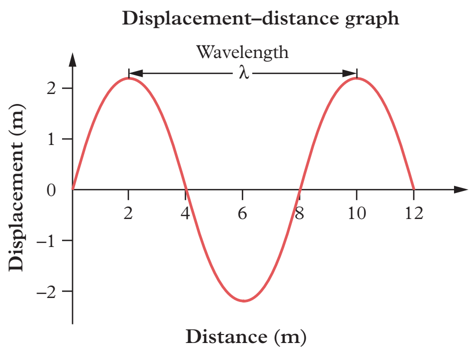


FIGURE 3 A displacement–distance graph allows you to determine wavelength.

in the ocean. The displacement of the particles is on the y-axis and distance along the direction in which the wave is propagating is on the x-axis. From this graph, the displacement (amplitude) and wavelength can be determined. The snapshot in Figure 3 has a wavelength of 8 m (x-axis) and an amplitude of 2 m (y-axis). The wavelength could also be read from the two equilibrium positions at distances of 0 m and 8 m.

The frequency cannot be determined from this graph alone. You need two things to calculate frequency:

- the position of the wave at another specified time (Worked example 12.2B)
- the wave speed, as it relates distance and time (Worked example 12.2C).

Worked example 12.2B

Interpreting a displacement–distance "snapshot" graph

Figure 4 shows snapshots of a wave at two different moments in time.

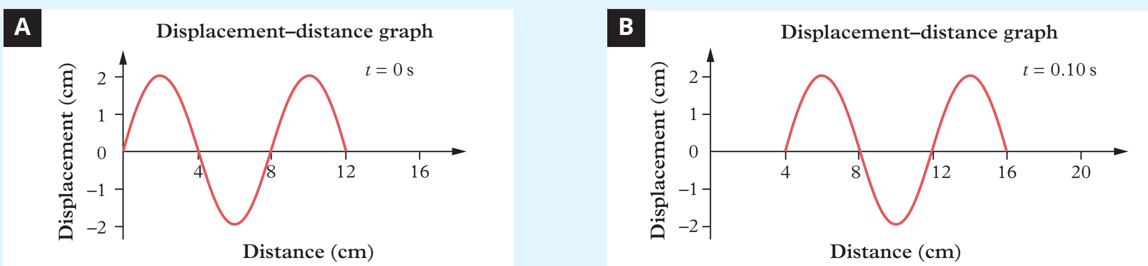
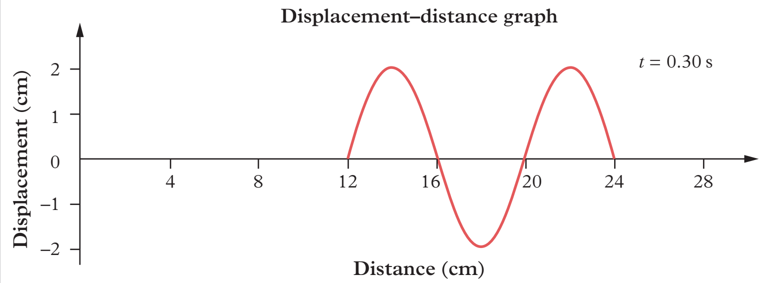


FIGURE 4 (A) The position of a wave at time zero; (B) the wave 0.10 s later

a **Calculate** the speed and frequency of the wave. (2 marks)

b **Construct** a displacement–distance graph for the wave after another 0.20 s. (2 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. "Construct" means to display information in a diagrammatic form. We need to apply the wave equation and draw a graph. The questions are worth 2 marks each, so we must gather the correct information, correctly apply the formula, complete the calculation, then draw the graph.
Step 2: Select the correct formulas and gather any data required.	$v = \frac{s}{t}$ $s = 4\,\text{cm}$, $t = 0.10\,\text{s}$, $v = ?$ $v = f\lambda$ λ (from the graph) $= 8\,\text{cm}$, $f = ?$
Step 3: Substitute the known values into the formulas and find the unknowns. Make sure you have included the correct units and significant figures.	**a** $v = \frac{s}{t}$ $= \frac{4\,\text{cm}}{0.1\,\text{s}}$ $= 40\,\text{cm}\,\text{s}^{-1}$ (1 mark) $f = \frac{v}{\lambda}$ $= \frac{40\,\text{cm}\,\text{s}^{-1}}{8\,\text{cm}}$ $= 5\,\text{Hz}$ (1 mark)

Think	Do
Step 4: Determine the distance the wave has moved in 0.20 s using the velocity. Figure 4B showed the snapshot at 0.10 s. After an additional 0.20 s, the snapshot will be for 0.30 s.	**b** $s = vt$ $= 40 \times 0.20$ $= 8$ cm (1 mark) In 0.20 s, the wave has moved 8 cm, so we add 8 cm to where the wave starts in time = 0.20 s: 4 + 8 = 12 cm. So, the wave starts at 12 cm.  (1 mark)

Your turn

Figure 5 shows the displacement–distance graph for a wave at $t = 0$ s (solid line) and $t = 0.882$ s (dashed line).

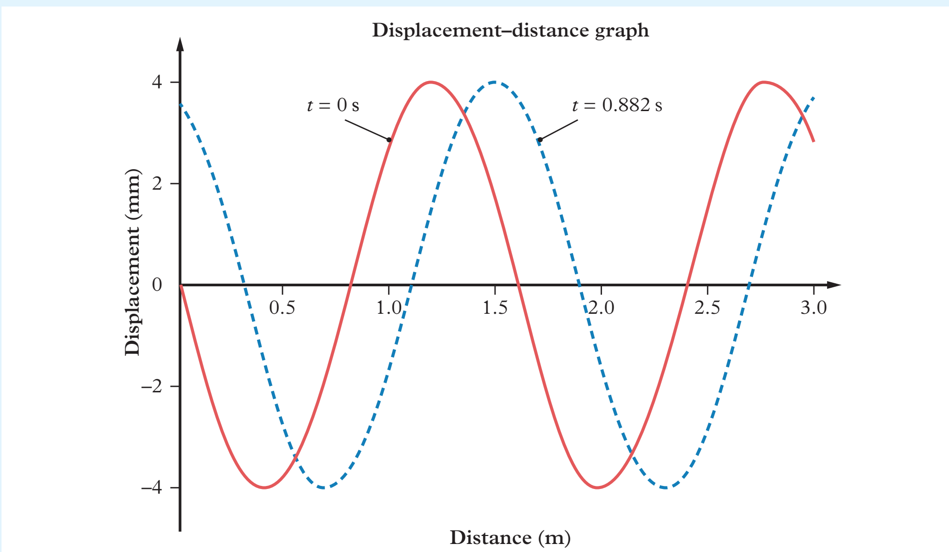


FIGURE 5 The position of a wave at time zero and 0.882 seconds later

Calculate

a its velocity (2 marks)

b the frequency. (2 marks)

Displacement–time graphs ("history graphs")

The second type of graph is the displacement–time graph (sometimes referred to as "history graph"), which indicates the displacement of a single particle in the medium as the wave passes. This allows the period, *T*, and hence the frequency, *f*, to be calculated. These graphs look very much the same as the displacement–distance (snapshot) graphs with crests and troughs, but they are very different diagrams. Students tend to get them confused, so be very careful.

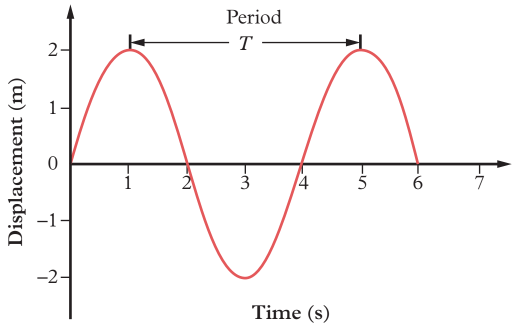


FIGURE 6 Displacement–time (history) graph of the same wave as in the snapshot graph in Figure 3

The history graph in Figure 6 is of the wave motion shown in Figure 3. It represents the position of a single point or particle in the medium (water, string, or spring) and how its displacement changes with time over 6 seconds. At the start ($t = 0$ s), the particle has zero displacement, but after 1 second ($t = 1$ s) it has moved and now has a displacement of 2 m in the positive direction (upwards). After another second ($t = 2$ s), it has moved down and is now back in its original equilibrium position. This continues. The particle is moving down and by $t = 3$ s it is at a displacement of –2 m. At $t = 4$ s, it is moving up and is back to its equilibrium position.

Determining the period

The period of the wave is the time for one complete oscillation and in Figure 6 that is shown to be 4 s. This can be read off the graph as the amount of time elapsed between the two crests. Alternatively, you can read off the time between two moments when the particle has the same phase – that is, any two consecutive positions on the curve that have the same displacement and are moving in the same direction. We have used adjacent crests, but it could also be the two equilibrium positions at $t = 0$ s and $t = 4$ s, where the particle's displacement is the same (zero) and in both cases it is moving "up".

Calculating frequency and wave speed

The frequency can be calculated as shown:

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{4} \\ &= 0.25\,\text{Hz} \end{aligned}$$

If we know the frequency is 0.25 Hz and we know the wavelength from Figure 3 is 8 m, we can calculate the wave speed:

$$\begin{aligned} v &= f\lambda \\ &= 0.25 \times 8 \\ &= 2\,\text{m}\,\text{s}^{-1} \end{aligned}$$

Study tip

When you see a graph, the first thing to do is to check the *x*-axis to see if it is distance (snapshot) or time (history). The distance between crests will give you either wavelength (snapshot) or period (history).

Worked example 12.2C

Interpreting a displacement–time "history" graph

A wave is created on a spring. The displacement of point P is given by the graph (Figure 8).

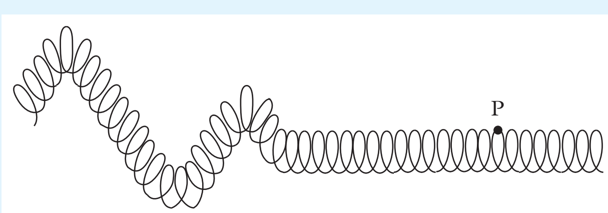


FIGURE 7 Imagine sending a wave down a Slinky towards point P.

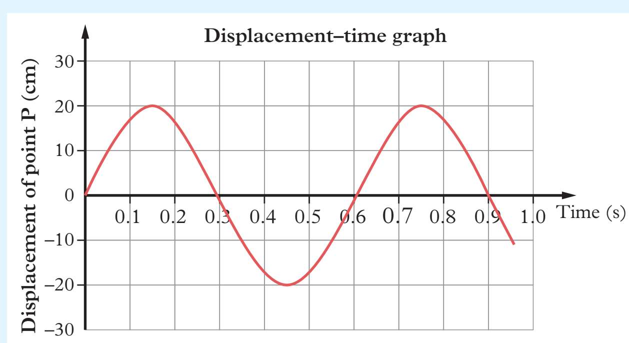


FIGURE 8 Displacement–time graph for point P on the spring

a **Calculate** the period of the wave. (1 mark)

b **Identify** the amplitude of the wave. (1 mark)

c If the wave is moving at $5\,\text{cm}\,\text{s}^{-1}$ to the right, **calculate** the wavelength of the wave. (2 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. "Identify" means to recognise and state. We need to apply the wave equation. The questions are worth a total of 4 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formula and gather any data required.	$v = f\lambda$ $v = 5\,\text{cm}\,\text{s}^{-1}$
Step 3: Using Figure 8, determine the period. Choose two points that are in phase and one period apart.	**a** The wave repeats itself after 0.6 s, therefore the period is 0.6 s. (1 mark)
Step 4: Using Figure 8, determine the amplitude. This is the maximum displacement of a particle on the wave from the equilibrium position.	**b** 20 cm (1 mark)
Step 5: Substitute the known values into the formula and find the unknowns. Make sure you have included the correct units and significant figures.	**c** $T = 0.6\,\text{s}$ $\lambda = \frac{v}{f}$ $= v \times \frac{1}{f}$ $= v \times T$ $= 5\,\text{cm}\,\text{s}^{-1} \times 0.6\,\text{s}$ (1 mark for substitution) $= 3\,\text{cm}$ (1 s.f.) (1 mark for correct answer)

Your turn

Figure 9 shows the motion of an ocean wave.

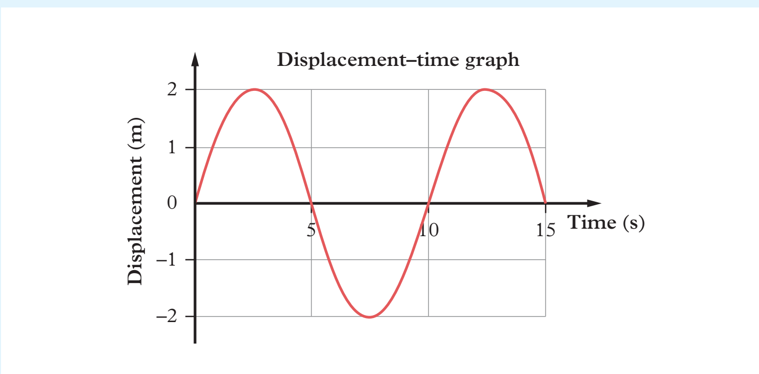


FIGURE 9 Displacement–time (history) graph for an ocean wave

Determine the

a frequency of the waves (2 marks)

b amplitude of the waves (1 mark)

c wavelength if the speed of the wave is $4\,\text{m}\,\text{s}^{-1}$. (2 marks)

Study tip

Displacement–distance (snapshot) graphs can be used to determine amplitude, *A*, and wavelength, λ. The distance between successive crests is the wavelength. Displacement–time (history) graphs can be used to determine amplitude, *A*, and period, *T*. The distance between successive crests is the period.

Study tip

The velocity of the wave links the snapshot and history graphs together as it combines distance and time.

Check your learning 12.2

Check your learning 12.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Define** the terms "wavelength", "crest" and "frequency" for a transverse wave and for a longitudinal wave. (6 marks)

2 **Explain** what is meant by the period of a transverse wave and a longitudinal wave. (1 mark)

3 **Describe** the wave equation and state the SI units for the quantities. (2 marks)

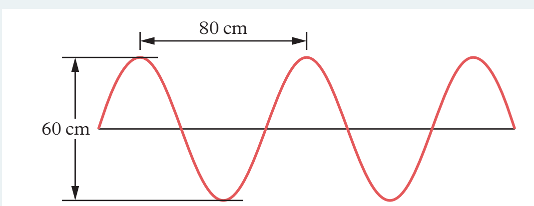
4 The speed of an ocean wave is $3.0\,m\,s^{-1}$. If the wavelength is 5.0 m, **calculate** its frequency. (2 marks)

5 For the wave on a spring in the figure, **determine** the value (in cm) of the

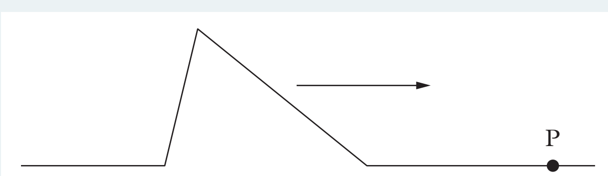
a wave height (1 mark)

b amplitude (1 mark)

c wavelength. (1 mark)



6 **Sketch** a displacement–time graph for point P on a string in the figure. (2 marks)



Analytical processes

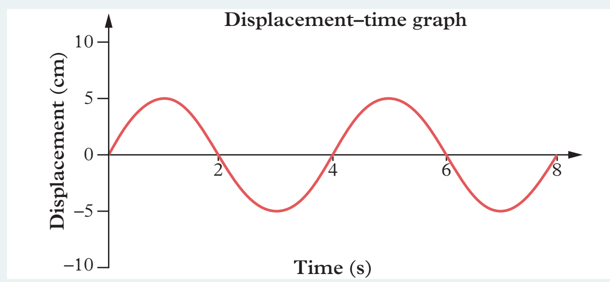
7 **Distinguish** between displacement–distance and displacement–time graphs. (2 marks)

8 Two students 5.0 m apart "flicked" a spring to create waves. They found that when they flicked it twice per second, 10 wave crests were created between the two students. **Determine** the velocity of the waves. (3 marks)

9 Figure 1 shows a transverse wave. If this wave is travelling to the right, **determine** the direction of movement of points B and C at this time. (2 marks)

Knowledge utilisation

10 The figure shows a displacement–time graph of particle A on a particular spring.



a **Determine** the frequency of the wave. (2 marks)

b **Determine** the location (displacement) of the particle at 3 s. (1 mark)

c **Predict** whether the particle was moving towards or away from the equilibrium position between 3 s and 4 s. **Justify** your reasoning. (2 marks)

Lesson 12.3
Waves and boundaries

Key ideas

→ The speed of a wave changes as it moves from one medium to another.

→ Reflection of waves at fixed and free boundaries can result in phase changes.

→ When waves undergo reflection and transmission at boundaries between two media, there can be a phase change.

→ Two-dimensional waves reflect according to the law of reflection.

How does the medium affect the speed of waves?

Learning intentions and success criteria

The speed of a wave is a characteristic of the medium in which it is moving. This changes when a wave moves from one medium to another. This can be seen in Table 1.

TABLE 1 Speed of waves in different media

Wave type	Medium	Speed (ms^{-1})
Sound	carbon dioxide	259
	air	331
	hydrogen	1,290
	pure water	1,480
	salt water	1,540
	glass (pyrex)	5,640
	steel	5,960
Earthquake	crust	(transverse) 3,500
		(longitudinal) 8,000
	mantle	(transverse) 6,500
		(longitudinal) 11,000

Real-world physics

Earthquakes and tsunamis

When surface forces cause the tectonic plates to rub together, they can cause earthquakes, which have devastating impacts over a wide area. Energy from earthquakes is propagated through the Earth via seismic waves. These waves can be longitudinal or pressure waves (P-waves) or transverse or shear waves (S-waves). The waves travel at different speeds, depending on the type of waves and the composition of the material they pass through. In rock, for example, the speed of longitudinal P-waves is higher than the speed of transverse S-waves.

Both types of earthquake waves travel more slowly in less rigid material such as sand and mud. P-waves have speeds of 4 to 7 $km\,s^{-1}$, and S-waves from 2 to 5 $km\,s^{-1}$. P-waves get progressively further ahead of the S-waves as they travel through Earth's crust. The time between the arrival of P-waves and S-waves is measured with a device called a seismometer, which can be used to calculate the distance to the source of the earthquake.

Seismometers and ocean sensors provide early warning of earthquakes and tsunamis to help save lives. Early warning is needed as tsunamis travel at about 700 km h^{-1} in the deep ocean. The National Oceanic and Atmospheric Administration in the United States has recorders in the Pacific Ocean. Once an earthquake is detected, it sends warnings to areas that may be affected. Many nations around the Indian Ocean agreed to the construction of the Indian Ocean Tsunami Warning System, which became active in 2006. It consists of 25 seismographic stations and various floating sensors. Australia, Indonesia and India are responsible for leading the tsunami warning system in the area.

FIGURE 1 Earthquakes can produce devastating tsunamis.

Apply your understanding

1 **Compare** the speed of seismic waves from an earthquake with those from a tsunami. (3 marks)

2 **Calculate** the time interval between a P-wave travelling at 5 km s^{-1} and an S-wave travelling at 3 km s^{-1} over a distance of 600 km. (5 marks)

3 "We can't stop earthquakes, so we should not bother monitoring them." **Propose** two arguments supporting this claim and two counter-arguments. (4 marks)

Skill drill

Exploring the detection of P- and S-waves

Science inquiry skills: Processing and analysing data (Lesson 1.7)

Earthquakes produce P-waves, which are longitudinal waves, and S-waves, which are transverse waves. Both are formed at the quake site and radiate outwards through Earth's crust, where they are detected by seismic stations around the world. Because P-waves travel faster than S-waves, they are detected first. The time delay between P- and S-waves can be used to determine how far away the earthquake occurred from each seismic station.

Figure 2 shows the relationship between arrival times and distance from the epicentre of the earthquake. S–P time is the time difference between the arrival of P-waves and the arrival of S-waves. Table 2 shows the time of detection of P- and S-waves at three seismic stations for a devastating earthquake.

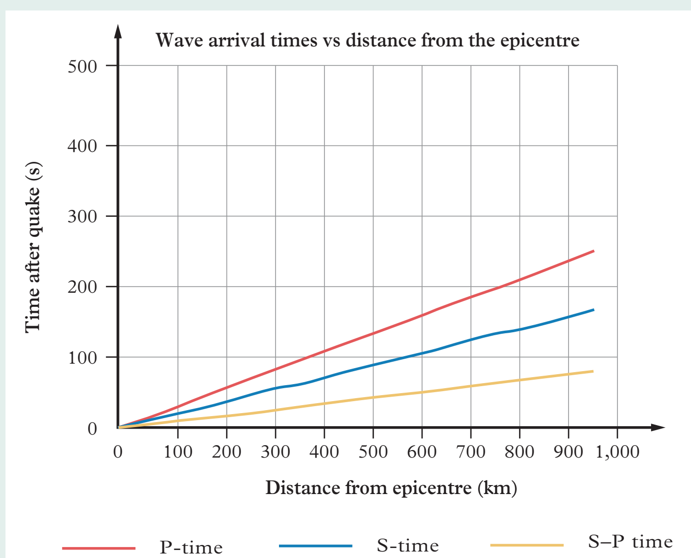


FIGURE 2 Graph of wave arrival times versus distance from the epicentre

TABLE 2 Wave arrival data for seismic stations

Station	Arrival time of P-waves	Arrival time of S-waves	S–P time (s)	Distance from epicentre (km)
A	07:20:15	07:21:40		
B	07:19:05	07:19:50		
C	07:19:35	07:20:35		

Practise your skills

1 **Calculate** the S–P time for each seismic station and **determine** the distance from each seismic station to the epicentre of the earthquake. (3 marks)

2 **Determine** how long after the earthquake P- and S-waves would be detected at a seismic station 1,500 km from the epicentre. (3 marks)

How are waves reflected in one dimension?

What happens when a wave strikes a barrier and bounces off, or strikes a boundary between one medium and another? We can first consider waves in one dimension, where the waves are propagated in a single line. Waves and springs can be used to investigate this principle. For example, what happens when a pulse sent down a single spring reaches the other end?

A wave as it approaches the other end of the spring is called an **incident wave** (or pulse). When it reaches the end, it changes direction and moves back towards the source of the disturbance. This wave is called the **reflected pulse** and the process is called **reflection**.

incident wave
an approaching wave

reflected pulse
the wave being reflected; also known as the reflected wave

reflection
the process by which incident waves at a boundary change direction, returning into the same medium

How are pulses reflected from an end?

How the pulse is reflected depends on whether the spring has a **fixed end** or a **free end**.

Reflection from a fixed end

When a spring or a rope is laid on the floor and someone presses the end to the ground, this is called a fixed end (or boundary). A **boundary** is also a change in the media, such as between springs of different weights.

When a pulse (the incident wave) is sent down the spring to a fixed end, the pulse is reflected and comes back along the spring. The returning pulse has approximately the same amplitude as the incident wave (Figure 3). Some energy will inevitably be lost, so it cannot be exactly the same amplitude. The reflected pulse is said to be phase inverted, half a wavelength out of phase, or 180° out of phase, with the incident pulse. There are a lot of different terms to describe it, but "inverted" is common. The speed of the reflected pulse and the incident pulse will be the same, as the medium has not changed.

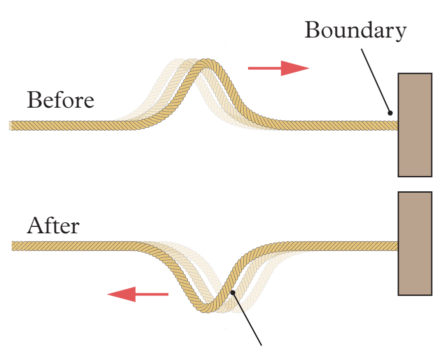


FIGURE 3 Reflection from a fixed end

fixed end
a boundary condition where the medium at a boundary is fixed in place so it cannot move

free end
a boundary condition where the medium at the boundary is free to move

boundary
a change in the media, such as between springs of different weights, or an interface between two different materials; e.g. air and glass; deep water and shallow water; light and heavy springs

Reflection from free ends

Reflection can also occur if the spring has a free end (not fixed to a wall or the floor). When reflection occurs from a free end, the pulse comes back on the same side as the incident pulse (Figure 4). A pulse reflects from a free end with no phase change. As with reflection from fixed ends, the amplitude only decreases slightly.

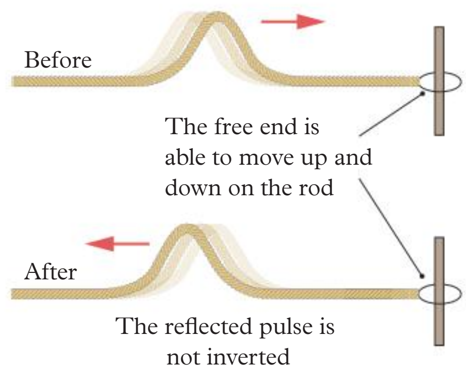


FIGURE 4 Reflection from free ends

Challenge

Double explosions

A boat catches fire, and the skipper jumps overboard and swims away. The skipper hears an explosion while underwater. He lifts his head out of the water and hears another explosion. Bystanders say there was only one explosion, but the skipper says there were two. Who is correct? **Explain**. (3 marks)

FIGURE 5 Is it possible to hear two explosions?

transmitted pulse the pulse that has passed through a boundary between one medium and another

transmission the passage of a wave through a boundary between one medium and another

How are pulses reflected and transmitted at boundaries?

We will now consider a wave that meets a boundary between two different springs. When a wave passes through the boundary into the new medium, it becomes a **transmitted pulse**. This process is called **transmission** (from the Latin “trans-” = “across” + “mittere” = “send”). Heavy (more dense) and light (less dense) springs are a good way to demonstrate this (Figure 6).

In diagrams, springs can be represented using thick and thin lines for heavy and light springs, respectively (Figure 7).

FIGURE 6 Heavy spring (left) and a Slinky (right) side by side

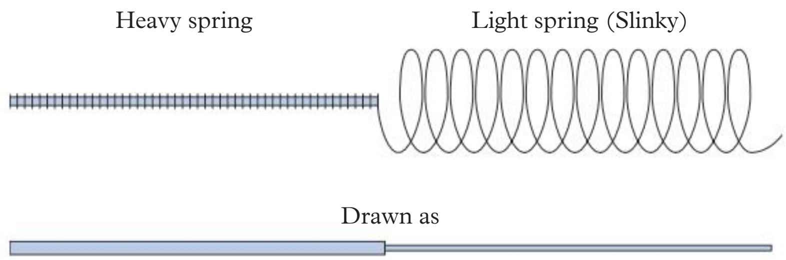


FIGURE 7 Heavy springs are drawn with a thick line and light springs (Slinky) are drawn as a thin line.

Lighter to heavier springs

A pulse that travels from a lighter spring to a heavier spring is shown in Figure 8. When the pulse meets the boundary or join of the two springs, some of the pulse is transmitted and continues on into the more dense spring, and some of the pulse is reflected. At this point, the transmitted pulse is upright, in phase or on the same side of the spring as the incident pulse, i.e. it is not inverted. The reflected pulse is upside-down or out of phase, i.e. it is inverted. As far as the reflected pulse is concerned, the boundary is behaving like a fixed end.

Since the pulse has broken up, the amplitudes (energy) of both the reflected and transmitted pulses are smaller than the incident pulse. The amplitudes of both reflected and transmitted pulses are determined by the relative densities of the two media. If the second medium is much heavier, the transmitted pulse will be small and the reflected pulse will be large. The more dense the medium, the smaller the amplitude.

The velocity of the transmitted pulse depends on the medium but will be lower than that of the incident or reflected pulses. However, the velocity of the reflected pulse will be the same as that of the incident pulse as the pulses are travelling in the same medium.

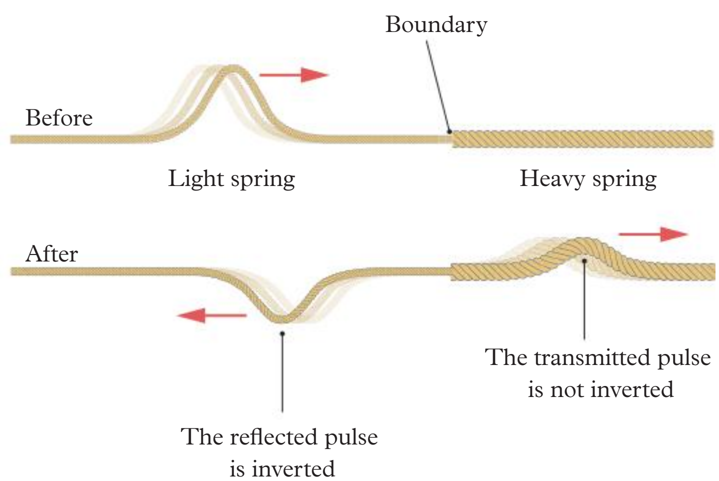


FIGURE 8 Waves going from a light spring to a heavy spring

Heavier to lighter springs

Figure 9 shows a pulse that travels from a heavier spring to a lighter spring. Both reflection and transmission occur in this scenario. The transmitted and reflected pulses will be seen on the same side of the spring as the incident pulse (in phase with the incident pulse). They are not inverted. The boundary behaves like a free end for the reflected pulse.

In general, when waves go from a less dense to a more dense medium, the reflected pulse will be

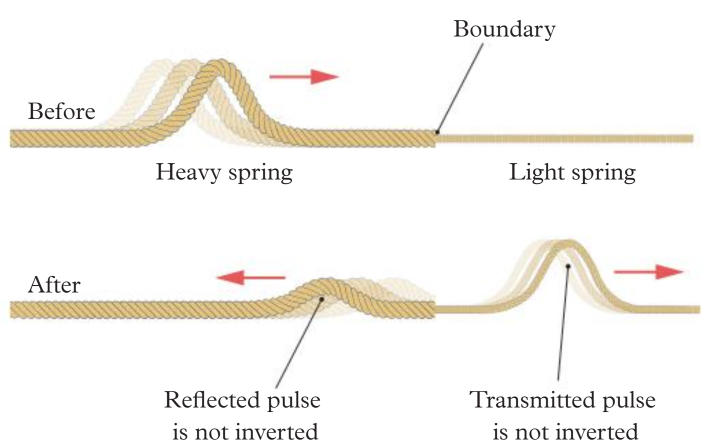


FIGURE 9 Waves going from a heavy spring to a light spring

out of phase and the transmitted pulse will be in phase. When waves go from a more dense medium to a less dense medium, the reflected and transmitted pulses will both be in phase. This is summarised in Table 3.

TABLE 3 The phase relationships between reflected and transmitted pulses, with respect to the incident pulse when it meets various boundaries

Boundary	Reflected pulse	Transmitted pulse
Fixed end	inverted	–
Free end	not inverted	–
Light medium to heavy medium	inverted	not inverted
Heavy medium to light medium	not inverted	not inverted

How are waves reflected in two dimensions?

normal
a line perpendicular to a surface, barrier or boundary

angle of incidence
the angle between the normal and the direction of propagation of an incident wave

angle of reflection
the angle between the normal and the direction of propagation of a reflected wave

Reflection also occurs for waves in two dimensions, such as water waves striking a barrier or light waves striking a reflective surface, such as a mirror. This means that waves are propagated in two dimensions (across a surface rather than in a single line). Figure 10 shows wave crests in a ripple tank entering from the bottom, striking the wooden barrier and reflecting to the left.

Diagrams for two-dimensional reflection are more complicated as there are two lines you need to be concerned with:

- Direction of propagation (direction of energy transfer)
- Wavefronts (the line of crests perpendicular to direction of propagation)

There are three angles to worry about too:

- The **normal** (right angle to the surface of the barrier)
- **Angle of incidence** (angle between the incoming direction of propagation and the normal)
- **Angle of reflection** (angle between the outgoing direction of propagation and the normal)

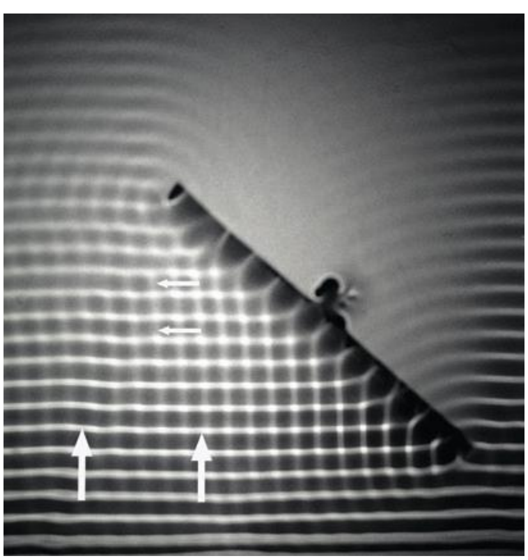


FIGURE 10 Straight wavefronts approach from the bottom and are reflected to the left from a barrier in a ripple tank.

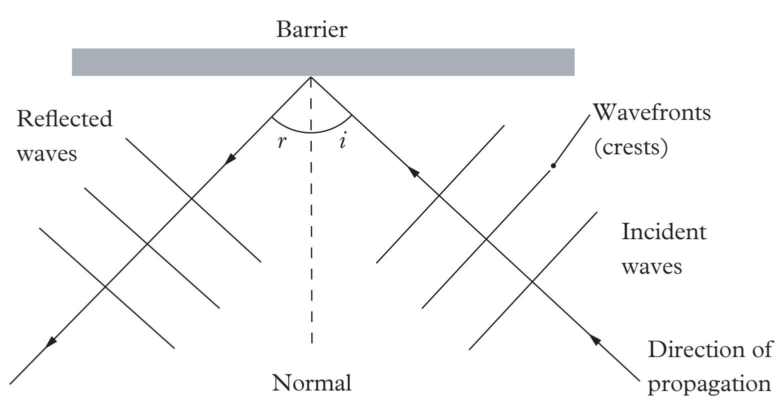


FIGURE 11 When a straight wave is reflected, angle *i* equals angle *r*.

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What we find is that the angle of incidence ($\angle i$) is equal to the angle of reflection ($\angle r$). This is the **law of reflection**:

$$\angle i = \angle r$$

It is true for water waves and for electromagnetic waves, using the wave model for light.

law of reflection
the angle of incidence equals the angle of reflection; $\angle i = \angle r$

Check your learning 12.3

Check your learning 12.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** a fixed end and a free end for a wave travelling on a spring. (2 marks)

2 **Sketch** and label a diagram to show phase relationships for a travelling wave after free-end and fixed-end reflection. (2 marks)

3 **Sketch** and label a diagram to show phase relationships for the transmitted and reflected waves for a pulse going from
- **a** heavy to light springs (2 marks)
- **b** light to heavy springs. (2 marks)

4 **Describe** the change of speed for a pulse going from
- **a** a light to a heavy spring (1 mark)
- **b** a heavy to a light spring. (1 mark)

5 **Explain** whether the frequency of a travelling wave changes at a boundary when it is
- **a** reflected (1 mark)
- **b** transmitted. (1 mark)

6 **Identify** the relationship between the angle of incidence and angle of reflection for a wave at a boundary. (1 mark)

Analytical processes

7 **Contrast** reflection and transmission. (2 marks)

8 **Clarify** what is meant by “phase change on reflection”. (3 marks)

9 For water waves in two dimensions, **describe** how the direction of propagation relates to the wavefront. (1 mark)

10 A pulse seems to increase speed when it is going from one spring to another. **Apply** your understanding of speed, frequency and wavelength to **deduce** whether the pulse would be going from a light to a heavy spring, or the reverse. (2 marks)

11 A reflected wave from a fixed boundary will have less energy than before it was reflected. **Analyse** this situation and **explain** with justification how this affects the reflected pulse’s wavelength, frequency, speed and amplitude. (4 marks)

Knowledge utilisation

12 Pulses of similar amplitude are sent down from either end of a stretched spring. **Propose** how you could identify whether the pulses passed through each other and went to opposite ends, or if they just reflected off each other in the middle and returned to the end they started at. (3 marks)

13 A student tried to send a wave down a stretched spring on the floor but found it hard because the floor was carpeted. When the student tried again on a smooth vinyl floor, it was much easier to produce waves. **Assess** the differences in the floor surfaces and **propose** why this would affect the wave formation. (3 marks)

Practical

Lesson 12.4
Longitudinal and transverse waves on springs

Learning intentions and success criteria

Video demonstration

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Lesson 12.5
Superposition of waves

Key ideas

→ When simple waves superpose, the resulting wave is the algebraic sum of the displacements of the waves.

→ Destructive interference is when no wave or a smaller wave is produced at the intersection between two pulses.

→ Constructive interference is when a larger wave is produced at the intersection between two pulses.

→ Standing waves have stationary oscillation patterns due to the superposition of waves.

Learning intentions and success criteria

What is interference?

There are many instances where one wave meets another. These situations can be natural or artificially produced. What happens when waves produced by two passing boats in the ocean cross over one another? Do they cancel each other out, resulting in the elimination of both waves? The intersection of two waves can be seen by producing pulses in a spring, one from each end.

In Figure 1, pulses are seen to add together when they pass over each other (superpose), producing a much larger, or smaller or differently shaped wave. The type of resulting wave depends on whether the pulses were produced on the same side or on opposite sides of the spring. However, once they have passed, the pulses continue as though they had not met.

Figure 1 also shows the resulting pattern produced when two pulses intersect. If they are produced on opposite sides of the spring, **destructive interference** occurs – this produces a smaller wave or no wave at all at that instant. If the pulses are produced on the same side of the spring, **constructive interference** occurs – this produces a supercrest.

destructive interference
the interference of two or more waves superposing to produce a resultant wave with reduced amplitude

constructive interference
the interference of two or more waves superposing to produce a resultant wave with increased amplitude

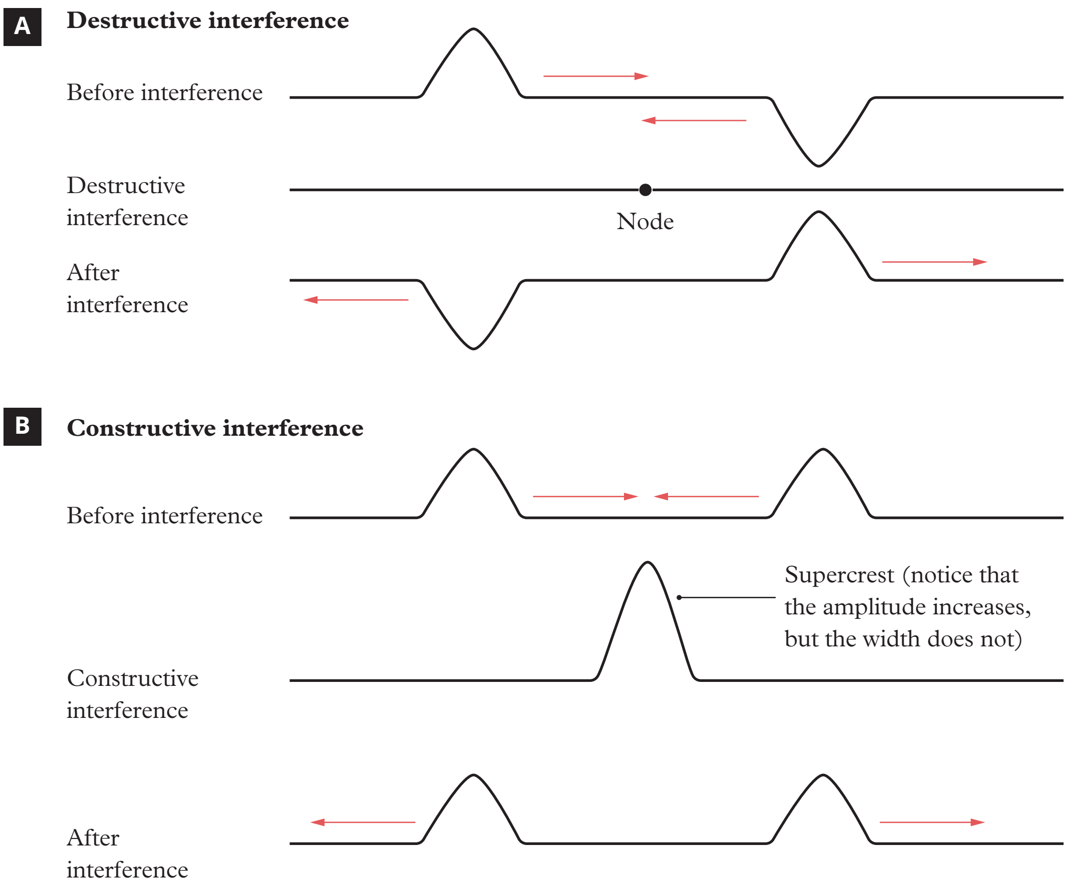


FIGURE 1 Superposition of simple waves may cause (A) destructive or (B) constructive interference.

Destructive interference in **simple waves** will appear as smaller amplitude (springs), smaller wave height (water waves), or quieter (sound waves). For light (Module 14) it will appear darker.

Constructive interference in simple waves will appear as larger amplitude (springs), larger wave height (water waves), louder (sound waves), or brighter (light waves).

simple wave
a wave that forms a strictly periodic pattern with one wavelength and one wave period and propagating in one direction, unlike real waves which are irregular and composites of simple waves

TABLE 1 Summary of constructive and destructive interference

Wave type	Constructive interference	Destructive interference
Spring	larger amplitude	smaller amplitude
Light	brighter	darker
Water	large height	small height
Sound	louder	quieter

This process is explained by the principle of **superposition**. The resulting wave can be obtained by adding the displacements of the pulses from the equilibrium positions at several points (Figure 2).

superposition
when two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves

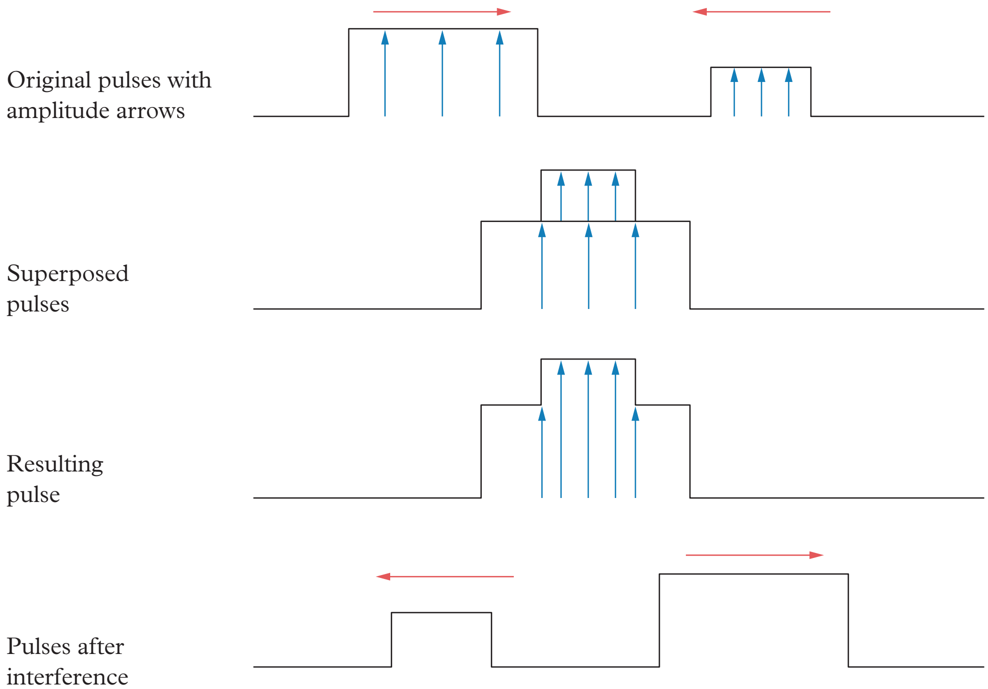


FIGURE 2 Superposition of two pulses

Worked example 12.5A

Representing the superposition of two superposing pulses

Construct the wave pattern produced when each of the two pulses shown in Figure 3 progresses five squares and they overlap. (1 mark)

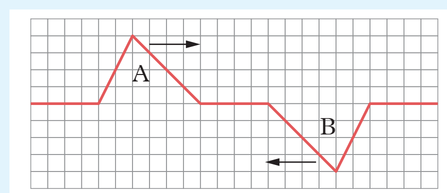
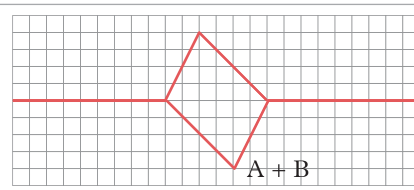
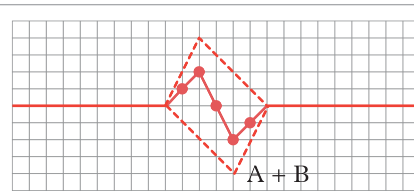


FIGURE 3 Two pulses, A and B

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Construct" means to display information in a diagrammatic form. We need to use the principle of superposition. The question is worth 1 mark so we must apply the principle of superposition and draw the wave pattern.
Step 2: Recall the principle of superposition.	The resulting wave is obtained by adding the displacements of pulse A and pulse B, from the equilibrium positions, at several points.
Step 3: The pulses have progressed five squares, so shift the original pulses in their direction of propagation by five squares.	
Step 4: Add the displacements of pulse A and pulse B at each square where the two waves overlap. This produces the wave shown by the solid line.	 (1 mark)

Your turn

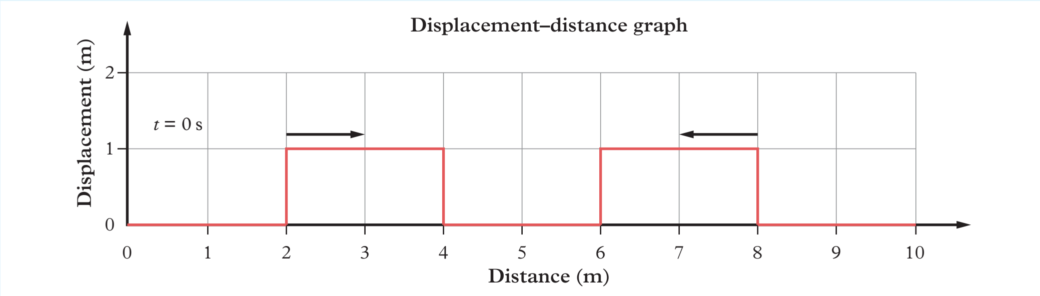


FIGURE 4 Displacement–distance graph

A square wave is travelling at 0.5 m s^{-1} (Figure 4). **Construct** the wave pattern produced when

a each of the two pulses progresses one and a half squares (1 mark)

b 4 seconds have passed (i.e. $t = 4$ s). (1 mark)

What are standing waves?

If a series of waves of the same amplitude and frequency are created from each end of the same spring of the same amplitude, a stationary wave or **standing wave** is created. This occurs because of the continued cancellations and additions of the waves as they travel along the spring and pass through each other. The result is a wave that looks like it is standing still.

When the first crests meet, they produce a pulse of twice the amplitude. At another position later (a quarter of a period), the pulses have moved so the crest of one is interacting with the trough of another (destructive interference), producing a point of zero displacement called a **node**. The displacement remains at zero at the node through the whole period of the wave. The node sits at the equilibrium position.

Another quarter of a period later, each pulse has moved another quarter of a wavelength and the two crests and two troughs again meet, producing supercrests and supertroughs called **antinodes**. These points have the furthest displacement from the equilibrium position. The characteristic standing wave pattern is shown in Figure 5.

standing wave
wave with stationary vibration patterns formed due to the superposition of waves with particular frequencies

node
point in a medium that is not displaced as a wave is propagated through it

antinode
the point where there is maximum amplitude of vibration; further displacement from equilibrium

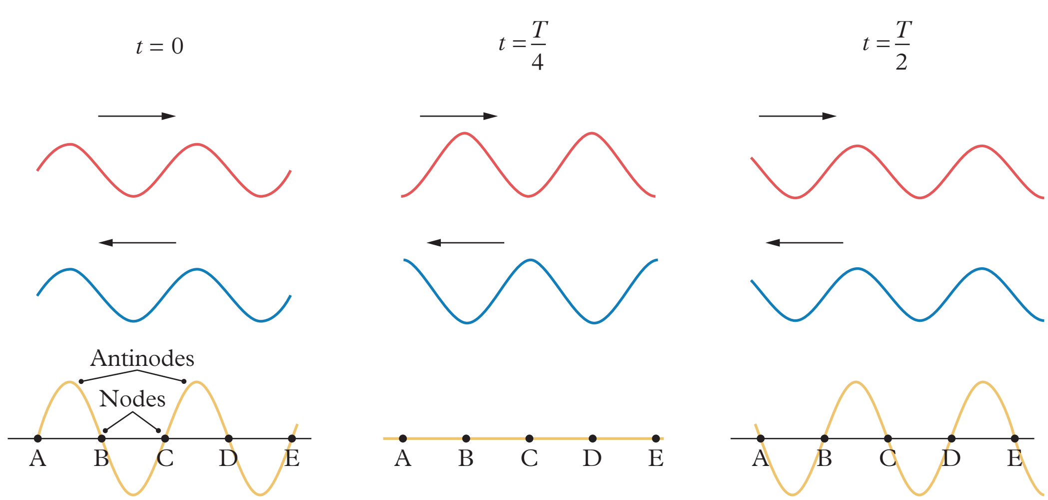


FIGURE 5 Two identical waves (red and blue) are sent along a spring from either end. The three yellow curves show the superposition of the waves when they first meet and overlap ($t = 0$), and then after they have progressed $\frac{1}{4}$ wavelength ($t = \frac{1}{4}T$), and $\frac{1}{2}$ wavelength ($t = \frac{1}{2}T$). The points A, B, C, D, E are nodes (which sit at the equilibrium position), and in between them are the antinodes (supercrests and supertroughs with the largest amplitudes).

The distance between two successive nodes of a standing wave is half of a wavelength. Figure 6 shows a standing wave produced by the continual generation and reflection of waves off a point fixed (with your finger) to the floor. Oscillation only occurs between the dotted and solid lines. Waves are sent down from the left and reflected back to the left. Because the end is fixed to the floor, there is also phase inversion of the returning wave. Parts of the wave stay stationary (nodes) but other parts flip between maximum amplitudes on either side of the spring (antinodes). The wavelength of the standing wave is the distance between crests or troughs on either the black line or the dotted line. Be careful with this. It is easy to get wrong.

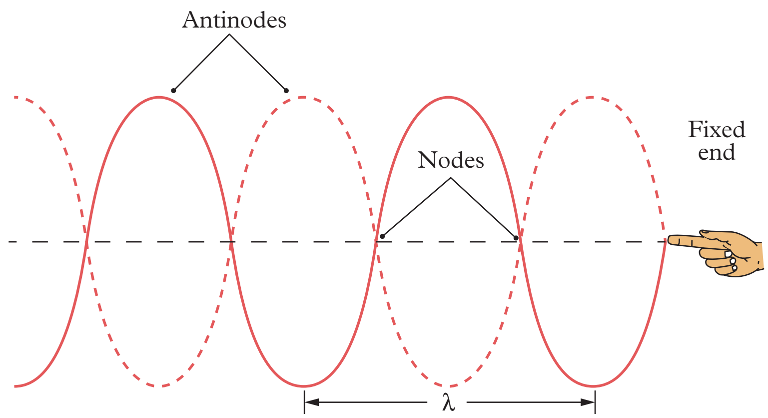


FIGURE 6 Standing waves formed by reflection off a fixed end. The wavelength is the distance between crests or troughs of either the solid line or the dotted line.

Real-world physics

Wave motion in sports equipment

When a ball is hit with a tennis racquet, the racquet rings out like a guitar string. This because a standing wave forms with nodes and antinodes in various places between the ends. One of the simplest standing waves is one in which nodes form about 10 cm from the ends. This is shown on the diagram in Figure 7. The node on the strings is called the "string node". This is usually called the "sweet spot" and helps tennis players have better control of the ball. The other node is called the "handle node". Knowledge of these points helps players develop their game.

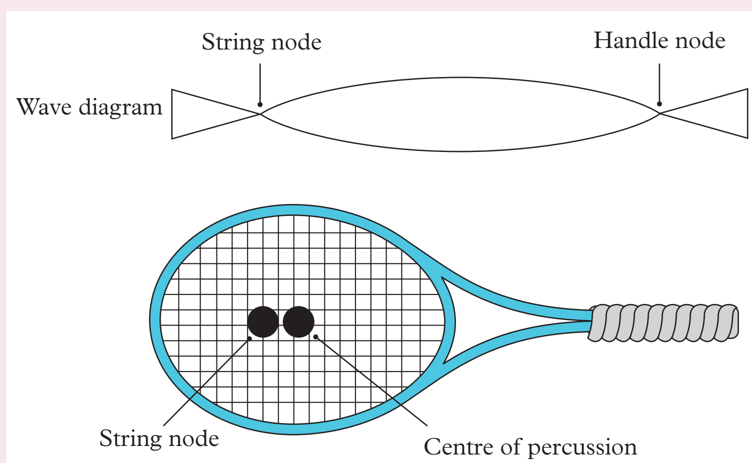


FIGURE 7 The string node of the standing wave is just left of the centre of the strings.

Apply your understanding

1 A tennis racquet is 62 cm long and the vibration nodes are 10 cm from each end. **Calculate** the distance between nodes. (1 mark)

2 **Determine** the wavelength of the standing wave based on these two nodes. (2 marks)

3 The standing wave for the racquet has a velocity of 345 m s^{-1}. **Calculate** the frequency at which the racquet vibrates. (2 marks)

Check your learning 12.5

Check your learning 12.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** superposition in the context of transverse waves. (3 marks)

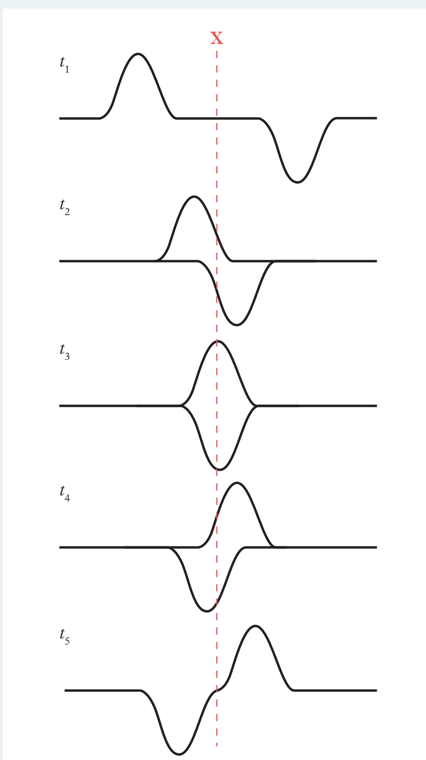
2 **Define** the terms "node" and "antinode". (2 marks)

3 **Recall** the conditions that are necessary for standing waves to form. (2 marks)

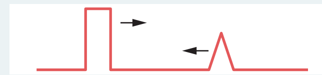
Analytical processes

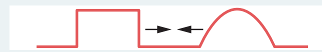
4 **Distinguish** between constructive and destructive interference. (2 marks)

5 Two identical waves are produced on either end of a rope, as shown. **Deduce** what you would notice about point X as the waves move through. (2 marks)

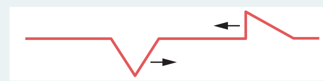


6 Use the principle of superposition to **determine** the resulting waveform when the pulses shown are superposed on each other.

a  (1 mark)

b  (1 mark)

c  (1 mark)

d  (1 mark)

Knowledge utilisation

7 Two triangular pulses are travelling along a spring at $3\,\text{cm}\,\text{s}^{-1}$, approaching each other from opposite directions. Each pulse has a wavelength of 12 cm and an amplitude of 4 cm. The moment when both pulses just touch is considered to be $t = 0$ s.

a **Interpret** the data and plot the shape of the wave at $t = 0$. (1 mark)

b **Deduce** and plot the shape at $t = 0.5$ s. (1 mark)

c **Deduce** and plot the shape at $t = 1$ s. (1 mark)

d **Justify** with evidence whether this is an example of constructive or destructive interference. (2 marks)

Lesson 12.6
Refraction and diffraction of waves

Key ideas

→ Refraction is the change in the direction of a wave when it travels from one medium to another.

→ Diffraction is the bending and spreading of waves as they pass through a slit or around objects.

→ Refraction and diffraction are characteristic of both mechanical and electromagnetic waves.

Learning intentions and success criteria

What is refraction?

Refraction and diffraction are two properties of waves commonly seen in nature. They both occur in two dimensions so cannot be shown on a spring. They need a medium and are best demonstrated in water and air.

refraction
the process in which incident waves at a boundary change direction and speed when passing into another medium

Refraction is the changing in direction and speed of waves as they go from one medium to another. For example, water waves can undergo refraction when they travel from one depth of water to another, as this acts as two different mediums. Another example is light undergoing refraction when light rays pass from air to water, from air to glass or from glass to water.

The term refraction comes from the Latin for "break", referring to the broken (bent) path waves take as they pass from one medium to another.

Deep to shallow water

When a wave hits the boundary between two depths of water at an angle, it changes direction. Deep and shallow water act as two different media, even though they are the one substance. The speed of waves in shallow water is slower than in deep water, so refraction can occur. Because frequency remains the same after passing from one medium to the other, the wavelength must get smaller – as speed decreases, wavelength must also decrease.

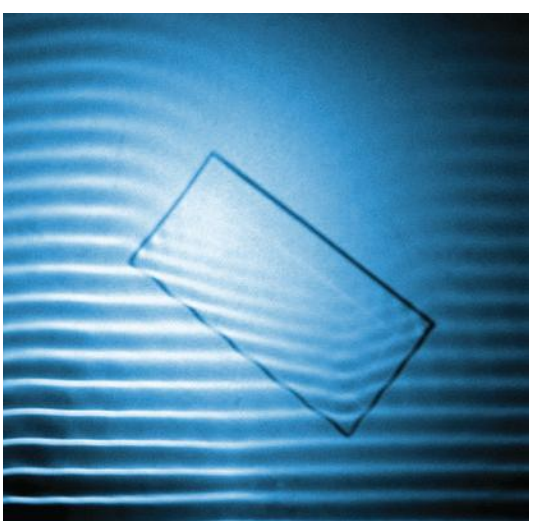


FIGURE 1 Waves going from deep water (bottom) to shallow water (over the glass block) refract.

Figure 1 shows an overhead view of a ripple tank. It has a tray of water of 1 cm depth and a submerged glass block over which the water is 0.4 cm deep. The water waves in deep water are moving from the bottom and strike the shallow water above the glass block. Note that the waves are bent. This is because their reduced velocity causes them to lag behind the deep water waves. The wavelength is also reduced. This change in depth has caused bending, which is called refraction.

Light also undergoes refraction as it passes from one medium to another. For the wave model of light, you can picture it having a high speed in air and a slow speed, smaller angle and shorter wavelength in all other substances, such as water, glass and plastic. Its frequency doesn't change upon refraction. You will learn more about this in Module 14.

Challenge

Is this refraction?

Light travelling from distant stars generally travels in straight lines. One hundred years ago, Einstein predicted that light from distant stars could be bent by a strong gravitation field, such as when it passes massive stars, galaxies or black holes. This is known as "gravitational lensing" and has been confirmed numerous times. **Deduce** whether it is correct to call this an example of refraction, as the light is bent. **Draw a conclusion**, with evidence, about whether it meets the full definition of refraction. (3 marks)

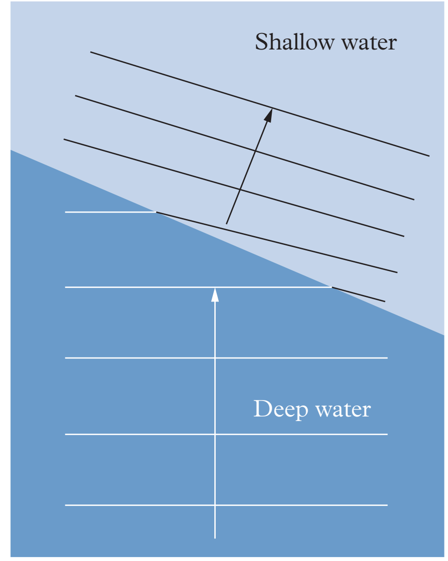


FIGURE 2 Refraction is the change in direction and speed of incident waves at a boundary when passing into another medium.

What is diffraction?

Another property of waves is often observed when waves from the ocean enter an inlet. These waves form a circular pattern. Figure 3 shows an example of **diffraction** of water waves as they pass through gaps in the rocks.

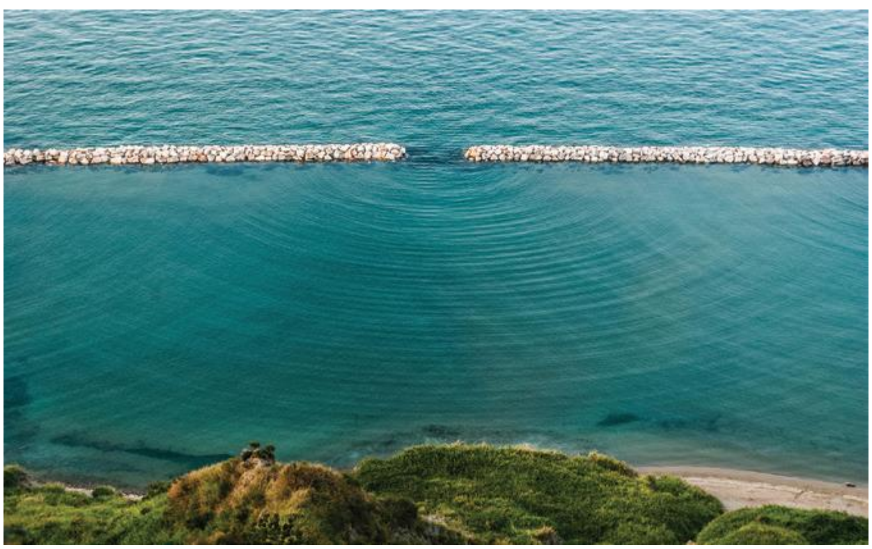


FIGURE 3 Diffraction of ocean waves in the sea seen along the coastline near Pesaro, Italy

This diffraction can also be seen in a ripple tank by placing two large blocks of glass or metal obstacles to produce a gap (also called an aperture) in front of the straight waves. As the waves pass through the gap, they produce a circular wave (Figure 4). This bending of waves as they pass through a gap is called diffraction, from the Latin "diffractus" meaning "to break apart". Similar bending occurs if waves pass around the end of an obstacle.

Study tip

Students find the "5-S" rule useful here: shallow (depth), short (wavelength), slow (speed), small (angle), same (frequency) all go together.

diffraction
a phenomenon in which, if a wavefront is partially blocked by an obstacle, the unblocked part of the wavefront diffracts (bends) into the region behind the obstacle

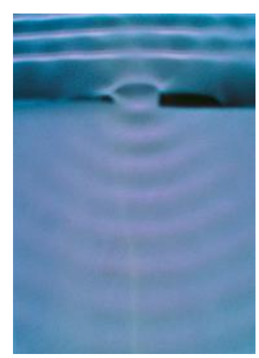


FIGURE 4 Straight waves passing through a small opening in a barrier in a ripple tank are diffracted.

Changing the slit width

If the aperture (the opening/gap) is small compared with the wavelength of the waves, the shape of the waves passing through the aperture will be more curved. If the aperture is large, the resulting waves will be straighter except for the edges. This can be seen in a ripple tank by changing the position of the obstacles making up the gap (Figure 5).

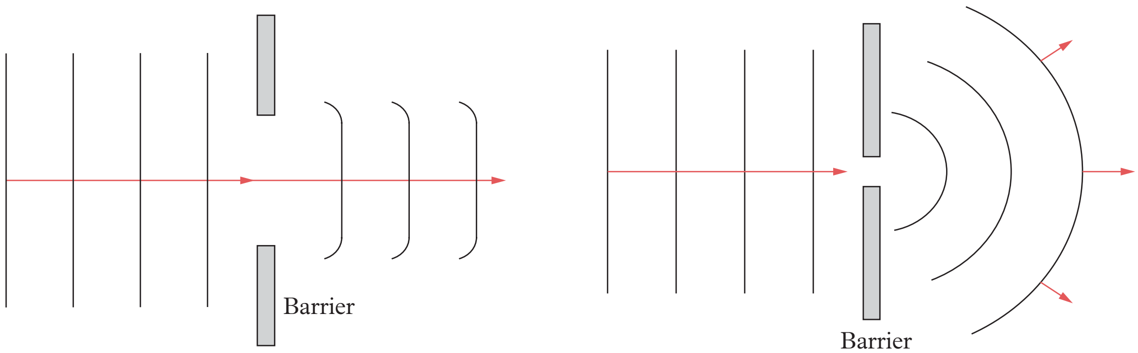


FIGURE 5 Diffraction is more noticeable when the size of the gap is similar to the wavelength of the waves. A small gap produces more diffraction than a large gap.

Changing the wavelength

Changing the wavelength of the waves also affects the diffraction pattern. Diffraction is more noticeable if a wavelength is equal to or greater than the opening. It is the relative difference in the size of the wavelength and the size of the gap that is important (Figure 6).

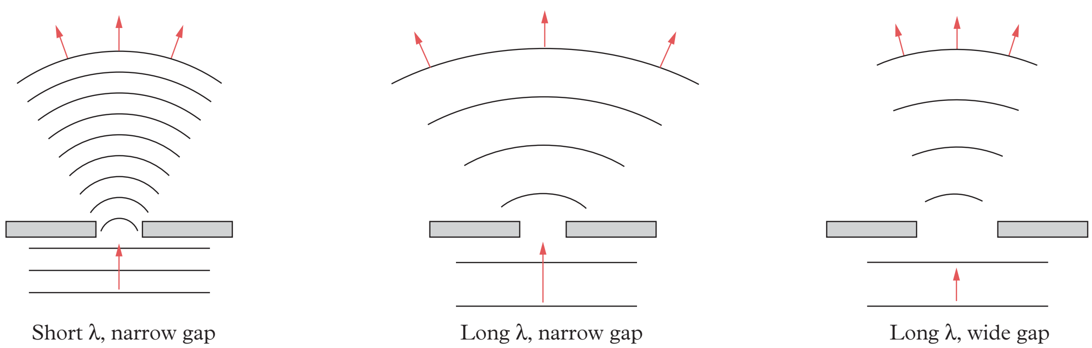


FIGURE 6 Diffraction is greater when the wavelength is large and the gap narrow.

A diffraction pattern can be observed in the ocean around boats, large rocks and buoys. The amount of diffraction depends on the size of the object compared with the wavelength. If the object is large compared with the wavelength, a significant diffraction pattern occurs around the edges of the object, producing a shadow zone. There is no change to the wavelength as the wave passes through the gap, which means the velocity does not change either.

FIGURE 7 A speedboat acts as a barrier to produce a diffraction pattern in its wake.

Describing diffraction

The syllabus requires you to "describe" diffraction. That means give a definition and some additional information. You would define it by talking about the bending of waves around an obstacle or through a gap in a barrier. The extra information would be about the effect of the gap or barrier width, or about the change of wavelength. You do not have to go into detail about how diffraction works. That would be to "explain" diffraction, and you do not have to do that. Practise writing out your own description of diffraction.

Check your learning 12.6

Check your learning 12.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** what changes the amount of refraction of a water wave. (2 marks)

2 **Explain** whether direction, speed, frequency or wavelength change when refraction occurs. (3 marks)

3 **Recall** the conditions under which diffraction occurs. (1 mark)

4 **Recall** which of speed, frequency or wavelength changes for diffraction. (2 marks)

5 **Explain** whether a 4 cm gap or a 2 cm gap in a barrier would produce the larger diffraction with a 3 cm wavelength water wave. (2 marks)

6 **Sketch** a water wave diffracting through a gap between two rocks. (1 mark)

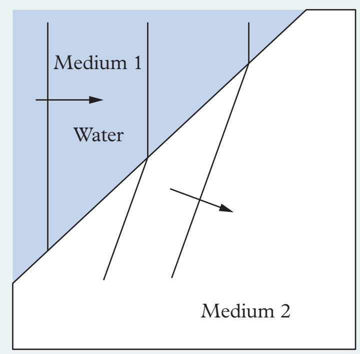
7 **Explain** what the terms short, slow, small, shallow and same refer to in the 5-S rule. See Study tip in Lesson 12.6. (1 mark)

8 **Summarise** the conditions under which refraction occurs. (4 marks)

Analytical processes

9 Water waves are seen to strike a 75 cm gap in some rocks at a speed of 2.5 m s^{-1} and undergo diffraction. **Determine** the frequency of these waves if the wavelength equals the width of the gap. (2 marks)

10 A water wave refracts at a boundary where it enters water of different depth.



Deduce whether medium 2 is shallower or deeper than medium 1 (the water on the left) and **justify** your response. (2 marks)

Knowledge utilisation

11 AM radio waves have wavelength of about 400 m, whereas the wavelength of FM radio waves is about 3 m. **Propose** why AM radio waves can be heard behind hills whereas FM cannot. (3 marks)

12 When a wave refracts, there is no change in frequency. Use the wave equation to **predict** the velocity of a refracted light wave if its incident velocity is 3×10^8 m s^{-1}, its wavelength is 450 nm, and its refracted wavelength is 600 nm (3 s.f.). (2 marks)

MODULE 12

Lesson 12.7
Review: Waves

Summary

12.1
- Mechanical waves transfer energy through a medium.
- The amplitude of a wave indicates its energy.
- In transverse waves, particles move perpendicular to the direction of propagation, whereas in longitudinal waves, they move parallel to the direction of propagation.

12.2
- Waves are characterised by their amplitude, wavelength, crests, troughs and phases.
- Frequency is the number of waves passing through a point per second.
- Period is the time taken for a full wave cycle to occur.
- The velocity of a wave is the product of wavelength and frequency.

12.3
- The speed of a wave changes as it moves from one medium to another.
- Reflection of waves at fixed and free boundaries can result in phase changes.
- When waves undergo reflection and transmission at boundaries between two media, there can be a phase change.
- Two-dimensional waves reflect according to the law of reflection.

12.4
- Practical: Longitudinal and transverse waves on springs

12.5
- When simple waves superpose, the resulting wave is the algebraic sum of the displacements of the waves.
- Destructive interference is when no wave or a smaller wave is produced at the intersection between two pulses.
- Constructive interference is when a larger wave is produced at the intersection between two pulses.
- Standing waves have stationary oscillation patterns due to the superposition of waves.

12.6
- Refraction is the change in the direction of a wave when it travels from one medium to another.
- Diffraction is the bending and spreading of waves as they pass through a slit or around objects.
- Refraction and diffraction are characteristic of both mechanical and electromagnetic waves.

Key formulas

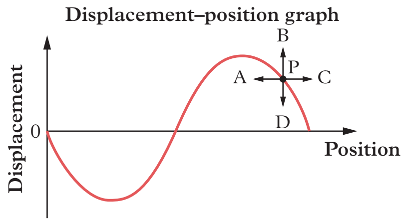
Wave equation	$v = f\lambda$
Period of a wave	$f = \frac{1}{T}$

Review questions 12.7A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 The graph is a displacement–position graph of a transverse wave travelling from left to right. Which arrow represents the direction of the velocity of the particle marked P?

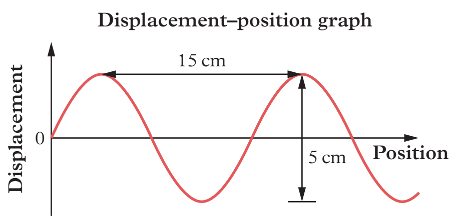


A Arrow A **B** Arrow B
C Arrow C **D** Arrow D

2 Particles of a medium are vibrating in the same direction as energy transport. This is characteristic of which sort of wave?

A Longitudinal **B** Electromagnetic
C Standing **D** Transverse

3 The graph is a displacement–position diagram of a wave.



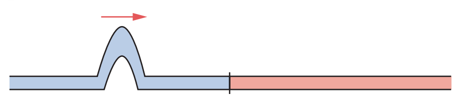
The amplitude of the wave is

A 2.5 cm. **B** 5 cm. **C** 7.5 cm. **D** 15 cm.

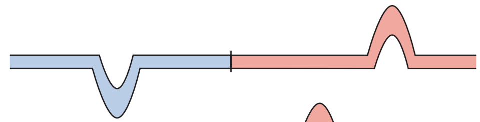
4 A node is a point located along the medium where there is always

A a crest of double height.
B a crest of half height.
C constructive interference.
D destructive interference.

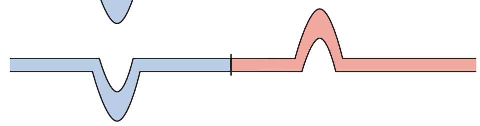
5 A heavy spring and a light spring are joined together as shown in the diagram, but you are not told which is which. A pulse is generated at the end of one spring and travels along towards the boundary. At the boundary, some of the energy is transmitted and some reflected. Which one of the diagrams shows the position and orientation of the pulse shortly afterwards?



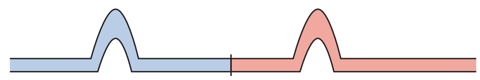
A



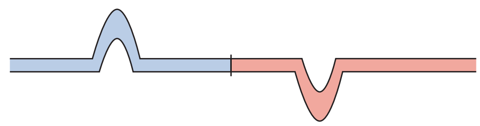
B



C



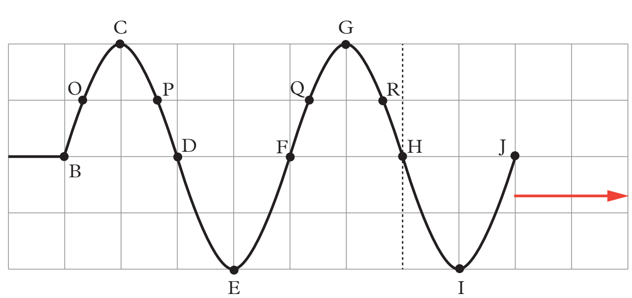
D



6 Which of the following statements about waves is correct?

A Mechanical waves require a medium through which to propagate; electromagnetic waves do not.
B Electromagnetic waves are compression waves; mechanical waves can be either transverse or compression waves.
C The speed of a wave in a medium depends on its frequency.
D When a wave meets a barrier, it leaves a space behind it with no wave motion.

Use the following image to answer questions 7 and 8.



7 The following figure shows a displacement–distance diagram of a wave.

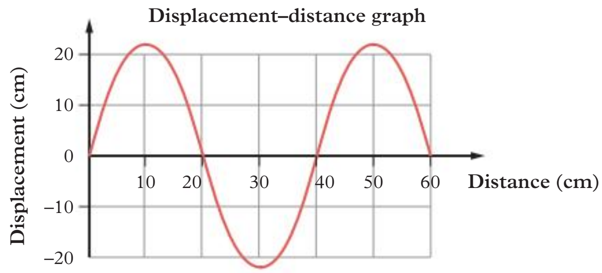
Which of the following represents the wavelength?

A CE **B** BD **C** CG **D** DF

8 Which point is a half-wavelength out of phase with point C?

A P **B** D **C** E **D** G

9 In the displacement–distance graph, the period of the wave is 2 seconds.



Its velocity is

A $10\,cm\,s^{-1}$ **B** $20\,cm\,s^{-1}$

C $40\,cm\,s^{-1}$ **D** $60\,cm\,s^{-1}$

10 Recall which of the following produces standing waves.

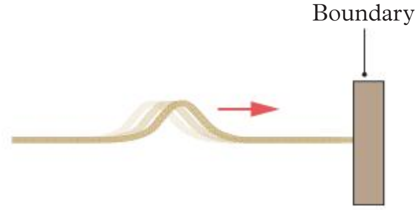
A Identical waves travelling in opposite directions in a medium

B Inverse waves crossing over each other as they pass through a medium

C Superposition of different wave forms in the same medium

D Superposition of identical wave forms in different media

11 Consider the following figure.



Which of the diagrams A–D correctly shows the nature of the wave after reflection?

A

B

C

D

Review questions 12.7B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

12 A Slinky is used in an experiment on wave motion.

a **Explain** what happens to the mass per unit length (metre) of the Slinky when it is stretched. (2 marks)

b **Explain** what happens to the speed of a pulse in the Slinky spring if the spring is stretched. (2 marks)

13 **Explain** the difference between a longitudinal and a transverse wave without using the word "propagation" but explaining it instead. (2 marks)

14 The speed of sound in salt water is $1{,}450\,m\,s^{-1}$, and it is $340\,m\,s^{-1}$ in air. The frequency of the sound being generated by an engine is 550 Hz.

Determine the

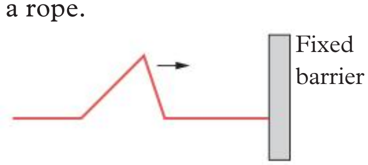
a wavelength of the sound in air (2 marks)

b frequency of the sound in salt water (1 mark)

c wavelength of the sound in salt water. (2 marks)

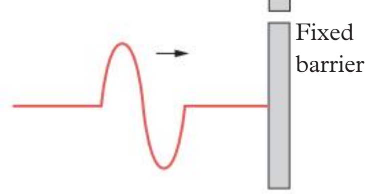
15 **Sketch** diagrams to illustrate the reflected pulses in the four situations shown. Each pulse is created in a rope.

a



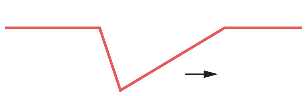
(1 mark)

b



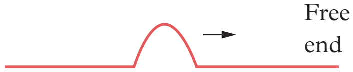
(1 mark)

c



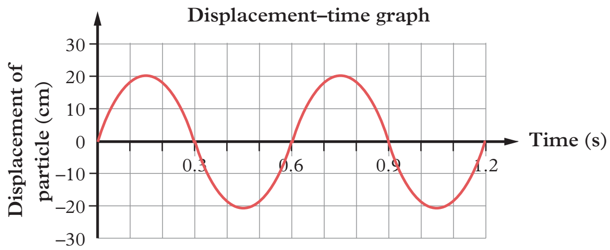
(1 mark)

d



(1 mark)

16 The graph shows the displacement of particles in a rope with time as a wave passes.



Calculate the

a amplitude of the wave (1 mark)

b period of the wave (1 mark)

c frequency of the wave. (2 marks)

17 **Classify** the particular type of wave in which the particles move

a at right angles to the direction of propagation (1 mark)

b in the same direction as the wave is moving. (1 mark)

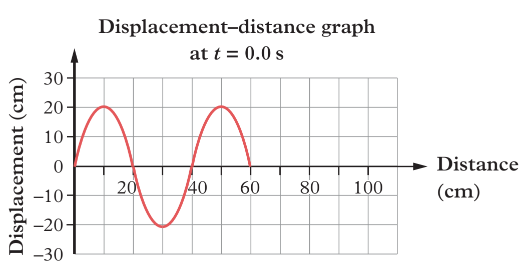
Analytical processes

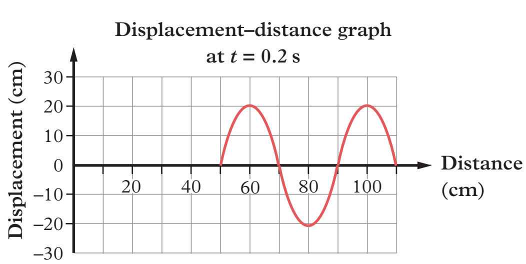
18 **Consider** a dinghy anchored in the ocean that is seen to bob up and down as waves pass.

a **Deduce** what type of waves they are and **explain** your reasoning. (3 marks)

b **Identify** the physical feature of the wave that indicates the energy the wave possesses. (1 mark)

19 The position of a wave at two instants in time is shown.





From these graphs

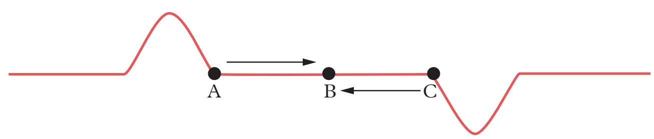
a **identify** the amplitude of the wave (1 mark)

b **determine** the wavelength of the wave (1 mark)

c **calculate** the velocity of the wave. (2 marks)

Use the following information to answer questions 20 and 21.

The figure shows pulses on a spring approaching each other.



20 **Determine** what happens when the two pulses have each moved along by the width of one pulse. Draw a diagram to support your answer. (3 marks)

21 **Determine** what happens as the two pulses cross each other when they have each moved along by three times the width of a pulse. Draw a diagram to support your answer. (3 marks)

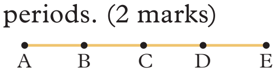
22 The figure shows waves approaching each other on a spring. The points A, B, C, D and E are at intervals of half a wavelength, $\frac{\lambda}{2}$.

a Redraw the diagrams to **deduce** the standing wave pattern that will form as the waves interact

i after 2 periods (2 marks)

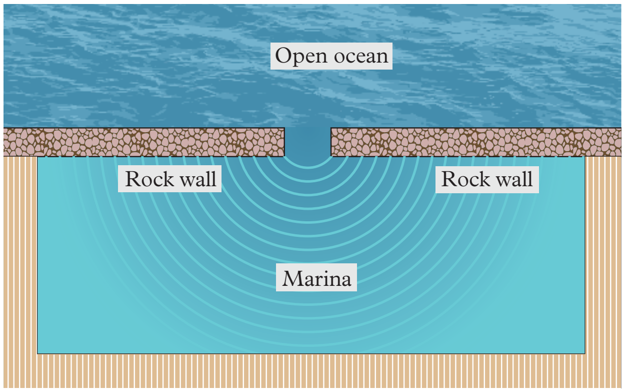
ii after $2\frac{1}{4}$ periods (2 marks)

iii after $2\frac{1}{2}$ periods. (2 marks)



b **Determine** which point or points (A, B, C, D, E) will be a node. **Explain** your reasoning. (3 marks)

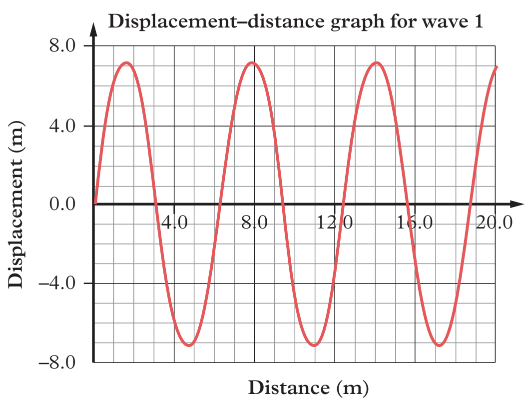
23 The entrance to a marina is between two rock walls.

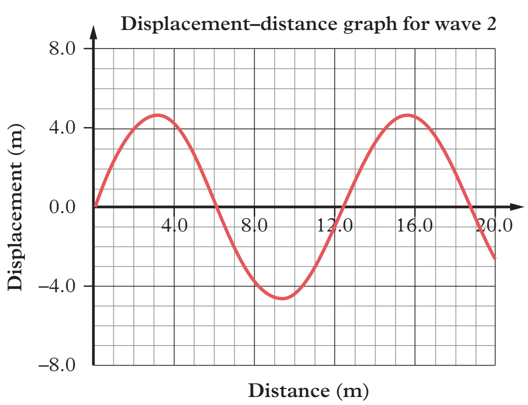


The predominant wave pattern in the ocean outside the marina is shown. Redraw the diagram and show the expected wave pattern inside the marina. **Explain** the pattern you have drawn. (3 marks)

Knowledge utilisation

24 Two continuous transverse waves are sent down from opposite ends of a spring.





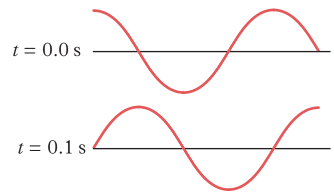
a **Calculate** the maximum amplitude that would be observed when the waves interact in the middle. (2 marks)

b **Calculate** the minimum amplitude that would be observed when the waves interact in the middle. (1 mark)

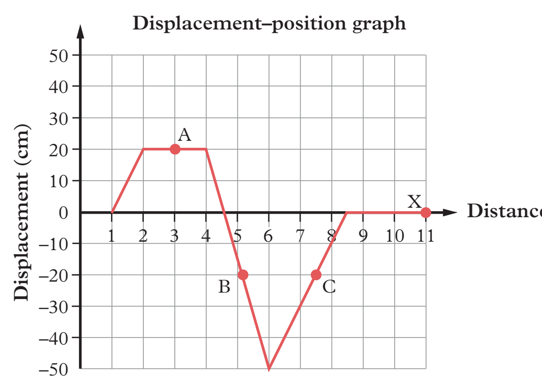
c The experiment was repeated, but this time the middle of the spring was fixed firmly to the floor before the waves were sent down. **Determine** what would be noticed in each half of the spring. (5 marks)

25 Two weekend anglers find that their 4 m boat bobs up and down 2 times in 20 seconds, and exactly 3 wave crests can fit under the boat at any one time. **Determine** the velocity of the waves. **Hypothesise** whether the anglers were catching any fish. (4 marks)

26 The figure shows a wave in the same section of a string at two different times. **Propose** the greatest possible period of the wave and **justify** your response. (2 marks)



27 The graph illustrates a transverse pulse moving to the right along a stretched spring at a speed of $5.0\,\mathrm{m\,s^{-1}}$.



a **Explain** which of the points (A–C) on the spring has the greatest speed at this instant. (3 marks)

b **Calculate** the instantaneous velocity of point C. (1 mark)

c **Sketch** the displacement–time graph and the velocity–time graph for point X on the spring. Take the zero for time at the instant shown in the graph. (2 marks)

d **Propose** why this particular situation is very unlikely. (2 marks)

28 Waves refract when they pass from one medium to another, including water waves moving between bodies of water at different depths. When waves refract, the frequency, *f*, does not change, but the wavelength, λ, and the velocity, *v*, of the wave change. Students took measurements of waves in a ripple tank, as the waves travelled from deep to shallower water. **Calculate** the missing data values. (6 marks)

	Deep water		Shallow water	
f (Hz)	λ (cm)	*v* (cm s^{-1})	λ (cm)	*v* (cm s^{-1})
2	3.0		2.5	
5		10		4
	4.25		3	3

Data drill

Slinky experiments

A student investigates the behaviour of longitudinal and transverse waves on springs in relation to reflection from fixed and free ends, and transmission or reflection at a medium boundary. They used a Slinky as the light spring and a dense wire spring as the heavy spring and sent transverse pulses down them. Their results are summarised in Table 1.

TABLE 1 Results table

Trial	Conditions	Reflection (phase change)	Transmission (phase change)
1	Fixed end	yes	not applicable
2	Free end	no	not applicable
3	Light to heavy	yes	no
4	Heavy to light	no	no

Apply understanding

1 **Identify** the type of variables used in this experiment: continuous or categorical. (1 mark)

2 **Identify** two controlled variables in Trial 3 and Trial 4. (2 marks)

Analyse evidence

3 **Classify** the phase change on reflection, with reference to the change in the type of spring (light/heavy) at the boundary. (2 marks)

4 The Slinky was allowed to hang vertically by the top end and a pulse was sent down. **Identify** which number trial (1, 2, 3, 4) this would be. (2 marks)

Interpret evidence

5 **Determine** whether there is sufficient evidence to conclude that a boundary has no effect on the phase of a transmitted wave. (2 marks)

6 **Justify** the claim that “when a heavy spring is connected to a light spring, the light spring acts as a free end”. (3 marks)

Module 12 checklist: Waves

Quizlet: Revise key terms online to test your understanding

MODULE

13 Sound

Introduction

Opera singers are rumoured to be able to shatter a glass with their voice. This seems unlikely as it has to be an impossibly loud sound, but it can be done with amplified sound from a loudspeaker. Sound is a form of energy that travels from the source to the receiver by means of waves. Sound waves are longitudinal mechanical waves – waves that require a medium for transmission.

Prior knowledge

Prior knowledge quiz

Check your understanding of sound waves before you start.

Subject matter

Science understanding

→ Describe the concepts of fundamental (or first) harmonic and natural frequency.

→ Solve problems involving standing wave formation in pipes open at both ends, closed at one end, and on stretched strings using $L = n\frac{\lambda}{2}$ and $L = (2n - 1)\frac{\lambda}{4}$.

→ Describe the concept of resonance in a mechanical system.

→ Identify that energy is transferred efficiently in resonating systems.

Science as a human endeavour

→ Consider how acoustical engineering can reduce noise pollution by planning structures that absorb sound waves or that do not reflect and amplify sound in an unwanted way.

Science inquiry

→ Investigate fundamental and harmonic wavelengths in pipes.

→ Investigate the speed of sound in air at a specific temperature.

Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 13.2 Fundamental and harmonic wavelengths in pipes

Lesson 13.3 Speed of sound in air using a closed-end pipe over water

Lesson 13.1
Properties of sound waves

Key ideas

→ Sound waves are propagated through oscillation of particles in a medium.
→ The speed of sound depends on the medium through which the sound waves are travelling.

Learning intentions and success criteria

How are sound waves propagated?

You may have noticed that at a school athletics carnival, the starter's pistol releases a puff of white smoke along with the loud "bang". This is so timekeepers 100 m away can start their watches immediately and not have to wait for the sound to arrive. Even though the light signal and the sound travel through air, their speeds are vastly different.

Sound waves are longitudinal waves that produce compressions and rarefactions of the air particles in the direction of propagation – that is, the air particles oscillate parallel to the wave. The amplitude (energy) of the sound waves directly indicates the loudness of the sound.

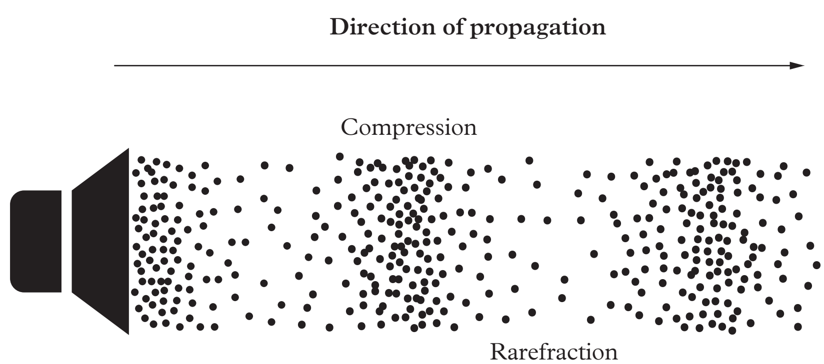


FIGURE 1 Sound waves cause particles to oscillate in the direction of wave propagation. The pattern of propagation includes volumes of increased particle density (compressions) and reduced particle density (rarefactions).

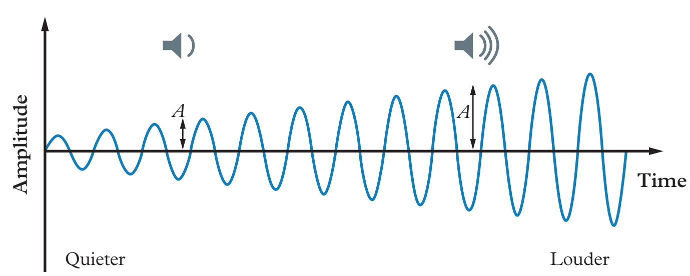


FIGURE 2 Low amplitude sound waves are quieter than high amplitude sound waves.

A medium is required to transmit sound (energy) waves and it is the collision of the particles of the medium that carries the energy. Without a medium such as air, sound cannot propagate, so sound waves do not travel in a vacuum. Space is the closest approximation to a perfect vacuum – which is why space stations have to communicate via radio waves, not sound waves. Radio waves are electromagnetic waves that do not require a medium for their propagation.

As sound is a wave, the properties common to all waves apply to sound. Sound waves can be reflected, refracted, diffracted, and can interfere. The wave equation $v = f\lambda$ used for water waves applies to sound waves too.

What is the speed of sound?

The speed of sound is how quickly sound waves are propagated through a medium. The more rigid the particles in a medium, the faster the sound will travel through it. Remember the kinetic particle model of matter from Unit 1: particles in a solid have less kinetic energy and are held in place, whereas gas particles are more freely moving and are loosely packed. When the particles can collide more frequently, they can pass on energy more easily. In general, this means that sound travels more quickly through solids and liquids than it does through gases. This is shown in Table 1.

TABLE 1 The speed of sound in various media

Medium	v (m s^{-1})
Gases at 0°C	
Air	331
Carbon dioxide	259
Oxygen	316
Helium	965
Hydrogen	1,290
Liquids at 20°C	
Ethanol	1,160
Mercury	1,450
Water, fresh	1,480
Sea water	1,540
Human tissue	1,540
Solids	
Polyethylene	920
Marble	3,810
Glass, Pyrex	5,640
Lead	1,960
Aluminium	5,120
Steel	5,960

Challenge

Underwater sounds

If you put your head under water while having a bath, you can hear sounds from all over the house that you wouldn't normally hear. **Discuss** why. (2 marks)

FIGURE 3 Sound waves can be heard from all around your house if you put your head under water while having a bath.

Challenge

Candle in the wind

Put a lit candle in a room and open a door quickly. **Determine** how long the breeze takes to get to the candle by measuring the distance and the time. **Discuss** whether you think the breeze would travel at the speed of sound in air. (4 marks)

Temperature and speed of sound

In air, particles are loosely connected, and the speed of sound is approximately 343 m s^{-1} at 20°C. The speed of sound varies with atmospheric conditions such as temperature, humidity and air movement. As air temperature rises, the speed of sound increases by about 0.6 m s^{-1} for each degree. This is because the particles have more kinetic energy and can transfer energy in the direction of propagation more easily. At 0°C, sound travels at 331 m s^{-1}; at 20°C it travels at 331 + (0.6 × 20) = 343 m s^{-1}. This relationship can be used for any problem or laboratory work:

$$v = v_{0°C} + 0.6T$$

where $v_{0°C}$ is the velocity (in m s^{-1}) of a gas at 0°C and T is the temperature (in °C). For liquids, you would take the velocity at 25°C (or whichever value is cited) and ΔT would be the difference between the temperature of interest (T) and 25°C.

Worked example 13.1A

Calculating wavelength from frequency

Calculate the wavelength of the musical note middle-C, which has a frequency of 261.6 Hz on a day when the temperature is 25°C (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the wave equation. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required. Identify the medium and select the correct speed of sound value.	$v = f\lambda$ $v = v_{0°C} + 0.6T$ $v_{0°C} = 331\ \text{m s}^{-1}$ $v = ?$, $f = 261.6$ Hz, $\lambda = ?$
Step 3: Substitute the known values into the formula and find the speed of sound.	$v_{25°C} = 331 + (0.6 \times 25)$ $= 346\ \text{m s}^{-1}$ (1 mark)
Step 4: Substitute the known values into the formula and find the wavelength.	$346 = 261.6 \times \lambda$ $\lambda = \frac{346}{261.6}$ $= 1.323$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	1.3 m (2 s.f.) (1 mark)

Your turn

Calculate the frequency of the musical note A, which has wavelength of 79.3 cm on a day when the temperature is 30°C. Express your answer to the nearest whole number. (2 marks)

Speed of sound and frequency (pitch)

In gases other than air, the speed of sound is different. You may have seen people take a lung-full of helium gas from party balloons and when they speak, they sound like Alvin and the Chipmunks. The speed of sound in helium is about 965 m s^{-1}, which allows only the higher frequency sounds in air in the throat and mouth cavity to resonate.

As an orchestra warms up, the pitch of wind instruments becomes higher because the speed of sound in air increases and this stops some of the lower frequencies from resonating. However, string instruments go lower in pitch because the friction of the fingers rubbing over the strings heats them up and causes them to slacken.

Study tip

When answering questions from your Student Book, use 340 m s^{-1} for the speed of sound unless otherwise informed.

Challenge

Helium in an orchestra

In "The Song of the White Horse" by David Belford, the lead soprano is required to breathe in helium to reach the extremely high top note. If some of the helium was released into the middle of the accompanying orchestra, **predict** what would happen to the pitch of the wind, brass, strings and percussion instruments. (3 marks)

FIGURE 4 The pitch of instruments in an orchestra changes when atmospheric conditions such as temperature and humidity change.

Real-world physics

Noise pollution and acoustic design

Noise from roadways is a major source of noise pollution. Before the laws of physics can be applied to solve this issue, noise must be quantified so that it can be measured objectively.

Measuring sound intensity

Sound intensity is measured in the unit decibel (dB). Basically, it is a measure of the relative intensity (power per square metre) compared to a reference intensity. The formula is:

$$\beta = 10 \log_{10}\left(\frac{I}{I_0}\right)$$

where I is the intensity of sound in watts per square metre (W m^{-2}), I_0 is the reference level, taken as the least audible sound (10^{-12} W m^{-2}), and β is the relative intensity level in dB. It is an attempt to account for the perceived loudness of sounds as heard by the ear.

FIGURE 5 A noise-monitoring device placed near the most exposed facade of a residential building

In industry, the sound intensity level is often referred to as the sound pressure level (SPL). Ordinary conversation has an SPL of about 60 dB, and a noisy restaurant is 80 dB. A sound level meter has a display that gives a reading of the SPL in dB. The meter uses a weighted average of the SPL values over a range of frequencies in the audible region to approximate the human ear – less weighting for the low frequencies and more weighing for the mid-range frequencies. This is called a dBa measurement.

Measuring road noise

Placing a sound level meter in the correct location is critical for measuring SPLs beside a roadway to determine if nearby homeowners are being subjected to excessive noise. The sound level meter must be positioned on a stand exactly 1 m in front of the nearest window facing the roadway.

Different Australian states have different standards, but in Queensland, the level generally has to be less than an average of 63 dB over a certain time for residential, educational, community and health buildings.

Reducing road noise

It is not possible to eliminate excess noise completely, but it can be managed to keep it within reasonable limits. There are four ways of controlling noise from traffic:

1 **Regulate traffic to minimise impact**. There are already many regulations about traffic noise control such as ensuring mufflers are in working order, limiting use of air brakes by trucks, and reducing road speeds in residential areas.
2 **Limit generation of noise**. Most road noise is from tyres on the road, and the only way to reduce this is by using low-noise pavement.
3 **Reduce transmission of noise**. Barriers can be constructed to stop sound travelling (Figure 6).
4 **Insulate occupants from the noise**. Some form of insulation or sound proofing could be used to stop sound from reaching the inside of a house.

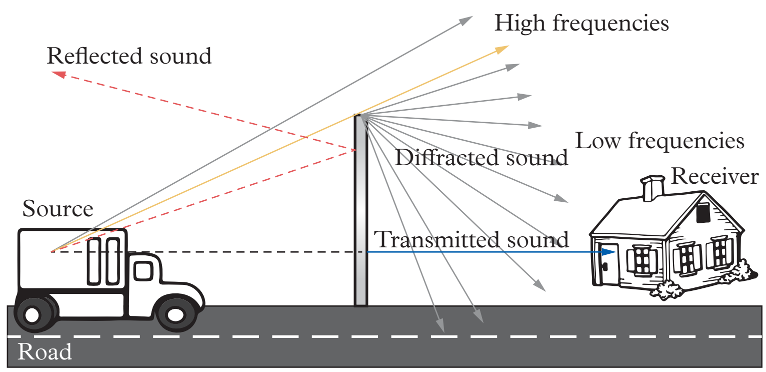


FIGURE 6 Sound propagation paths in the presence of a noise barrier. Note that the low frequencies are diffracted down behind the fence. The transmitted sound is reduced by the barrier and could be eliminated entirely with a good barrier.

Apply your understanding

1 **Explain** the meaning of "decibel". (3 marks)
2 **Explain** why sound barriers are not as effective for low frequency sounds. (2 marks)
3 **Evaluate** whether it is true to say: "If the intensity of a sound is doubled, the decibel level doubles". (2 marks)

Check your learning 13.1

Check your learning 13.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** why sound is a longitudinal wave. (1 mark)
2 **Explain** how sound propagates in air. (3 marks)
3 **Describe** how the speed of sound in air varies with temperature. (2 marks)
4 **Explain** why sound travels faster in water than in air. (3 marks)
5 A sound wave has a frequency of 800 Hz and a wavelength of 42 cm.
   a **Calculate** the speed of the sound wave. (2 marks)
   b **Calculate** the air temperature at the time. (3 marks)

Analytical processes

6 A student sounds a whistle in the back of the classroom with a frequency of 1,000 Hz.

a **Calculate** the wavelength for this sound using 340 $m\,s^{-1}$ for the speed of sound. (2 marks)

b **Determine** how long it will take the noise to reach the teacher in the front of the room 3.0 m from the student. (2 marks)

7 When watching the fireworks at the local show, you observe the flashes from the exploding fireworks in the sky 0.50 s before you hear them. Assuming light travels almost instantaneously, **determine** how far away from you the fireworks are exploding. (2 marks)

8 A person standing on an observation platform in the mountains shouts and then hears the echo off a cliff 1.5 s later. **Determine** how far the cliff is from the platform. Hint: echoes are reflections of the source sound back to where it originated. Use 340 $m\,s^{-1}$ for the speed of sound. (2 marks)

Knowledge utilisation

9 Students sitting in the stands at an athletic competition 200 m from the starting line see the smoke from the starting pistol 0.6 s before hearing the sound of the gun. **Determine** the air temperature from this information. (4 marks)

Practical

Lesson 13.2

Fundamental and harmonic wavelengths in pipes

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Practical

Lesson 13.3

Speed of sound in air using a closed-end pipe over water

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Learning intentions and success criteria

Video demonstration

Lesson 13.4
Standing waves in strings and pipes

Key ideas

→ Strings and pipes produce standing wave patterns.

→ The first harmonic or fundamental frequency is the lowest frequency produced by a string or pipe.

Learning intentions and success criteria

What are the patterns of vibration in strings?

When a guitar string is plucked, the string vibrates back and forth – often so fast that you cannot see it moving. The pulse you create by plucking the string travels along the string where it reflects off the end and comes back along the string to interfere with the next pulse coming down. Because the incoming and reflected waves have the same frequency, speed and amplitude, a standing wave is created.

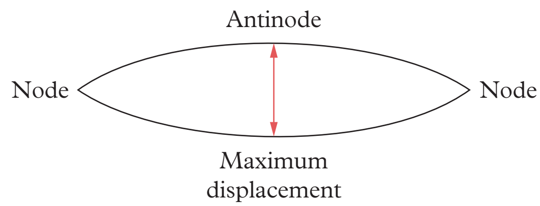


FIGURE 1 The length of the string is equal to $\frac{1}{2}\lambda$. This diagram is the first pattern we obtain, so it is called the fundamental frequency or first harmonic.

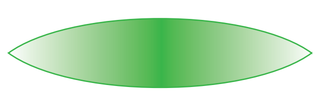
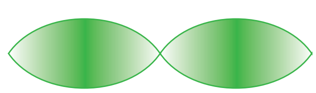
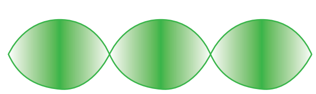
A number of different standing wave patterns (or **modes**) can form in a string. Recall from Module 12 that nodes are formed at the fixed ends. Figure 1 shows the simplest standing wave pattern established in a guitar string. This is the first way a string can vibrate, so we say it has a mode of vibration of $n = 1$ and is called the **fundamental** (or first) **harmonic**. It is the lowest frequency produced. The term "harmonic" refers to the integer (whole number) multiple of the fundamental frequency.

mode
different standing wave patterns formed in strings and air columns (pipes)

fundamental harmonic
the minimum frequency at which a vibrating medium will form a standing wave; the lowest natural frequency produced by an object or musical instrument; also called the fundamental frequency or first harmonic

Table 1 shows the first three modes of vibration for a string.

TABLE 1 Harmonics for a string

Standing wave pattern (strings)	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
	$\frac{1\lambda}{2}$	$\lambda_1 = 2L$	$f_1 = \frac{v}{2L}$	f_1	Fundamental frequency or first harmonic	1
	$\frac{2\lambda}{2} = \lambda$	$\lambda_2 = L$	$f_2 = \frac{2v}{2L}$	$f_2 = 2f_1$	Second harmonic	2
	$\frac{3\lambda}{2} = 1\frac{1}{2}\lambda$	$\lambda_3 = \frac{2L}{3}$	$f_3 = \frac{3v}{2L}$	$f_3 = 3f_1$	Third harmonic	3

Study tip
Harmonics primarily deals with the wavelength and frequency of sound waves, rather than their amplitude.

- For the first harmonic ($n = 1$), the length of string (L) is $\frac{1}{2}\lambda$ (or $\frac{\lambda}{2}$).
- For the second mode of vibration ($n = 2$), the length of the string is equal to λ. When you calculate its frequency using the wave equation, you find its frequency is twice the fundamental frequency. Thus, it is called the second harmonic.
- For the third mode of vibration ($n = 3$), the length is equal to $1\frac{1}{2}\lambda$. Its frequency is three times the fundamental frequency, so it is called the third harmonic.

What is the relationship between wavelength and string length?

A pattern emerges that relates the wavelength of the standing wave to the length of the string:

$$L = n\frac{\lambda}{2}$$

where L = length of string, n = the mode of vibration and λ = wavelength of the wave in the medium (string).

In Table 1, the frequency for each mode of vibration has also been calculated.

- For the first harmonic, the length $L = \frac{\lambda_1}{2}$. This can be rearranged to give $\lambda_1 = 2L$. The wave equation, $v = f\lambda$, can be rearranged to $f = \frac{v}{\lambda}$ and we can substitute $2L$ for λ to give $f_1 = \frac{v}{2L}$. Here, the velocity v is the speed of the wave in the string and not in the surrounding air.
- For the second harmonic, $\lambda_2 = L$ and we can substitute this into the wave equation $f = \frac{v}{\lambda}$ to get $f_2 = \frac{v}{L}$. If we write this as $f_2 = \frac{2v}{2L}$, we can see a pattern emerging. The value $f_2 = \frac{2v}{2L}$ for the second harmonic is twice $f_1 = \frac{v}{2L}$ of the first harmonic.
- Then we can go on to the third harmonic and so on. Strings produce all harmonics (first, second, third, fourth, etc.)

From the calculations in Table 1, we have developed an alternative formula for strings:

$$f_n = \frac{nv}{2L}$$

which gives the frequency of the nth harmonic. But note that:

$$f_n = nf_1$$

which says the frequency of the nth harmonic is n times the frequency of the first harmonic.

In both these formulas, f = frequency of the sound, n = the mode of vibration, v = velocity of the wave in the medium (the string) and L = length of the string. Again, v is the velocity of the wave in the string itself, not of the sound it makes in air.

Worked example 13.4A

Calculating the frequency of harmonics in a guitar string

A guitar string is 85.0 cm long and plucked in the centre to produce the fundamental frequency (first harmonic). The speed of the wave in the string is 420 m s^{-1}.

a **Calculate** the frequency of the vibration (3 s.f.). (2 marks)

b **Calculate** the frequency of the third harmonic (3 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the string harmonics formula and the wave equation. The questions are worth 2 marks, and 1 mark respectively, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$L = \frac{n\lambda}{2}$ L = 85.0 cm, n = 1 (first harmonic), λ = ? $v = f\lambda$ v = 420 m s^{-1}, f = ? $f_n = nf_1$

Think	Do
Step 3: Substitute the known values into the formula and find the wavelength.	**a** $\frac{85.0}{100} = \frac{1 \times \lambda}{2}$ $\lambda = 1.7\,\text{m}$ (1 mark)
Step 4: Substitute the known values into the formula and find the first harmonic.	$420 = f \times 1.7$ $f = 247.06$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	247 Hz (3 s.f.) (1 mark)
Step 6: Substitute the known values into the formula and find the third harmonic.	**b** $f_n = nf_1$ $= 3 \times f_1$ $= 3 \times 247$ $= 741.18$
Step 7: Finalise your answer and make sure you have included the correct units and significant figures.	741 Hz (3 s.f.) (1 mark)

Your turn

Banjo strings are 66.0 cm long. When the thickest string is plucked in the centre, it produces the fundamental frequency of 130.8 Hz.

a **Calculate** the speed of the progressive wave in this string (3 s.f.). (2 marks)

b **Calculate** the frequency of the fourth harmonic (3 s.f.). (2 marks)

What are the patterns of vibration in closed-end pipes?

Wind instruments, such as the flute, produce standing waves in an air column or pipe. As with stringed instruments, the particles in the pipe can vibrate in a number of ways. The way a particle vibrates also depends on the nature of the instrument – whether it has a closed-ended pipe (e.g. the clarinet family of instruments) or an open-ended pipe (e.g. flutes and oboes).

Let us imagine that we have taken a piece of plastic drainpipe and sealed one end with a plastic cap – this sealed end is the boundary. We can place a sound generator at the other end to act as the source of sound waves. Any waves produced will move back and forth between the ends of the pipe, creating standing waves.

Suppose that the generator is producing sound waves into the closed-end pipe. It will sound very loud at particular frequencies. For example, if a 1.0 m closed-end pipe is used, when the frequency gets to 80 Hz, the vibrating air sounds very loud. If the frequency is continuously increased, the sound will go soft again. Then, at approximately 240 Hz, another loud point will be reached, and then it will go soft and then loud again at 400 Hz, and so on.

Let's have a look at a closed-end pipe (Figure 2). The dots represent air particles at different points along the pipe. At the open end, the air particles in the pipe can move more freely; this point is the antinode where they have the greatest displacement. The air particle at the open end (dot 1) is free to move back and forth, as shown by the black horizontal arrow. In a waveform diagram, the displacement is shown by redrawing the length of the arrow in the vertical direction. We can do this for all the particles to see the maximum displacement at every point along the pipe.

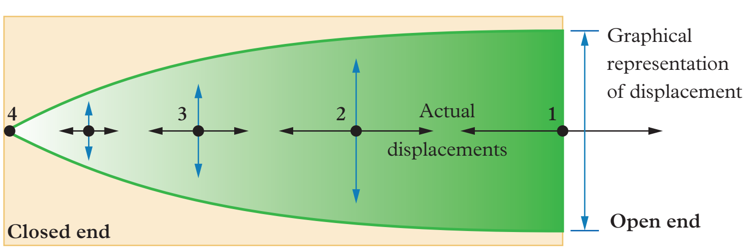


FIGURE 2 Air movement in a closed-end pipe

Moving further to the left, the displacement gets smaller, as shown by dots 2 and 3 where the lengths of the horizontal and vertical arrows get smaller until we reach the closed end (dot 4), where the particle cannot move, so the arrow length is zero. This point is the node.

In closed-end pipes, the standing wave has one-quarter of the wavelength (Figure 3). The length of the tube L is just one-quarter of the wavelength, or $L = \frac{1}{4}\lambda$.

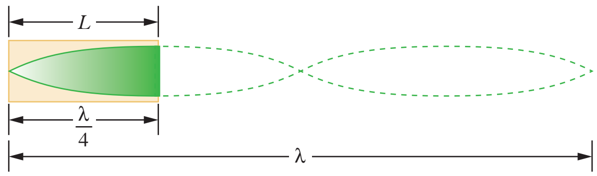
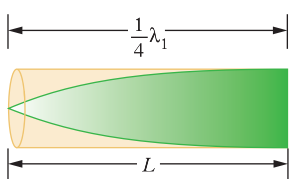
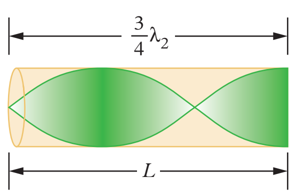
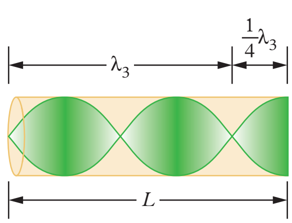
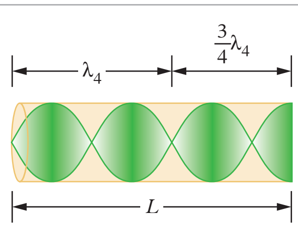


FIGURE 3 The standing wave has one-quarter of the wavelength.

This is the fundamental frequency or first harmonic for closed-end pipes. Table 2 shows the fundamental frequency and the next three harmonics in a closed-end pipe. Unlike string harmonics (and open-end pipe harmonics, which you will learn about next), the subsequent closed-end pipe has odd harmonics. There is no such thing as a second harmonic or fourth harmonic, etc., since the open end must be an antinode and the closed end must be a node. Despite this, each mode is still numbered sequentially, so $n = 1$ for the first harmonic, $n = 2$ for the third harmonic, $n = 3$ for the fifth harmonic, and so on. The frequency of the third harmonic is double the fundamental frequency.

TABLE 2 Harmonics for a closed-end pipe

Standing wave pattern (closed-end pipe)	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
	$\frac{1\lambda_1}{4}$	$\lambda_1 = 4L$	$f_1 = \frac{v}{4L}$	f_1	Fundamental frequency or first harmonic	1
	$\frac{3\lambda_2}{4}$	$\lambda_2 = \frac{4L}{3}$	$f_3 = \frac{3v}{4L}$	$f_3 = 3f_1$	Third harmonic	2
	$\frac{5\lambda_3}{4}$	$\lambda_3 = \frac{4L}{5}$	$f_5 = \frac{5v}{4L}$	$f_5 = 5f_1$	Fifth harmonic	3
	$\frac{7\lambda_4}{4}$	$\lambda_4 = \frac{4L}{7}$	$f_7 = \frac{7v}{4L}$	$f_7 = 7f_1$	Seventh harmonic	4

What is the relationship between wavelength and closed-end pipe length?

In the table, we can see a pattern for wavelength:

$$L = (2n - 1)\frac{\lambda_n}{4}$$

where L = length of the closed-end pipe, n = mode of vibration, and λ_n = wavelength of the standing wave in the pipe vibrating in its nth mode of vibration.

We can rearrange the formula to $\lambda_n = \frac{4L}{(2n-1)}$ and substitute into the wave equation $v = f\lambda$ to produce alternative formulas:

$$f_n = \frac{v}{\lambda_n}$$
$$f_n = \frac{(2n-1)v}{4L}$$
$$f_n = (2n - 1)f_1$$

Worked example 13.4B

Determining the fundamental frequency of a closed-end column

The speed of sound waves in air at a particular temperature is 340 m s^{-1}. **Determine** the fundamental frequency (first harmonic) of a closed-end air column that has a length of 67.5 cm (3 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the closed-end pipe harmonics formula and the wave equation. The question is worth 2 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$L = (2n - 1)\frac{\lambda_n}{4}$ L = 67.5 cm, n = 1 (first harmonic), λ = ? $v = f\lambda$ v = 340 m s^{-1}, f = ?
Step 3: Substitute the known values into the formula and find the wavelength.	$\frac{67.5}{100} = ((2 \times 1) - 1)\frac{\lambda_1}{4}$ $\frac{67.5}{100} = \frac{1\lambda_1}{4}$ λ_1 = 2.7 cm (1 mark)
Step 4: Substitute the known values into the formula and find the first harmonic.	$340 = f \times 2.7$ $f = 125.9$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	126 Hz (3 s.f.) (1 mark)

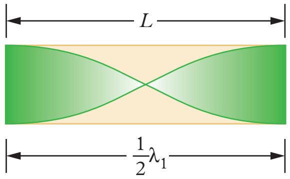
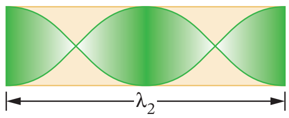
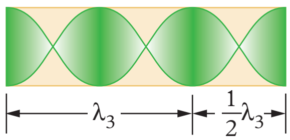
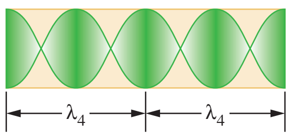
Your turn

A closed-end air column has a length of 19.0 cm and produces a fundamental frequency of 440 Hz. **Calculate** the speed of sound in air when this sound is produced (3 s.f.). (2 marks)

What are the patterns of vibration in open-end pipes?

Pipes open at both ends have maximum air displacements at both ends, as illustrated in Table 3. The frequency of the second harmonic is double the fundamental frequency.

TABLE 3 Harmonics for an open-end pipe

Standing wave pattern	L	λ	$f = \frac{v}{\lambda}$	f	Name	n
	$\frac{\lambda_1}{2}$	$\lambda_1 = 2L$	$f_1 = \frac{v}{2L}$	f_1	Fundamental frequency or first harmonic	1
	λ_2 or $\frac{2\lambda_2}{2}$	$\lambda_2 = L$	$f_2 = \frac{2v}{2L}$	$f_2 = 2f_1$	Second harmonic	2
	$\frac{3\lambda_3}{2}$	$\lambda_3 = \frac{2L}{3}$	$f_3 = \frac{3v}{2L}$	$f_3 = 3f_1$	Third harmonic	3
	$\frac{4\lambda_4}{2}$	$\lambda_4 = \frac{2L}{4}$	$f_4 = \frac{4v}{2L}$	$f_4 = 4f_1$	Fourth harmonic	4

What is the relationship between wavelength and open-end pipe length?

The formula that relates length of pipe and wavelength for the various modes of vibration is:

$$L = n\frac{\lambda_n}{2}$$

where L = length of the open-end pipe, n = mode of vibration (1, 2, 3, 4 …), and λ_n = the wavelength of the standing wave for the nth mode of vibration. This is the same as the formula for strings.

We can rearrange the formula to $\lambda_n = \frac{2L}{n}$ and substitute into the wave equation $v = f\lambda$ to produce alternative formulas:

$$f_n = \frac{v}{\lambda_n}$$

$$f_n = \frac{nv}{2L}$$

$$f_n = nf_1$$

Study tip

Length and wavelength have the same relationship for string harmonics and open-end pipe harmonics – calculations involve the same formula. Closed-end pipe harmonics use a different formula.

Worked example 13.4C

Determining the length of an open-end pipe

The speed of sound waves in air at 25°C is 346 m s^{-1}. In an experiment, students want to make an open-end pipe that has a fundamental frequency for the musical note C3, which is 130.8 Hz. **Determine** the length of such a pipe (3 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Determine" means to establish after a calculation. We need to apply the wave equation and the open-end pipe harmonics formula. The question is worth 2 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.

Think	Do
Step 2: Select the correct formulas and gather any data required.	$v = f\lambda$ $v = 346\,\mathrm{m\,s^{-1}}$, $f = 130.8\,\mathrm{Hz}$, $\lambda = ?$ $L = n\frac{\lambda_n}{2}$ $n = 1$ (fundamental frequency), $L = ?$
Step 3: Substitute the known values into the formula and find the wavelength.	$346 = 130.8 \times \lambda$ $\lambda = 2.645\,\mathrm{m}$ (1 mark)
Step 4: Substitute the known values into the formula and find the length.	$L = 1 \times \frac{2.645}{2}$ $= 1.323$
Step 5: Finalise your answer and make sure you have included the correct units and significant figures.	1.32 m (3 s.f.) (1 mark)

Your turn

A student is trying to make an open pipe that plays the note A2 (110.0 Hz) and uses a pipe of length 147.8 cm. The speed of sound in air at the time is $340\,\mathrm{m\,s^{-1}}$. **Determine** whether this is the correct length and, if not, **identify** by how much the pipe should be shortened or lengthened (in cm, 3 s.f.). (3 marks)

Skill drill

Summarising data on harmonic frequencies in a pipe

Science inquiry skills: Processing and analysing data (Lesson 1.7)

Students set up an experiment to gather data about the harmonics of an open-end tube. Adjusting the frequency of the sound made by the frequency generator caused the particles in the pipe to vibrate at each of its harmonics. Frequencies were judged by having noticeably louder sound levels. The students completed three replicates and their results are shown in Table 4. The results were graphed in Figure 4.

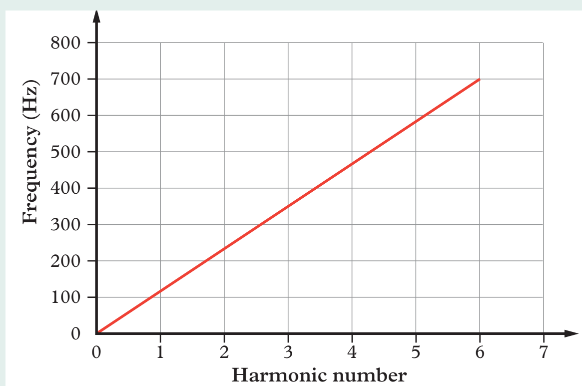


FIGURE 4 Frequency versus harmonic number

TABLE 4 Results of harmonic experiment

Harmonic number	Trial 1 f (Hz)	Trial 2 f (Hz)	Trial 3 f (Hz)	Average frequency (Hz)	Absolute uncertainty, δ (Hz)
1	115	118	116.5		
2	235.5	231.5	232		
3	351	348.5	349		
4	470	462	466		
5	581	588	578.5		
6	700	691	706		

Practise your skills

1 **Calculate** the average frequency for each harmonic. (6 marks)
2 **Determine** an equation for the relationship between frequency and harmonic number. (2 marks)
3 **Determine** the frequency of the seventh harmonic by using the equation derived in question **2**. (1 mark)

The formulas used throughout this section are summarised in Table 5.

TABLE 5 Formulas for string, open-end and closed-end pipe harmonics

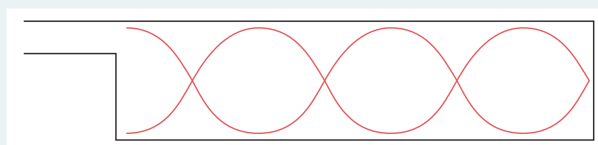
Strings and open-end pipes	$L = n\frac{\lambda_n}{2}$	$f_n = \frac{nv}{2L}$	$f_n = nf_1$
Closed-end pipes	$L = (2n-1)\frac{\lambda_n}{4}$	$f_n = (2n-1)\frac{v}{4L}$	$f_n = (2n-1)f_1$

Check your learning 13.4

Check your learning 13.4: Complete these questions online or in your workbook.

Retrieval and comprehension

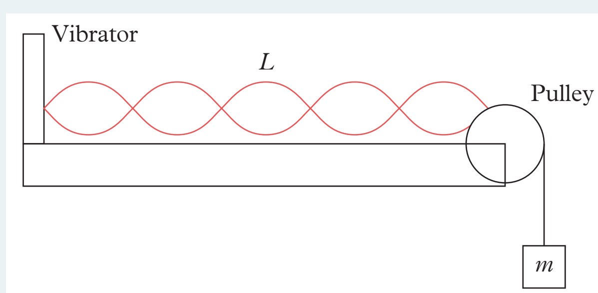
1 **Explain** the meaning of the symbols in the string formula $L = n\frac{\lambda_n}{2}$ and give an example of its use. (2 marks)
2 **Explain** whether strings produce all the harmonics (or just odd or even harmonics). (2 marks)
3 **Explain**, using a first and second harmonic example, whether you can have more than one wavelength at a time produced on a particular string. (3 marks)
4 **Explain** the meaning of the symbols in the open-end pipe formula $f_n = \frac{nv}{2L}$ and give an example of the formula's use. (2 marks)
5 **Calculate** the length of a guitar string that produces a fundamental frequency (first harmonic) of 261 Hz. The speed of waves in that particular guitar string is measured as 395 m s^{-1}. (5 marks)
6 The third harmonic of a violin string has a frequency of 1,200 Hz. **Calculate** its fundamental frequency. (2 marks)
7 A guitar string is 0.60 m long and the speed of the waves on it is 200 m s^{-1}. **Calculate** its fundamental frequency. (2 marks)
8 The figure shows the seventh harmonic in a closed-end pipe. **Sketch** a diagram showing the waveform for the ninth harmonic. (1 mark)



9 Two closed-ended pipe instruments of different lengths produce different frequencies.
Explain why the shorter instrument produces a higher frequency. (3 marks)
10 A student blows across the top of a test tube that has a 17.2 cm air column closed at one end. The speed of sound in the air in test tube is 340 m s^{-1}. **Calculate** the frequency of the first harmonic played by this instrument. (2 marks)

Analytical processes

11 A string that has a length of 2.5 m vibrates in five loops with a frequency of 2.00 Hz.



a **Determine** the wavelength. (2 marks)
b **Calculate** the wave speed. (2 marks)
c **Deduce** which harmonic it is. (2 marks)

12 A closed-end pipe produces both the third and fifth harmonics with frequencies of 1,100 Hz and 1,833 Hz respectively.
a **Calculate** the frequency of the first harmonic. (2 marks)
b If the air temperature is 20°C and v_{sound} = 340 m s^{-1}, **determine** the length of the pipe. (2 marks)

13 A student blows across the mouth of a closed-end plastic pipe 0.30 m long. **Determine** the fundamental frequency and the frequency of the fifth harmonic. Assume the speed of sound in air is 340 m s^{-1}. (2 marks)

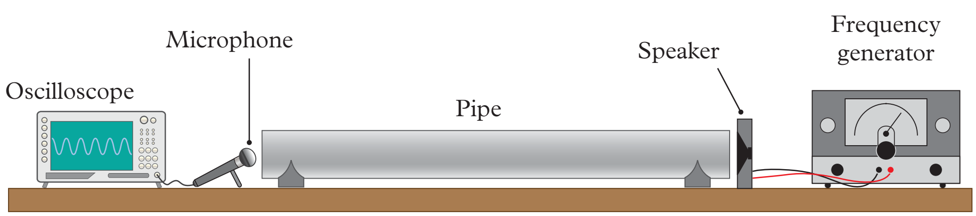
14 A sound generator is used to produce standing waves in an open-ended pipe of length 20 cm. The frequency of the generator is adjusted to various standing wave positions.
a **Sketch** the standing wave patterns when the pipe's length of 20 cm equals
i $1\frac{1}{2}\lambda$ (1 mark)
ii 3λ (1 mark)
iii $\frac{1}{2}\lambda$. (1 mark)
b **Determine** the resultant frequencies of the waves in the situations in part **a**.
Assume v_{sound} = 340 m s^{-1}. (3 marks)

Knowledge utilisation

15 To measure the speed of sound in air, students set up a source of sound at one end of an open cardboard pipe. This cardboard pipe had another open pipe fitted inside it that could be adjusted to change the length. Students set the frequency generator at 600.0 Hz and located the first loud point at a length of 9.8 cm (0.098 m). They repeated this two more times. The students then lengthened the pipe until the second loud point was located. They repeated this procedure for the first five loud points, testing triplicates for each one. The air temperature was 24.4°C and v_{sound} was 346 m s^{-1}. Their set-up is shown and their data is recorded in the table.

Harmonic (mode)	Length of pipe, *L* (m)		
N	Test 1	Test 2	Test 3
1	0.098	0.107	0.106
2	0.379	0.411	0.345
3	0.646	0.718	0.688
4	0.955	1.026	0.916
5	1.183	1.305	1.242

a **Calculate** the mean (average) length of the pipe for each resonance, and the absolute and percentage uncertainty (δ) of the mean for each. (3 marks)
b **Sketch** a graph of length, L, on the vertical axis vs harmonic number (mode, n) on the horizontal axis. Add error bars for the absolute uncertainty. **Identify** the trend by determining the equation for the line and calculating the R^2 value. (5 marks)
c Using the graph, **determine** the wavelength of the sound. (2 marks)
d **Calculate** the (observed) velocity of the sound using $v = f\lambda$. (1 mark)
e Draw maximum and minimum trendlines and **calculate** the gradients. Use the gradients to **calculate** the maximum and minimum values of the speed of sound. Express this as the uncertainty in the experimental value. (4 marks)
f **Calculate** the accepted velocity using $v = 331.5 + 0.6T$ where T = temperature in degrees Celsius. (2 marks)
g **Calculate** the absolute and percentage errors in velocity. (4 marks)
h Write a conclusion about the quality of the experiment and **justify** your answer. (4 marks)



Lesson 13.5
Resonance and natural frequency

Key ideas

→ When disturbed, an object will vibrate at its natural frequency.

→ Resonance occurs when an object is caused to vibrate at its natural frequency due to its proximity to another object vibrating at the same natural frequency.

→ Resonating systems involve efficient transfer of energy.

Learning intentions and success criteria

What is natural frequency?

Natural frequency is the frequency at which an object will vibrate when it is disturbed in some way. It is also called the resonant frequency. As an example, let us consider a tuning fork. When a tuning fork is struck on the bench, it vibrates at its natural frequency (as well as emitting a few other, but less intense, harmonics). This natural frequency depends on the length, thickness and composition of the tuning fork. It does not depend on the force applied to the fork.

FIGURE 1 A tuning fork

natural frequency the frequency at which an object will vibrate when an imposed frequency or force is applied; it is independent of the size of the stimulus, depending solely upon the size, shape and composition of the object; also known as resonant frequency

Forced vibration

Although all objects have a natural frequency, the intensity of the sound produced upon applying a force can be increased. For example, the intensity of the sound produced by a vibrating tuning fork can be increased by placing the end of the fork on a tabletop. The tabletop is forced to vibrate at the same frequency as the fork, thus intensifying the sound produced.

This **forced vibration** also occurs for a guitar string. When a guitar string is held between two clamps and plucked, it does not produce a very intense sound. However, when the string is attached across the bridge of a guitar and plucked, the sound is more intense because the wood of the guitar (the "soundboard") is forced to vibrate in response to the vibrating string.

forced vibration the tendency of one object to be forced into vibrational motion by an adjoining or interconnected object

What is resonance?

Resonance is the effect observed when a body is caused or forced to vibrate at its natural frequency without the object being physically disrupted. This phenomenon occurs when an object vibrating at its natural frequency is brought close to another object that shares the same natural frequency. The second object begins to vibrate with a greater amplitude (more energy) than it would if the frequency was not its natural or "resonant" frequency.

Using the tuning fork example, if another tuning fork of the same natural frequency is brought close to an already vibrating tuning fork, it too will begin to vibrate. We say that the first tuning fork has caused resonance in the second one.

resonance the process where in which the frequency of external force matches the natural frequency of the vibrating object, resulting in an increase in the amplitude of vibration

With resonance, energy is transferred efficiently from one object to another. If resonance is not occurring, the energy is dissipated (spread out) as heat and random vibrations of nearby matter. Resonance occurs in many different systems including strings, air columns and atoms.

Resonance on a swing

Imagine a child on a swing (Figure 2). Together, the child and swing are like a pendulum. The length of the swing is fixed, so the swing oscillates (swings back and forth) at a set frequency. You can't do a lot to change it, as the swing has a natural frequency.

FIGURE 2 A child being pushed on a swing is an example of resonance. Push at the right time and the energy will be transferred efficiently to the vibrating system and the amplitude will increase – the swing will resonate. Push at the wrong time and energy will be dissipated and the amplitude will decrease – it won't resonate.

To transfer energy to the swing, it must be pushed in time with the swinging movement – it must be pushed with the same frequency as the natural frequency. When this happens, the swing will get higher and higher. Of course, the pushing frequency must be in phase too. The swing must be pushed at exactly the right time or it won't go higher. The push must be applied at the end points of the cycle. A fraction of a second early or late and the swing will slow down. The external force will create resonance if it is applied with the natural frequency of the system and in phase.

At resonance, energy is transferred rapidly and efficiently to the oscillating system, and the amplitude of its oscillations grows (the swing gets higher and higher).

Resonance in pipes

When you blow across the top of a test tube, a loud sound can be heard. If test tubes are filled to different levels with water, you can obtain sounds of different frequencies that depend on the length of the air column above the water. The test tube is acting like a pipe closed at one end. You may have made straw clarinets in your science class. Straw clarinets are different lengths of plastic drinking straws that act as open-end pipes and produce notes of different frequencies, depending on their length. The straws are V-shaped at one end so they can vibrate.

We can use the idea of resonance to measure the speed of sound in air. By sounding a tuning fork over the open end of a plastic pipe whose length can be changed by raising and lowering it in water, we can achieve resonance. At some particular length of the pipe above water, you will find a point where the pipe begins to hum loudly. We can say the air in the pipe is resonating at the frequency of the tuning fork, and a standing wave is produced. When it is not resonating, the energy of the vibrations goes into the air and dissipates in all directions. At resonance, the energy is largely transferred to the air in the pipe to create the standing wave and the hum. At resonance, energy is being transferred efficiently.

Other examples of resonance

Examples of resonating musical instruments include wind instruments that use resonance in air columns to amplify tones made by lips or vibrating reeds. Other instruments also use air resonance in clever ways to amplify sound.

A violin and a guitar both have sounding boxes but with different shapes, resulting in different resonant frequencies. The vibrating string creates a sound that resonates in the sounding box, greatly amplifying the sound and creating overtones that give the instrument its characteristic "timbre" or sound. The more complex the shape of the sounding box, the greater its ability to resonate over a wide range of frequencies.

Resonance vibration is why soldiers avoid marching in step when crossing older bridges, as they might cause the bridge to resonate and possibly collapse. A similar problem occurred with the Millennium Bridge in London, but this situation was horizontal motion instead of vertical. When 2,000 people walked on the bridge on opening day on 10 June 2000, sideways motion of 1.3 Hz caused the bridge to lurch to one side. Pedestrians had to adjust their steps to keep from falling over, and they all did this at exactly the same time–that is, in phase and at the same frequency. The bridge was subsequently closed for two years while engineers tried to rid it of resonance problems.

FIGURE 3 Millennium Bridge, London

Check your learning 13.5

Check your learning 13.5: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** what a "natural frequency of vibration" means in the context of a pendulum. (2 marks)

2 **Explain** what resonance is and how it is produced. (2 marks)

3 **Explain** why some older cars and buses start to vibrate when their engines reach certain "revs" (revolutions per minute). (2 marks)

4 **Describe** the relationship between energy transfer and the resonance condition. (2 marks)

5 Students held a 220 Hz tuning fork over a pipe closed at one end (in water). They found two lengths that gave resonance. **Sketch** waveform diagrams to explain this observation. (4 marks)

6 **Recall** a practical example where resonance is a problem and **explain** how it could be reduced. (2 marks)

Analytical processes

7 A car travelling over a corrugated "washboard" road vibrates up and down very dramatically when its speed is $10\,\text{km}\,\text{h}^{-1}$. **Interpret** this scenario and **explain** how the driver could prevent this happening. (2 marks)

Knowledge utilisation

8 A child is being pushed on a swing that is oscillating at its natural resonant frequency of 1 complete swing every 4 seconds. The child stands up. **Predict** whether the resonant frequency will now be higher, lower or the same. **Justify** your response. (3 marks)

9 A claim was made that resonance in the Millennium Bridge was similar to soldiers marching in lockstep, but with horizontal instead of vertical motion. **Evaluate** what is meant by "horizontal instead of vertical". (3 marks)

MODULE 13

Lesson 13.6
Review: Sound

Summary

13.1
- Sound waves are propagated through oscillation of particles in a medium.
- The speed of sound depends on the medium through which the sound waves are travelling.

13.2
- Practical: Fundamental and harmonic wavelengths in pipes

13.3
- Practical: Speed of sound in air using a closed-end pipe over water

13.4
- Strings and pipes produce standing wave patterns.
- The first harmonic or fundamental frequency is the lowest frequency produced by a string or pipe.

13.5
- When disturbed, an object will vibrate at its natural frequency.
- Resonance occurs when an object is caused to vibrate at its natural frequency due to its proximity to another object vibrating at the same natural frequency.
- Resonating systems involve efficient transfer of energy.

Key formulas

Length of strings and open-end pipes	$L = n\frac{\lambda}{2}$
Length of closed-end pipes	$L = (2n - 1)\frac{\lambda}{4}$

Review questions 13.6A Multiple choice

Review questions: Complete these questions online or in your workbook.

(1 mark each)

1 Standing waves are produced by the superposition of two waves with

A the same amplitude, frequency and direction of propagation.

B the same amplitude and frequency, and opposite directions of propagation.

C the same amplitude and direction of propagation, but different frequencies.

D the same amplitude, different frequencies and opposite directions of propagation.

2 The fundamental frequency of a certain string is 100 Hz. The frequency of the next harmonic is

A 50 Hz.

B 200 Hz.

C 300 Hz.

D 400 Hz.

3 The fundamental frequency of an open tube will double if

A one of the open ends is closed.
B the length of the tube is doubled.
C the gas in the tube is changed to one with twice the speed of sound of the original gas.
D the radius of the tube is decreased to half its original value.

4 On a cold day the speed of sound in air is 320 m s^{-1}. A fundamental standing wave is produced in a tube at a frequency of 80 Hz. The next standing wave can be heard when the frequency reaches 240 Hz. Which of the following is correct?

A The tube is an open-end pipe with a length of 1 m.
B The tube is a closed-end pipe with a length of 1 m.
C The tube is an open-end pipe with a length of 4 m.
D The tube is a closed-end pipe with a length of 4 m.

5 A 4.0 m long wire with a mass of 60 g is under tension. A transverse wave is propagated on the wire. The frequency is 330 Hz, the wavelength is 0.20 m and the amplitude is 7.0 mm.
The time for a crest of the transverse wave to travel the length of the wire is closest to

A 53 ms.
B 61 ms.
C 75 ms.
D 82 ms.

6 A trombone, like some other brass instruments, resonates as a closed-end pipe. The fundamental frequency of a trombone is 116.5 Hz. The trombone will also resonate at a frequency of

A 175 Hz.
B 233 Hz.
C 290 Hz.
D 375 Hz.

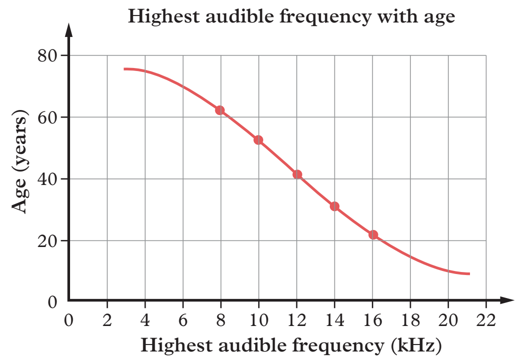
7 Which of these statements about the speed of sound in air is true?

A It is always the same.
B It varies proportionally with the frequency of sound.
C It decreases as the temperature increases.
D It increases as the temperature increases.

8 A party trick involves breathing in helium (from a balloon) and then speaking with a funny, high-pitched voice. Why does this effect happen?

A Sound travels much faster in helium than in air.
B Human vocal chords vibrate faster in helium than in air.
C The person performing the trick expects this to happen and subconsciously speaks in a higher tone.
D It doesn't really happen; it is an urban myth.

9 As people get older, their range of hearing gradually deteriorates, as shown by the drop in the highest frequency they can hear.



Which of the following sounds is audible for school students but inaudible to their 50-year-old teacher?

A The lowest note on a standard piano, 32 Hz
B The highest note produced by a piccolo, 3951 Hz
C A sound produced by a solar inverter, 8.2 kHz
D A dolphin call, 16 kHz

10 The fundamental frequency of an open tube of a certain length is 233 Hz. If the length of the tube is doubled, the fundamental frequency is

A 58 Hz.
B 116.5 Hz.
C 233 Hz.
D 466 Hz.

Review questions 13.6B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

11 **Explain** the difference between a transverse wave and a longitudinal wave, using labelled diagrams. (2 marks)

12 **Define** these terms in relation to a longitudinal wave: displacement, amplitude, compression, rarefaction, equilibrium position, mechanical wave, medium and propagation. (8 marks)

13 A classical guitar string has a "scale" (vibrating) length of 66.0 cm. **Calculate** the wavelengths of the first, second and third harmonics. (6 marks)

14 A student produces a note by blowing across the mouth of an open-end piece of plastic pipe 0.2 m long. **Calculate** the frequency of the third harmonic. (4 marks)

15 A string has a length of 65 cm and when vibrating, has a wavelength of 1.30 m. **Explain** whether it is vibrating in its fundamental mode. (3 marks)

16 The sixth string (low E) on a Fender guitar has a length of 648 mm and is tuned to a frequency of 82.1 Hz.

- **a** **Calculate** the speed of the wave in the string when it is vibrating in its fundamental mode. (4 marks)
- **b** **Calculate** the wavelength of the fundamental frequency and the second harmonic. (3 marks)

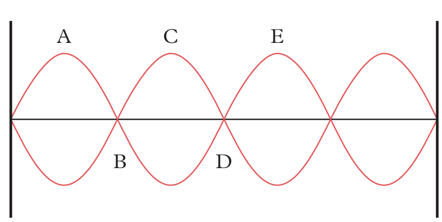
17 **Sketch** diagrams to show the standing waves set up in a harp string of length L when the length of the string corresponds to

- **a** two wavelengths (2 marks)
- **b** three and a half wavelengths (3 marks)
- **c** four wavelengths. (2 marks)

Analytical processes

(For all questions use $v_{sound} = 340\,\mathrm{m\,s^{-1}}$ unless otherwise specified.)

18 The following diagram shows a standing wave.



- **a** **Identify** the letters corresponding to nodes and antinodes. (2 marks)
- **b** **Determine** whether A and C, or A and E, are one wavelength apart. **Explain**. (3 marks)

19 A tuning fork produces 2.4×10^4 compressions and rarefactions in the air particles around it in 10 s. The distance between each compression is 0.14 m.

- **a** **Calculate** the frequency of the tuning fork. (2 marks)
- **b** **Determine** the velocity of sound in air. (2 marks)

20 In a thunderstorm, the lightning is seen before the thunder is heard, as the velocity of light is much greater than the velocity of sound ($v_{sound} = 340\,\mathrm{m\,s^{-1}}$). If the thunder is heard 10 s after the lightning is seen, **determine** how far away the storm is. Assume the velocity of light is instantaneous over this distance. (2 marks)

21 A marine survey vessel plotting the contours of the ocean floor sends an ultrasonic wave and receives an echo back 1.2 s later. **Determine** the depth of the ocean at this point. (The velocity of sound in sea water is $1{,}400\,\mathrm{m\,s^{-1}}$.) (2 marks)

22 Students experimenting with musical notes set up a row of test tubes in a test tube rack and fill them with water to various levels. The students can create different notes by blowing across the top of the tubes.

- **a** If the distance between the top of the water and the top of the test tube for the first tube is 8.0 cm, **determine** the fundamental frequency emitted by this tube. Assume $v_{sound} = 340\,\mathrm{m\,s^{-1}}$. (3 marks)
- **b** **Describe** what the students will need to do to create different frequencies, and calculate the distances from the top of the tubes to the water if they wish to create fundamental frequencies of
  - **i** half that in part **a** (3 marks)
  - **ii** twice that in part **a** (4 marks)
  - **iii** three times that in part **a**. (3 marks)

23 Open-end and closed-end pipes of different lengths can be used to produce the same fundamental frequency.

a **Calculate** the fundamental frequency produced by a closed-end pipe of length 25 cm. Assume v_{sound} = 341 m s^{-1}. (4 marks)

b **Determine** the length of an open-end pipe that would produce the same fundamental frequency. (2 marks)

c Even though open-end and closed-end pipes both can produce the same fundamental frequency, they would sound different. **Explain,** using the frequencies of their harmonics, why this occurs. (3 marks)

24 A pipe is open at both ends and is 0.58 m long.

a **Determine** the wavelength of the sound that would produce the fundamental frequency in this pipe. Assume v_{sound} = 342 m s^{-1} (4 marks)

b **Calculate** the frequency of the second and third harmonics. (2 marks)

25 The wavelength of the fundamental harmonic of a trumpet is 2.96 m.

a **Calculate** the frequency of the fundamental tone of the trumpet. The speed of sound in air is 345 m s^{-1}. (2 marks)

b The trumpet's harmonic series consists of integer multiples of f_1 (the fundamental tone). Given the information in Table 1, **calculate** the frequency and wavelength of the next three harmonics of the trumpet. (3 marks)

TABLE 1 The trumpet's harmonic series

Harmonic	Frequency (Hz)	Wavelength (m)
f_0	116.5	2.96
f_1		
f_2		
f_3		

c Given the information in Table 2, **determine** and **describe** what happens to the frequency of the trumpet's f_3 harmonic as the temperature varies. (2 marks)

TABLE 2 The speed of sound in air

Temperature (°C)	Speed of sound (m s^{-1})
0	331
15	340
20	343
25	346

d A trumpet is equipped with slides – sections of tubing that can be used to make the total length of tubing in the instrument a little more or a little less. **Describe** how these slides would need to be used on a day when the temperature is 15°C, to "correct" the frequency of f_3. (2 marks)

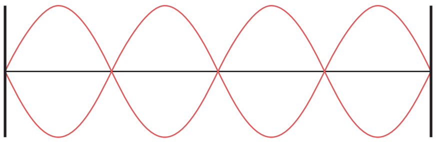
e Use the values you have calculated in part **c** to **construct** a graph showing the relationship between air temperature and f_3 frequency for a trumpet. Show a range of temperatures from 0°C to 30°C. (2 marks)

Knowledge utilisation

26 **Devise** a method for how you could demonstrate experimentally that sound waves transfer energy. (2 marks)

27 **Propose** whether any energy is lost when waves interfere both constructively and destructively. (4 marks)

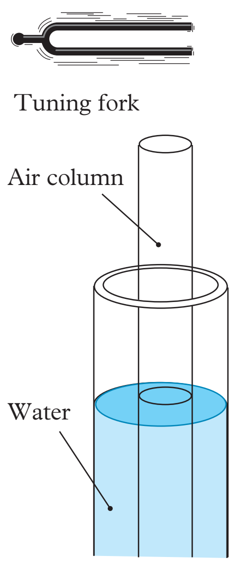
28 The figure shows a graphical representation of the displacement of particles of a standing wave in a musical instrument.



Justify whether the instrument is a string, an open-end pipe or a closed-end pipe. (3 marks)

29 **Discuss** the possibility of open-end organ pipes producing different frequency notes on hot and cold days. Use v_{sound} = 340 m s^{-1} on a cold day and 365 m s^{-1} on a hot day. (5 marks)

30 An open-end tube is placed into a container of water and a vibrating tuning fork is placed over the mouth of the tube. As the tube is raised so that a greater length of the tube is out of the water, resonance is heard. This occurs when the distance from the top of the tube to the water level is 21 cm, and again at 59 cm. The speed of sound is 334 $m\,s^{-1}$ in this experiment.



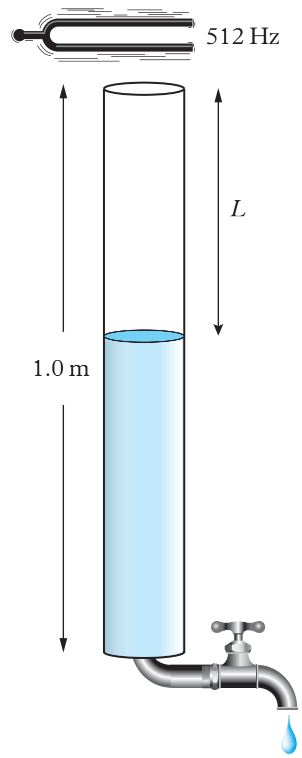
Determine the frequency of the tuning fork. Hint: draw diagrams of the standing waves produced for each length and deduce what the difference in the length corresponds to. (2 marks)

31 The vocal tract can be approximated as a 17.5 cm pipe closed at one end. It is made up of the mouth, pharynx and larynx, with the vocal cords making vibrations at one end.

a **Determine** the resonant frequency of the fundamental frequency and the next three harmonics when the speed of sound is 340 $m\,s^{-1}$ in the vocal tract. (5 marks)

b **Propose** a reason why men usually have lower resonant frequencies than women. (2 marks)

32 The figure shows a 1.0 m long vertical tube filled with water. The water is slowly let out by a tap at the bottom of the tube while a tuning fork of frequency 512.0 Hz is sounded and held over the top of the tube. Note: the speed of sound in air for this experiment is 340.0 $m\,s^{-1}$.



An observer is solely interested in any resonance sound coming from the tube due to the vibration of the tuning fork. **Determine** and **discuss** what the observer will hear from the time the tube starts to empty until it is empty of water. Use both calculations and diagrams to support your explanation. (14 marks)

Data drill

Speed of sound in air

A student performed an experiment to calculate the speed of sound in air at a specific temperature. A 512 Hz tuning fork was sounded above an air column in a tube in water (Figure 1). The length of the air column was adjusted until the first resonance position was detected. The air column was lengthened until a second resonance position was detected. The difference in length, ΔL, was recorded for each of the four trials. The air temperature was measured as 30.7°C. The accepted value for the speed of sound at this temperature was 349.4 m s^{-1}.

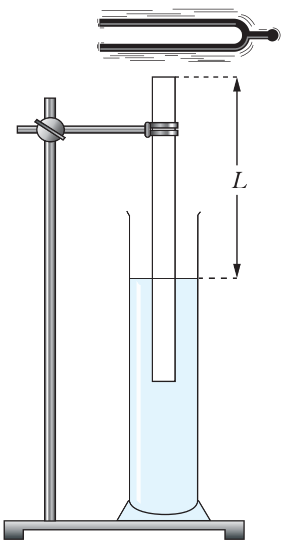


FIGURE 1 Set-up for the resonance experiment

TABLE 1 Results for the resonance experiment

Difference in length, ΔL, between first and second resonance positions						
Trial 1 (cm)	Trial 2 (cm)	Trial 3 (cm)	Trial 4 (cm)	Mean (cm)	Uncertainty (± cm)	Uncertainty (%)
33.7	35.4	36.3	34.8	35.1		

Apply understanding

1 **Calculate** the absolute uncertainty and the percentage uncertainty for the mean of the four trials. (2 marks)

2 **Calculate** the wavelength of the sound from the tuning fork using the formula $\lambda = 2 \times \Delta L$, including the percentage uncertainty. (2 marks)

3 **Calculate** the observed value for the speed of sound using the wave equation, including percentage uncertainty. (3 marks)

Analyse evidence

4 **Compare** the accepted and observed value for the speed of sound by identifying the absolute error and percentage error in the experimental result to the correct number of significant figures. (5 marks)

Interpret evidence

5 **Draw a conclusion** about whether this method accurately determines the speed of sound at a particular temperature. (2 marks)

6 **Deduce** how this experiment could be modified to obtain more accurate and precise data. (2 marks)

Module 13 checklist: Sound

Quizlet: Revise key terms online to test your understanding

MODULE 14 Light

Introduction

"Don't look at the Sun" is a familiar warning before a solar eclipse. This is when the Moon passes between us and the Sun and it is tempting to look up. We need a certain intensity of sunlight on the Earth's surface for us to survive, but the downside is that it will burn your eyes if you look at it directly.

Light has played an important role in the history of the universe and the evolution of humans, in particular. Light from the Sun supplies the energy for plants to photosynthesise and grow, which has the added advantage of providing a food source for other life forms and ultimately us.

A by-product of photosynthesis is the production of oxygen – a necessary ingredient for sustaining life on Earth. Solar energy is becoming more and more important in our transition away from fossil fuels. We rely on light for so much. For one thing, light allows humans to see.

Prior knowledge

Prior knowledge quiz

Check your understanding of light before you start.

Subject matter

Science understanding

→ Compare light to a mechanical wave.

→ Explain the concepts of reflection, refraction, total internal reflection, dispersion, diffraction and interference in relation to the wave model of light.

→ Describe polarisation using a transverse wave model.

→ Construct ray diagrams to demonstrate the reflection and refraction of light.

→ Solve problems involving the reflection of light on single plane mirrors and refraction of light through a single convex or concave lens using ray diagrams to identify the location, orientation and size of an image.

→ Describe the concept of Snell's Law.

- → Solve problems involving the refraction of light at the boundary between two mediums using $\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$.
- → Contrast the speed of light and the speed of mechanical waves.
- → Describe the concept of intensity and its proportionality to the square of the amplitude.
- → Solve problems involving the proportional relationship between intensity of light and the inverse-square of the distance from the source using $I \propto \frac{1}{r^2}$.
- → Determine the refractive index of a transparent substance from experimental data.

Science as a human endeavour

- → Appreciate the significant contributions of scientists such as Laura Bassi, Willebrord Snellius, Albert A Michelson and Edward W Morley.
- → Appreciate the role of experiments in furthering our understanding of light and its wave-like behaviour.
- → Consider the importance of wave properties in experiments such as those performed by Michelson and Morley to demonstrate light waves travel through a vacuum and not the luminiferous aether as was believed at the time.

Science inquiry

- → Consider the apparent position of objects under water in relation to observations made through different media.
- → Investigate the law of reflection.
- → Investigate the refractive properties of different substances.

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Practicals

oxforddigital **These lessons are available on Oxford Digital.**

Lesson 14.5 The law of reflection for images in a plane mirror

Lesson 14.7 Refractive properties of a transparent substance

Lesson 14.1
The wave model of light

Key ideas

→ Light is an electromagnetic wave that needs no medium for its propagation.
→ The wave and particle models are used to explain the behaviour of light.

Learning intentions and success criteria

light
an electromagnetic wave that does not need a medium for its propagation

What are the models of light?

Previously, we investigated the properties of mechanical waves – in particular, water and sound waves. Mechanical waves need a medium for their propagation, such as air, water and steel. The other type of wave is an electromagnetic wave, which does not require a medium for its propagation. Since **light** can travel through a vacuum, it is not modelled as a mechanical wave but, instead, as an electromagnetic wave. It is a form of electromagnetic radiation.

You would be most familiar with visible light, which enables objects to be seen. Visible light is just a small part of all the electromagnetic waves that exist. Radio waves, microwaves and infrared waves are all examples of electromagnetic waves.

There are two main models for light that provide understanding of its behaviour as it interacts with matter.

wave model of light
uses the characteristics of waves such as wavelength, frequency and speed to describe the behaviour of light such as interference, reflection and refraction

The wave model

The **wave model of light** was proposed in the mid-1600s as a useful tool to understand how energy spreads. From the late 17th century through to the 1860s, scientists continued to refine their understanding of light and its wave-like behaviour through experimentation. The current wave model describes a travelling energy wave using quantities such as wavelength, frequency and speed. The wave model explains diffraction and interference, and how light can "bend" around corners.

Study tip
In Unit 2, we consider light and explain its behaviour using the wave model.

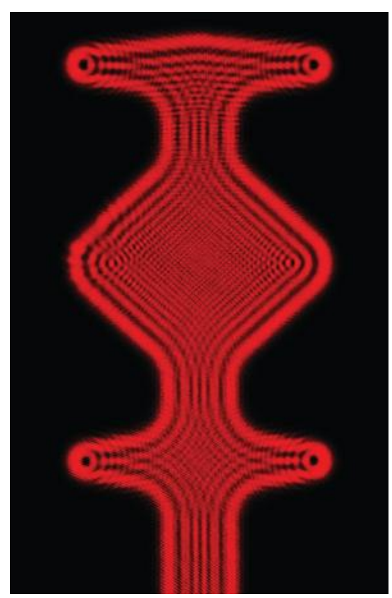


FIGURE 1 Diffraction of light through a razor blade. The diffraction of light occurs around the edges of objects and through small apertures because light bends as it passes near an object. The particle model can't explain this phenomenon because the light is not travelling in straight lines.

particle model of light
uses photons to describe the behaviour of light, such as the photoelectric effect and atomic spectra

The particle model

In the mid-1600s, European philosopher Pierre Gassendi asserted (without evidence) that light was made up of "corpuscles". He imagined that these were infinitesimally small, perfectly elastic particles that travelled in straight lines and lit up any object they met. The **particle model of light** disappeared for 250 years, despite Newton's defence of it, as interest in the wave model grew.

In 1927, the particle model returned as the only way to explain atomic spectra and the photoelectric effect, but it couldn't explain diffraction (Figure 1), interference and polarisation.

The quantum theory

The wave and particle models of light can be used to explain many of its characteristics, but neither can explain them all. In 1927, the quantum theory was developed to unify both models. The quantum theory says that light can be modelled as both a particle and a wave, and that they are complementary rather than rival concepts. The theory shows, in a systematic and logical way, that each model can be used in appropriate contexts.

In Unit 2, we will assume that light travels through space by means of waves that can also be depicted as **rays**. The particle model will be discussed in Unit 4. In this module, we will investigate the properties of light with respect to ray and wave characteristics: reflection and refraction for rays, and diffraction and interference for waves.

rays
straight line paths followed by narrow beams of light along which light energy travels; lines depicting the direction of propagation perpendicular to the wavefront

transparent
a substance through which you can see clearly because it allows light to pass through without appreciable scattering

rectilinear propagation
the property of light that characterises it as travelling in a straight line in a uniform medium

What are the properties of light?

Rectilinear propagation

In a homogenous (uniform) **transparent** medium, light travels in a straight line. This is known as **rectilinear propagation** of light and can be demonstrated by viewing the path of a laser light in air (Figure 2). The "recti" part just means "straight" in Latin.

Speed

The speed of light is a constant in a given medium and nothing can travel faster than light. In a vacuum, the speed of light is $2.998 \times 10^8\,\mathrm{m\,s^{-1}}$. However, light slows down when it moves through matter. The speed of light in water is about $2.25 \times 10^8\,\mathrm{m\,s^{-1}}$. In air, the slowing is quite negligible. For our calculations, we round off the speed of light to $3 \times 10^8\,\mathrm{m\,s^{-1}}$ in a vacuum (or in air).

FIGURE 2 A laser beam travels in a straight line.

Check your learning 14.1

Check your learning 14.1: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Recall** the speed of light in a vacuum (1 s.f.). (1 mark)

2 **Explain** why light cannot be modelled as a mechanical wave. (2 marks)

3 **Recall** whether light needs a vacuum for its transmission. (1 mark)

4 **Recall** two examples of electromagnetic radiation. (2 marks)

Analytical processes

5 On average, the Sun is 149.6 million kilometres away from Earth. **Determine** how long (in minutes) it takes light to travel from the Sun to Earth. (2 marks)

6 Physicists used to argue about which was the better model for light – the wave model or the particle model. **Consider** why they don't argue about this now. (2 marks)

Knowledge utilisation

7 **Predict** whether you could communicate on the Moon's surface using torches. (2 marks)

8 **Evaluate** whether the Sun would look any different than it does at the moment if different colours of light travelled at different speeds. (4 marks)

Lesson 14.2
Light: a transverse wave

Key ideas

→ Light is modelled as transverse waves composed of electric and magnetic fields.
→ Polarisation controls the amount of light transmitted by only allowing waves oscillating in a specific direction.

How are light waves propagated?

Learning intentions and success criteria

Scottish physicist James Clerk Maxwell (1831–1879) explained the nature of light waves based on electric and magnetic interactions, which is still the accepted theory today. He suggested that light waves are made up of synchronised oscillations of transverse electric and magnetic (electromagnetic) fields at right angles to each other, and propagated at the speed of light in a vacuum.

In general terms, Maxwell suggested that electromagnetic waves (such as light) are composed of two plane waves, in phase, and at 90° to each other. As these waves are propagated through space, they carry energy with them.

Maxwell also developed general mathematical equations for these electromagnetic waves. The experimental value for the speed of light was found to be close to that predicted by his equations, suggesting that light was electromagnetic in origin. Maxwell's theory of electromagnetic waves was developed before he applied it to light.

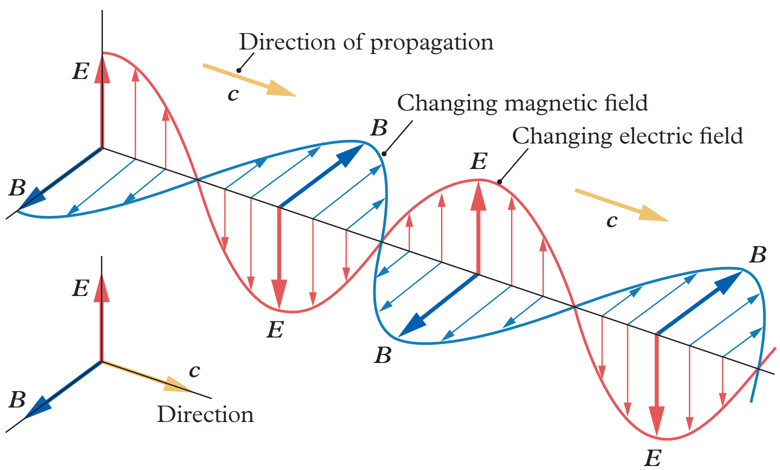


FIGURE 1 A light wave composed of magnetic, B, and electric, E, fields oscillating at right angles to each other and to the direction of propagation, c. The waves are shown here as propagating in one direction only; in reality, they would be in all directions.

What is polarisation?

In 1669, Danish scientist Erasmus Bartholin reported the strange behaviour of light as it passed through a crystal of calcite – it split the ray in two. One beam passed through unchanged, but the other was refracted and emerged parallel to the other beam (Figure 2).

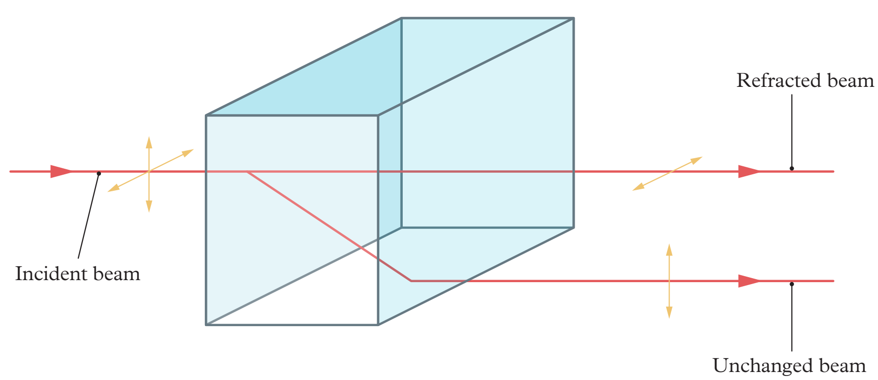


FIGURE 2 Bartholin observed that when a single beam of light was passed through a calcite crystal, it split into two parallel beams.

In 1690, Christiaan Huygens developed a wave theory of light that explained this double refraction, but it was not until 1704 that Isaac Newton gave it a name – **polarisation**. Newton said it was as if some of the particles of light were attracted like iron to the poles of a magnet. It wasn't until 100 years later that French army engineer Étienne-Louis Malus used the term "polarised light" to explain the phenomenon. He established that polarisation was a property of the light wave and not of the crystal.

polarisation
(linear) a process in which the electric field in light oscillates in a fixed plane perpendicular to the direction of propagation, in contrast to an unpolarised wave that allows oscillations in all directions perpendicular to the direction of propagation

We learned earlier that light is modelled as transverse waves with electric (E) and magnetic (B) fields oscillating at right angles to each other and to the direction of propagation. In discussing polarisation we need only consider the electric field, as that is the one that most interacts with matter. An ordinary beam of light can have its electric field vibrating in all directions. As we define the direction of polarisation as the direction in which the electric field is oscillating, we say that light is unpolarised. If the electric field vibrates in the same direction at all times at a particular point, the wave is described as linear or plane-polarised, or simply as "polarised".

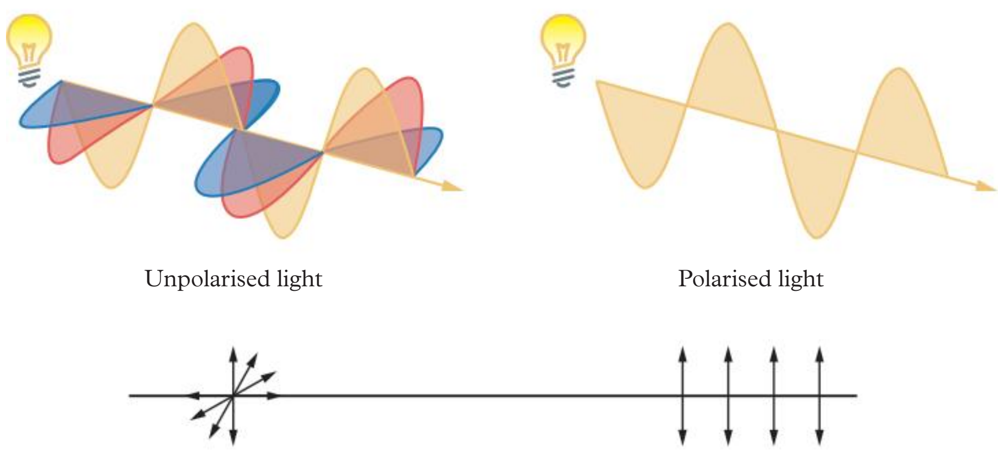


FIGURE 3 In unpolarised light, the electric field oscillates in all directions perpendicular to the direction of propagation, whereas in polarised light, it oscillates in a fixed plane – only one component of the electric field is allowed through.

Polarisers

A device that allows only one component of the electric field through is called a **polariser**. A model for this is a slit in a wall through which a spring or rope is threaded and shaken in all directions. The slit is comparable to the polariser: only those waves that are in the same plane as the slit will get through – the rest will be blocked. This is shown in Figure 4, where the up–down movements will go through, since the slit is also in the up–down direction, but the side-to-side movements will not. This is only a model for polarisation. Be aware that it tries to simplify the complex behaviour of atoms and light with a simple analogy that doesn't explain the physics of the process. The crests and troughs of the wave do not have a physical up-and-down extent in space. The ups and downs merely represent the strength and direction of the electric field at that point. The model just helps you learn that the electric field can be blocked by a polariser.

polariser
a device that allows only one component of the electric field to pass

We can measure the degree of polarisation of light by using a second polariser called an analyser (Figure 5). If the analyser is not in the same direction as the polariser, no light will be transmitted.

"Polaroid" is the brand name of synthetic materials that have these polarising properties. These materials polarise light; that is, they allow light waves vibrating in one direction through. If an analyser is placed after the polariser (Figure 5), it is possible to

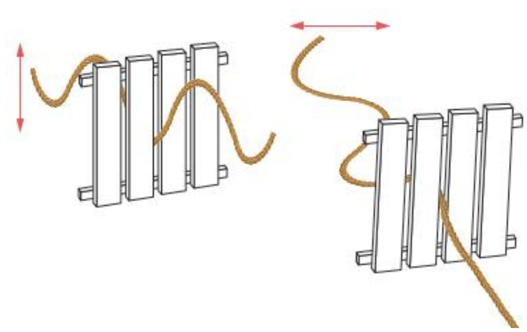


FIGURE 4 Transverse waves pass through the slit if it is in the same plane as the wave. When the waves are in a different plane, they do not pass through.

block out all light from the source by rotating the analyser. If the plane of the analyser and the polariser align, light will be seen. If the plane of the analyser and the polariser are at right angles, no light will be transmitted through the analyser. The amount of light transmitted will vary between these two extremes depending on the angle between the planes of the polariser and the analyser.

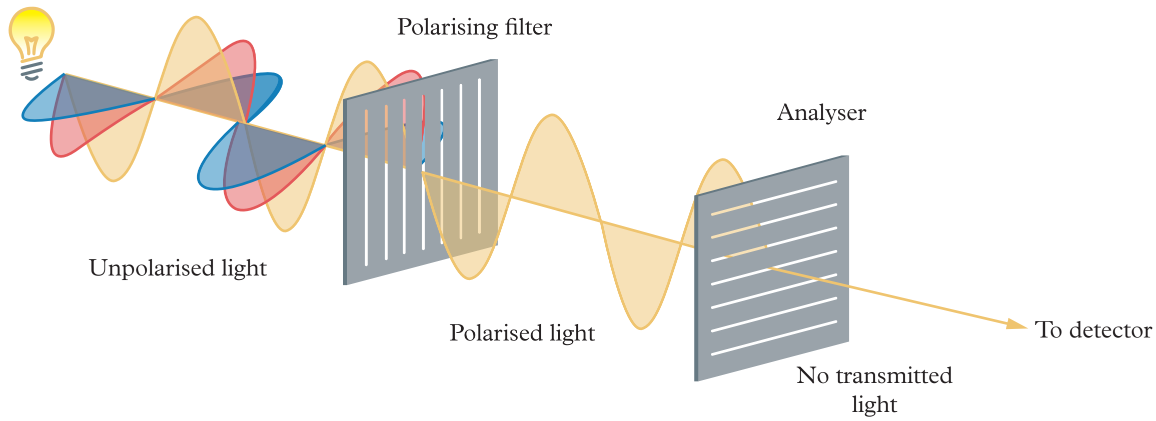


FIGURE 5 Polarisers allow only light waves in the plane of the polariser to pass through. The angles between the polariser and the analyser determine the amount of light that is transmitted. In this case, no light will be transmitted, as the analyser is at right angles to the polariser.

FIGURE 6 Polarised sunglasses use lenses with polarising properties.

Polaroids have a number of uses:

- Sunglasses – Polaroid sunglasses block annoying reflections from horizontal surfaces including wet roads and the ocean.
- Cameras – Crossed polarising filters can reduce the brightness of light entering a camera.
- Liquid crystal displays (LCDs) – The screens of calculators, phones, TV and digital watches use two pieces of polaroid that are crossed to produce dark symbols on a lighter background.
- Radio and TV waves – The electromagnetic radio and TV waves sent out from the big transmitters are usually polarised.

FIGURE 7 Sunlight is scattered by atoms in the atmosphere and the scattered light tends to oscillate in one direction, so we say it is polarised. A polarising filter (right) removes most of the scattered light, so the sky looks darker.

Real-world physics

Ruby Payne-Scott's world-famous radio wave research

Ruby Payne-Scott (1912–1981), was an Australian physicist and radio astronomer who obtained first-class honours in mathematics and physics at the University of Sydney. During World War II, she was employed by CSIRO (the Commonwealth Scientific and Industrial Research Organisation) to conduct research into new, top secret work investigating radar technology, which uses radio waves – a region of the electromagnetic spectrum with the longest wavelengths.

From this, Payne-Scott became Australia's expert on the detection of enemy aircraft. After the war, she joined a team to investigate the mysterious cosmic radiation that emanates from the Sun and other astronomical objects. Her work was published in the prestigious Proceedings of the Royal Society of London. It provided a foundation for future research in radio astronomy and allowed Australia to become a world leader in the field.

Ruby Payne-Scott was an outstanding physicist and an advocate for women's rights, confronting inequality and injustice wherever she saw it. Payne-Scott died in 1981 and The New York Times wrote that she laid the foundation for a new field of science called radio astronomy.

FIGURE 8 Ruby Payne-Scott was an Australian pioneer in radio physics and radio astronomy.

Apply your understanding

1 **Compare** the characteristics of radio waves and visible light. (3 marks)

2 **Explain** if the principles of polarisation described for light waves would apply to radio waves. (2 marks)

Check your learning 14.2

Check your learning 14.2: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Recall** what a transverse wave model is. (1 mark)

2 **Describe** polarisation in the context of sunglasses, using a transverse wave model. (2 marks)

3 **Explain** how a polariser works in terms of the electric field component of light, using a picket fence analogy. (3 marks)

4 **Describe** what you would notice if you were looking through polarising glasses at light reflected off a pond and then turned the glasses slowly through 180°. (2 marks)

5 Placing two polarisers and an analyser with their polarisation angles at 90° to each other has an effect on the incident light. **Describe** this phenomenon. (3 marks)

Knowledge utilisation

6 **Design** an experiment to investigate the intensity of light through a pair of polarisers as one of the polarisers is rotated through 180°. **Propose**, with reasons, what the intensity vs angle relationship may look like. (3 marks)

7 **Design** a test to decide whether the light directly from the Sun is polarised or unpolarised. (2 marks)

Lesson 14.3
Intensity

Key ideas

→ Intensity of light is the power transferred per unit area.
→ The intensity of light is proportional to the square of the amplitude of the waves.
→ The intensity of light decreases with distance in an inverse-square relationship.

Learning intentions and success criteria

How do we determine the intensity of light?

intensity
the average power per unit area carried by a wave

A light source, such as a bulb or the Sun, emits light in all directions. The total energy of all the light given off is termed the "luminous flux". People are usually interested in the amount of light falling on them – the energy falling on a given area in a given time. We are not as interested in the entire amount of energy given off by the source in all directions; we are interested in the **intensity** of the light received by us.

We can develop a formula to help determine intensity. Recall that power is the rate at which energy is transferred:

$$P = \frac{W}{t}$$

where W (work done) is energy transferred (ΔE) measured in joules (J); and P is power measured in watts (W) or joules per second ($\mathrm{J\,s^{-1}}$).

Intensity is the power transferred per unit area, A, where the area is measured on the plane perpendicular to the direction of propagation of the energy:

$$I = \frac{P}{A}$$

where the quantity "intensity" has the symbol I and the unit of watts per square metre ($\mathrm{W\,m^{-2}}$). The symbol A represents the area of a surface that light illuminates. The symbol A is also used elsewhere for amplitude. Don't get them confused.

You may recall that we used intensity as a measure of energy output of ionising radiation. We used "counts per second" as a measure of the intensity of the radiation from a particular source. The definition of intensity used in this module is more general, as it allows a comparison of radiation from different sources. In Worked example 14.3A, we see how intensity is calculated and how much energy is transferred in a given time.

Worked example 14.3A

Calculating energy transfer from intensity

The radiation falling on a surface of area $4.0\,\mathrm{m^2}$ has a power of 125.0 W.

a **Calculate** the intensity of the radiation on this surface (2 s.f.). (1 mark)
b **Calculate** how much energy (in J) is transferred to this surface in 1.0 second (2 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the intensity and power formulas. The questions are worth 1 mark each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$I = \frac{P}{A}$ $P = 125.0\,\text{W}$, $A = 4.0\,\text{m}^2$, $I = ?$ $P = \frac{W}{t}$ $t = 1.0\,\text{s}$, $\Delta E = ?$
Step 3: Substitute the known values into the formula and find the intensity.	**a** $I = \frac{125.0}{4.0}$ $= 31.25$
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures.	$31\,\text{W}\,\text{m}^{-2}$ (2 s.f.) (1 mark)
Step 5: Substitute the known values into the formula and find the energy.	**b** $125.0 = \frac{W}{1.0}$ $W = 125.0 \times 1.0$ $= 125$
Step 6: Finalise your answer for part **b** and make sure you have included the correct units and significant figures.	130 J (2 s.f.) (1 mark)

Your turn

The sunlight falling on a solar panel on a bright sunny day has an intensity of 1.10 kW per square metre.

a **Calculate** the power transmitted to a rooftop solar photovoltaic panel measuring 1.7 m × 1.0 m (2 s.f.). (1 mark)

b **Calculate** how much energy is delivered to the panel in 1.0 hour (2 s.f.). (1 mark)

Worked example 14.3B

Calculating intensity from energy transfer

A can containing 100.0 mL of water is placed near a high-intensity floodlight. The area of the can exposed to light is 8.0 cm × 15.0 cm and the energy delivered to the can was 1428 J in 5.0 minutes.

a **Calculate** the power of the radiation striking the surface of the can (2 s.f.). (2 marks)

b **Calculate** the intensity of the radiation at the surface, assuming it was all converted to thermal energy (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the power and intensity formulas. The questions are worth 2 marks each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$P = \frac{W}{t}$ $\Delta E = 1428\,\text{J}$, $t = 5.0\,\text{min}$, $P = ?$ $I = \frac{P}{A}$ $A = 8.0\,\text{cm} \times 15.0\,\text{cm}$, $I = ?$

Think	Do
Step 3: Substitute the known values into the formula and find the power. Make sure you complete any necessary conversions.	**a** $P = \frac{1428}{5.0 \times 60}$ $= 4.76$ (1 mark)
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures.	4.8 W (2 s.f.) (1 mark)
Step 5: For part **b** substitute the known values into the formula and find the intensity. Make sure you complete any necessary conversions.	**b** $I = \frac{4.76}{\frac{8.0}{100} \times \frac{15.0}{100}}$ $= 396.67$ (1 mark)
Step 6: Finalise your answer for part **b** and make sure you have included the correct units and significant figures.	$400\,\mathrm{W\,m^{-2}}$ or $4.0 \times 10^2\,\mathrm{W\,m^{-2}}$ (2 s.f.) (1 mark)

Your turn

A laser beam delivers 1.2 J of energy in 1.0 minute to a surface and is spread over a circular area of diameter 2.0 mm. **Calculate** the

a power being delivered to the surface (2 s.f.) (2 marks)

b intensity of the radiation in the beam area on the surface (2 s.f.). (2 marks)

What is the relationship between light intensity and amplitude?

With water waves, it takes energy to push the water up and down into a wave. The bigger the amplitude (height) of a wave, the greater the energy being transferred. The same is true of electromagnetic waves. The problem is that electromagnetic waves do not have particles that move up and down, unlike mechanical waves, so we use another property that they have: electric field strength. This has units in newtons per coulomb, $\mathrm{N\,C^{-1}}$, which relates force to units of electric charge. The magnetic field is just a multiple of this. Thus, the greater the intensity of a light source, the greater the amplitude of both the oscillating electric and magnetic fields of the electromagnetic radiation or light wave.

The intensity is found to be proportional to the square of the amplitude of the wave. That is, when you double the amplitude of a light wave, you increase the intensity fourfold (4×). For example, if a light wave has an amplitude of $2\,\mathrm{N\,C^{-1}}$, and you double this to $4\,\mathrm{N\,C^{-1}}$, the intensity will increase fourfold. However, to double the intensity, you only have to increase the amplitude by the square root of 2, or 1.4 times.

You are not required to do any calculations on intensity and amplitude. You just need to be able to describe the relationship:

$$I \propto A^2$$

where A is the amplitude of the electric or magnetic field.

What is the relationship between light intensity and distance?

Intensity of light decreases with distance. You know that the further away you are from a light, the dimmer it appears. For example, point S has the source power of P_S watts (Figure 1) which has radiated outwards in all directions (producing a spherical wave). The surface area

A (in m^2) of the sphere at a distance r (radius) is given by the formula $4\pi r^2$. The amount of the source power per square metre on the surface is then:

$$\frac{P}{A} = \frac{P_S}{4\pi r^2}$$

which, by definition, is the intensity I.

At a distance of $2r$, the power is now spread over four times the area, so the power per unit area is $\frac{1}{4}$ of the amount at r. Likewise, at a distance of $3r$, the intensity is $\frac{1}{9}$ of the intensity at r.

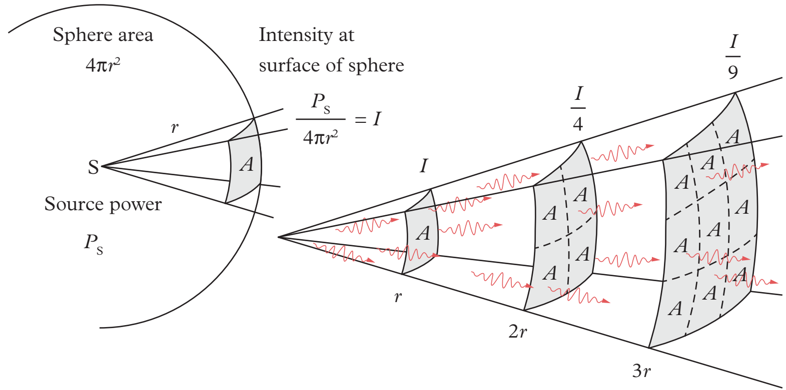


FIGURE 1 The energy twice as far from the source is spread over four times the area, hence one-quarter the intensity.

If a power source is radiating energy in all directions (producing a spherical wave), and no energy is absorbed or scattered by the medium, then the intensity decreases in proportion to distance from the object squared. This is an example of the inverse-square law:

$$I \propto \frac{1}{r^2}$$

To compare the intensity I_1 at a radial distance r_1 from a source to the intensity I_2 at a distance r_2, we can use the relationship:

$$I_1 r_1^{\,2} = I_2 r_2^{\,2}$$

This can be rearranged to give:

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$$

For example, the intensity of radiation from the Sun is 1,367 W m^{-2} at the distance of Earth (1 astronomical unit, AU) but is 9,126 W m^{-2} at the distance of Mercury (0.387 AU). So, an approximate threefold increase in distance results in an approximately ninefold decrease in intensity of radiation.

This relationship holds if the medium the light is travelling through doesn't absorb or scatter the light. The presence of dust will have such an effect. This caused a big problem for astronomer Harlow Shapley in 1918. He was using a huge telescope at the Mount Wilson Observatory in California, United States, to measure the diameter of Earth's Milky Way galaxy. Shapley's estimate of 300,000 light years was far too large as he was unaware that there was so much intervening dust. Today, 100,000 light years is the accepted value.

Worked example 14.3C

Calculating intensity with distance from source

The streetlights in Figure 2 are all 500 W sodium vapour lamps.

A student is standing 20.0 m from the first light. Assume there is no absorption or scattering of light.

a **Calculate** the intensity as measured from the student's position (2 s.f.). (2 marks)

b **Determine** where the student would have to stand to measure the intensity as half this (2 s.f.). (2 marks)

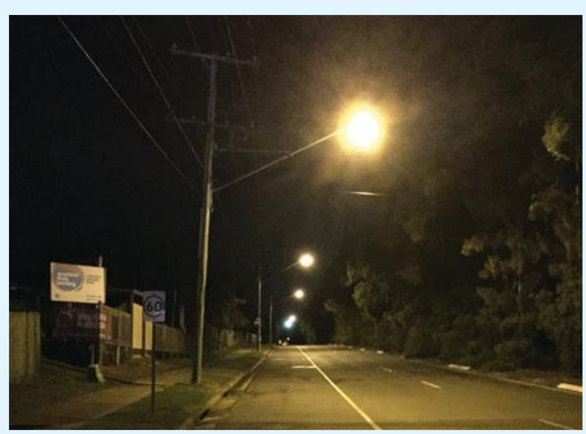


FIGURE 2 Sodium vapour lamps

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. "Determine" means to establish after a calculation. We need to apply the intensity and distance formulas. The questions are worth 2 marks each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$I = \frac{P}{4\pi r^2}$ $P = 500\,\text{W}$, $r = 20.0\,\text{m}$, $I = ?$ **a** $\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$ $I_2 = \frac{1}{2} \times I_1$, $r_1 = 20.0\,\text{m}$, $r_2 = ?$
Step 3: Substitute the known values into the formula and find the intensity.	$I = \frac{500}{4\pi(20.0)^2}$ $= 0.09947$ (1 mark)
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures.	$0.10\,\text{W}\,\text{m}^{-2}$ (2 s.f.) (1 mark)
Step 5: The question asks for the distance required to halve the intensity.	**b** $I_2 = \frac{0.00947}{2}$ $= 0.04973$
Step 6: Substitute the known values into the formula and find the distance r_2.	$\frac{0.00947}{0.04973} = \frac{r_2^2}{20.0^2}$ $r_2{}^2 = 799.99$ $r_2 = 28.28$ (1 mark)
Step 7: Finalise your answer for part **b** and make sure you have included the correct units and significant figures. You need to say that this is the distance from the light, rather than just leaving it as an r_2 value.	28 (2 s.f.) i.e. 28 m away from the light (1 mark)

Your turn

A room lamp is rated as 65 W and illuminates a book page measuring 27 cm by 22 cm whose surface is perpendicular to the light striking it. The page is 3.5 m away from the light. Assume there is no absorption or scattering of light (the air is clean).

- **a** **Calculate** the intensity of light falling on the book page (2 s.f.). (2 marks)
- **b** **Determine** the energy falling on the page per second (2 s.f.). (2 marks)
- **c** **Calculate** where the book would have to be placed to receive three times as much illumination (2 s.f.). (2 marks)

Check your learning 14.3

Check your learning 14.3: Complete these questions online or in your workbook.

Retrieval and comprehension

1. **Explain** what is meant by "intensity follows the inverse-square relationship with distance". (2 marks)
2. **Describe** the relationship between intensity and amplitude of a light wave. (2 marks)
3. A bright torch has a light intensity of $15.0\,\text{W}\,\text{m}^{-2}$ at a distance 1.00 m away.
   - **a** **Calculate** the intensity of the torch at 100.0 m distance. (2 marks)
   - **b** **Determine** the distance where the intensity would be half that which it is at 1.0 m. (2 marks)

Analytical processes

4. The amount of sunlight reaching the surface of Earth on a particular day is $340\,\text{W}\,\text{m}^{-2}$.

a **Calculate** how much power (in W) is received by a solar photovoltaic panel measuring 1.2 × 0.9 m on a roof. (1 mark)

b **Calculate** how many 60 W light bulbs this is equivalent to. (1 mark)

c **Determine** the energy of the radiation transferred to the solar panel in 8 hours. (1 mark)

5 The intensity of a radio signal is 0.120 W m^{-2} at a distance of 16.0 m from a small transmitter. Without using a calculator, **determine** the intensity of the signal

a 8.0 m from the transmitter (1 mark)

b 4.0 m from the transmitter. (1 mark)

6 A pet shop owner has a glass tank with an open top measuring 50.0 cm × 120.0 cm. The owner wants to illuminate the plants inside with light of 10 W. **Determine** the power of the bulb that must be used in a light fitting 60.0 cm directly above the tank. (2 marks)

7 Assume the helium–neon lasers commonly used in student physics laboratories have power outputs of 0.50 mW.

a A laser beam is projected onto a circular spot 1.00 mm in diameter. **Calculate** the intensity of the light at the spot. (4 marks)

b An intensity of 100 W cm^{-2} is required to set fire to paper. **Determine** how many laser beams, each with a 1.00 mm spot, would be necessary to achieve this. (2 marks)

Knowledge utilisation

8 **Decide** if intensity and power are the same thing. (2 marks)

9 A student wants to start a fire from moonlight. Bright moonlight intensity is $\frac{1}{5{,}000{,}000}$ that of the Sun (Sun is 1,000 W m^{-2}), so the student plans to use a lens of 5 m diameter and concentrate the light down to a 1 cm^2 spot. For a fire, the student needs 100 W cm^{-2}, so they think it will work. **Evaluate** this proposal. (8 marks)

Lesson 14.4
Reflection in plane mirrors

Key ideas

→ The first law of reflection states that the incident ray, reflected ray and normal are in the same plane.

→ The second law of reflection states that the angle of incidence is the same as the angle of reflection.

→ Ray diagrams show the paths of light as they reflect off plane mirrors.

How do your eyes see light?

Learning intentions and success criteria

Light boxes and lasers are devices that can be used to produce beams or rays of light. Light boxes are common devices used in schools to produce thin beams or rays of light for the investigation of optics in the laboratory (Figure 1). Lasers emit light of one wavelength. You cannot see the light of a laser or the light from a light box unless the light strikes a wall or an object (including dust in the air). This is because your eye and brain only respond to light when it strikes your eye.

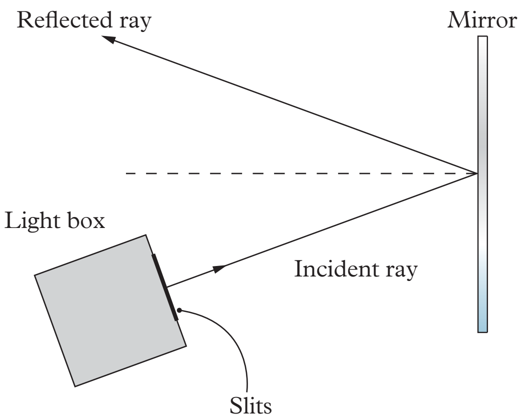


FIGURE 1 Light boxes that produce thin beams of light (rays) are used in laboratory optical investigations.

Similarly, the Sun is a source of light. In the same way, the lake and mountains in the photo in Figure 2 are seen because the Sun illuminates them, and they reflect light to the eyes.

FIGURE 2 An early morning reflection on Lake Matheson at Fox Glacier, New Zealand. What is the difference between the real image and its reflection? Can you tell if this image has been rotated and is now upside down?

first law of reflection
the incident ray, the reflected ray and the normal to the surface of the mirror all lie in the same plane

second law of reflection
the angle of reflection is equal to the angle of incidence when both angles are measured with respect to the normal to the mirror

How is light reflected?

The reflection of light can be explained using a plane mirror. This usually consists of a flat piece of glass that has its back coated with a thin layer of aluminium, and then a layer of paint to prevent the aluminium from flaking off. What happens to a ray of light when it strikes a plane mirror? Everyone would say it is reflected, but in what way is it reflected?

The first law of reflection

The light ray that strikes the mirror is the incident ray, the ray that leaves the mirror is the reflected ray, and the perpendicular to the mirror is the normal (Figure 3). If you shine a laser at an angle into a mirror to provide the incident ray, this incident ray, the normal and the reflected ray all lie in the same plane. This is the **first law of reflection**.

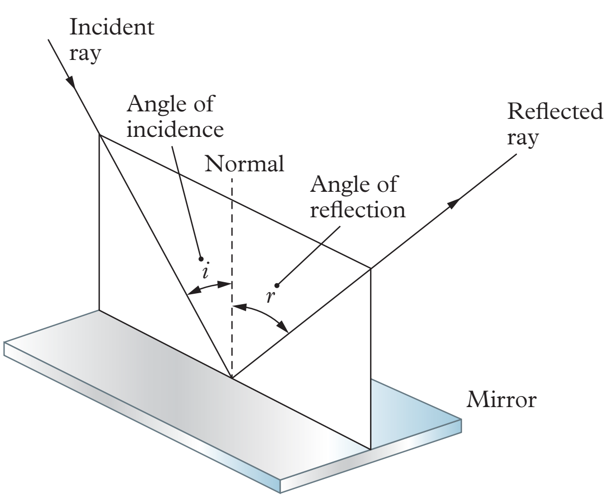


FIGURE 3 The common terms associated with rays of light and plane mirrors

The second law of reflection

The angle between the incident ray and the normal is the angle of incidence ($\angle i$), and the angle between the reflected ray and the normal is the angle of reflection ($\angle r$). The angle of incidence equals the angle of reflection. This is the **second law of reflection**:

$$\angle i = \angle r$$

How are images reflected from a mirror?

When you look into a mirror, you see an image of yourself. The image is the same size as the object (you) and it is upright. It looks like it is behind the mirror, about the same distance you are in front of it. It is also laterally inverted.

For example, the person in Figure 4 raises their right hand, and the image appears to raise its left hand.

The position of an image can be found by using a **ray diagram**, which shows where the rays go (Figure 5). For example, object X is on the left and object Y is on the right. In the image, X′ is on the image's right. Both objects appear to be projecting behind the mirror at the same distance as they are in front of it.

ray diagram
a representation of the possible paths light can take to get from a source or object to an observer or screen

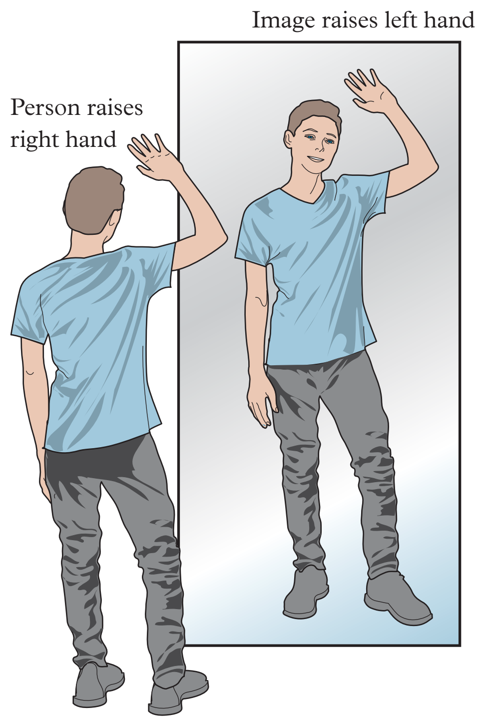


FIGURE 4 Lateral inversion in a plane mirror

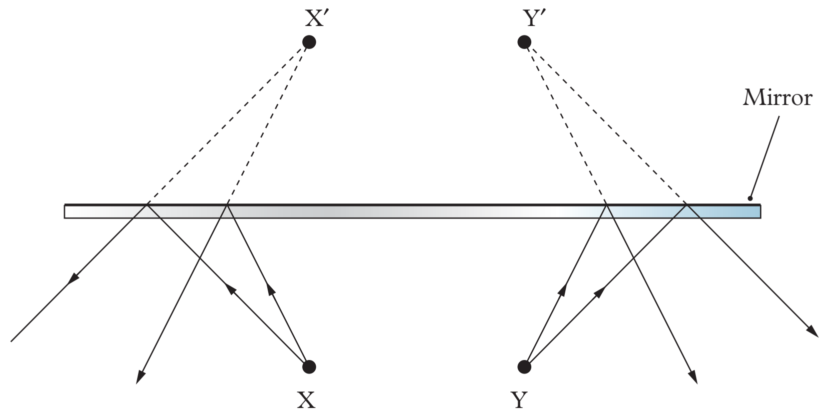


FIGURE 5 A ray diagram shows lateral inversion in a plane mirror.

Instead of your face or objects X and Y, we can consider a pin. Look at the image of the head of a pin in a plane mirror (the upper dot in Figure 6). The rays from the pin head reflect off the mirror and spread out (diverge) as they move towards your eyes. When your eyes see the rays (the dotted line), your brain projects them backwards to where the brain thinks they must have come from. These rays appear to meet behind the mirror and your brain interprets this as the location for the image of the pin head. The rays don't actually pass through the image, but just appear to. For this reason, we call it a **virtual image**.

virtual image
an image through which the rays of light from the object do not actually converge but only appear to

real image
an image through which the rays of light from the object actually converge

The opposite of a virtual image is a **real image**. Examples of real images include the image seen on a cinema screen (the source being the projector), or the image produced on the retina of your eye when you look at something. The cornea and lens of your eye focus the rays of light from an object to make an image on your retina. The rays of light actually pass through the image, so it is a real image.

Let's return to the formation of images by a plane mirror. If you study the ray diagram in Figure 6 you can confirm the following observations:

- The image is the same distance behind the mirror as the object is in front.
- The line joining the object to the image is perpendicular to the mirror.

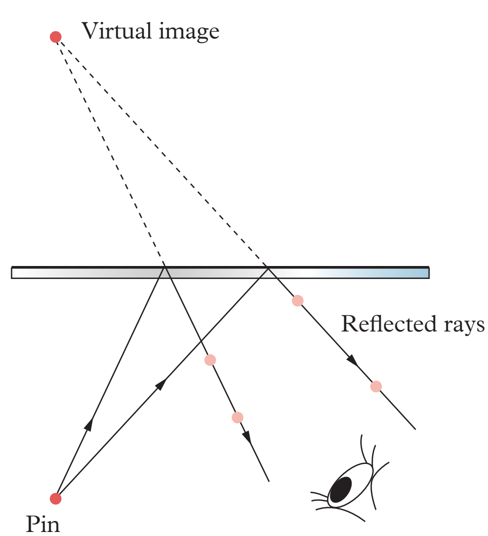


FIGURE 6 Two rays are needed to determine the position of the image (virtual image).

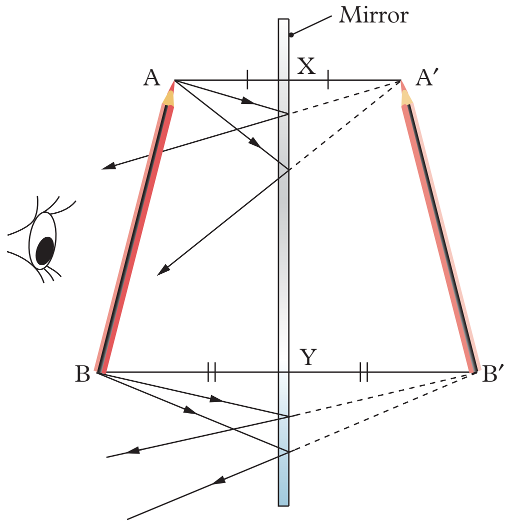


FIGURE 7 An image of pencil AB is formed in the mirror, and represented by the paler pencil A′B′.

Let us now look at a solid object such as a pencil. Figure 7 shows the image of pencil AB in a mirror. The image of A can be established by using two rays from point A reflecting from the mirror to your eyes. The same applies to B. To position an object, two rays are needed. The brain uses the fact that light travels in straight lines and traces the rays back to where they appear to come from.

Pencil A′B′ slopes the opposite way. This is because the image of an object lies the same distance behind a mirror as the object does in front. Therefore AX = XA′, and BY = YB′. The same applies for all points between A and B. Notice also that the image A′B′ is the same size as AB.

Worked example 14.4A

Constructing and labelling a ray diagram for a plane mirror

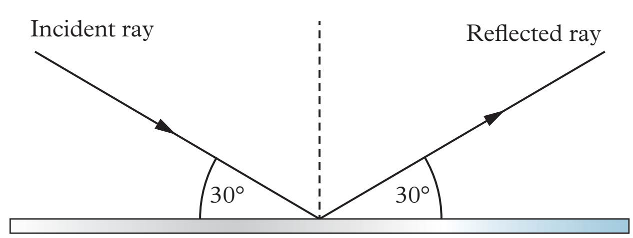
A ray of light strikes a plane mirror at an angle of 30° to its surface.

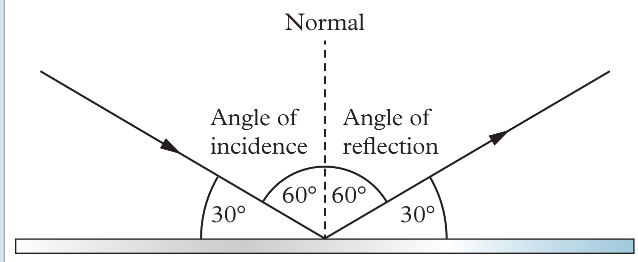
a **Construct** an accurate ray diagram and **identify** the incident ray and reflected ray. (3 marks)

b **Identify** the following by labelling the diagram with

 i the angle of incidence and its magnitude (1 mark)

 ii the angle of reflection and its magnitude. (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Construct" means to display information in a diagrammatical or logical form. "Identify" means to locate, recognise and/or name. We need to draw a diagram and label the components specified in the questions. The questions are worth a varying number of marks, so we must recall the correct information, construct the diagram and label it correctly.
Step 2: For part **a**, draw a ray diagram showing a straight line representing the mirror surface. Add the incident (incoming) and reflected (outgoing) rays using directional arrows. You will also need to include the normal at the point of contact – this is perpendicular to the mirror surface.	**a** The incoming ray has an angle of 30° to the surface. (1 mark) The outgoing ray is reflected at 30° to the surface. (1 mark) The normal is shown with the dashed line. (1 mark) 
Step 3: For part **b, i,** identify the angle of incidence. It is the angle between the incident ray and the normal. For part **b, ii,** identify the angle of reflection. It is the angle between the reflected ray and the normal. The question asks for the magnitude, so you will need to calculate this.	**b** **i** Magnitude of the angle of incidence = 90 − 30 = 60° (1 mark) **ii** Magnitude of the angle of reflection = 90 − 30 = 60° (1 mark)

Think	Do
Step 4: Finalise your answer and include all labels.	 (1 mark for each angle label)

Your turn

A ray of light strikes a mirror and reflects off it. The angle between the incoming ray and the outgoing ray is 50°. **Construct** a ray diagram and **identify** the angle of incidence and the angle of reflection and their magnitudes. (5 marks)

Check your learning 14.4

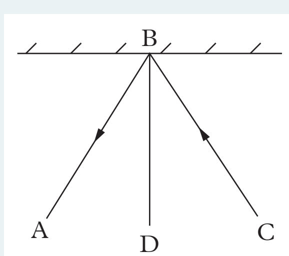
Check your learning 14.4: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** two significant facts about an image of yourself in a plane mirror. (2 marks)

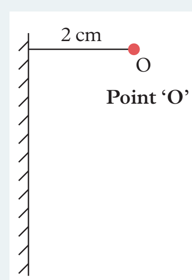
2 One method of taking your own photo is to photograph your image in a large mirror. If you are standing 2.0 m in front of the mirror, **explain** how far away the camera would see the image. (2 marks)

3 **Identify** the angle of incidence, the angle of reflection, the incident ray, the reflected ray and the normal. (3 marks)



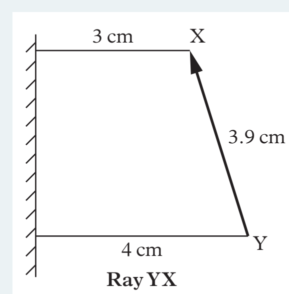
4 **Sketch** accurate ray diagrams to find the image of each object.

a



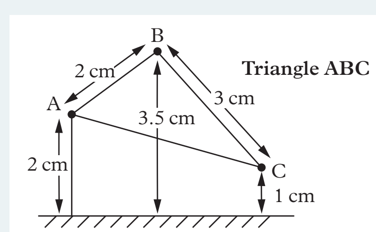
(1 mark)

b



(1 mark)

c



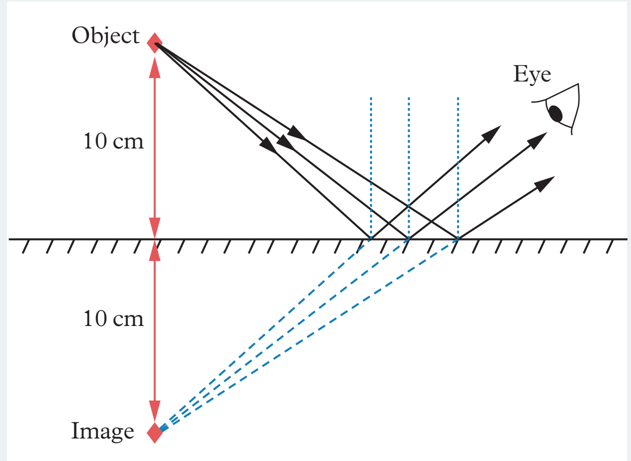
(1 mark)

Analytical processes

5 **Contrast** a real image and a virtual image and give an example of each. (2 marks)

6 **Deduce** why some police cars and ambulances have the words printed back to front. (1 mark)

7 A ray diagram of the reflection of a small object in a plane mirror is shown. **Analyse** the diagram and **explain**, in terms of the law of reflection, how the eye sees an image as shown. (3 marks)



8 If you wish to view your whole body in a mirror, **determine** what the minimum length the mirror would have to be and where on the wall it would need to be placed. (3 marks)

Practical

Lesson 14.5
The law of reflection for images in a plane mirror

Learning intentions and success criteria

Video demonstration

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Lesson 14.6
Refraction of light

Learning intentions and success criteria

Key ideas

→ Light is refracted when it passes from one medium to another. For a given angle of incidence, the amount of refraction depends on the refractive index of each medium.

→ Snell's law relates the angle of incidence, angle of refraction, velocity of light passing through two media, their wavelengths and refractive indices.

→ Different wavelengths of light are refracted to different degrees, giving rise to dispersion.

How is light refracted?

Early hunters took into account the refractive properties of water to accurately spear-fish. Human understanding of refraction has developed, and refraction of light is now used in applications such as communication technology and medicine. The development of optical fibres has revolutionised the way we receive data from all over the world, and their use in exploratory surgery has reduced the amount of time we spend in hospital. This is discussed in Lesson 14.7.

Remember that refraction is the changing in direction of waves as they go from one medium to another. For light waves, this occurs when light passes from one medium to another, such as when light rays pass from air to water, from air to glass or from glass to water. This change in direction can be easily observed in the case of light – the light rays bend at the boundary between the media.

The amount of refraction depends on the **optical density** of the medium through which the light waves pass. The term "optical density" (when used for refraction) is a measure of the relative speed at which light travels through the medium. The more optically dense a medium, the slower light travels through it. It has nothing to do with mass density, which is the mass of a substance divided by its volume.

optical density
a measure of the relative speed of light in a medium; the higher the optical density, the slower the speed; quantified as absolute refractive index

In general, light rays bend towards the normal when they pass from a less optically dense medium to a more optically dense medium (i.e. when light slows down). The reverse is also true – light rays bend away from the normal as they pass from a more optically dense medium to a less optically dense medium.

Consider the analogy of a car hitting a flooded section of a road at an angle. As one of the car's front wheels hits the water, it slows down while the other wheel keeps going at the original speed (Figure 1). Therefore, the direction of the car changes – it bends into the water. The new direction of the car will be closer to the normal and the car will slow down.

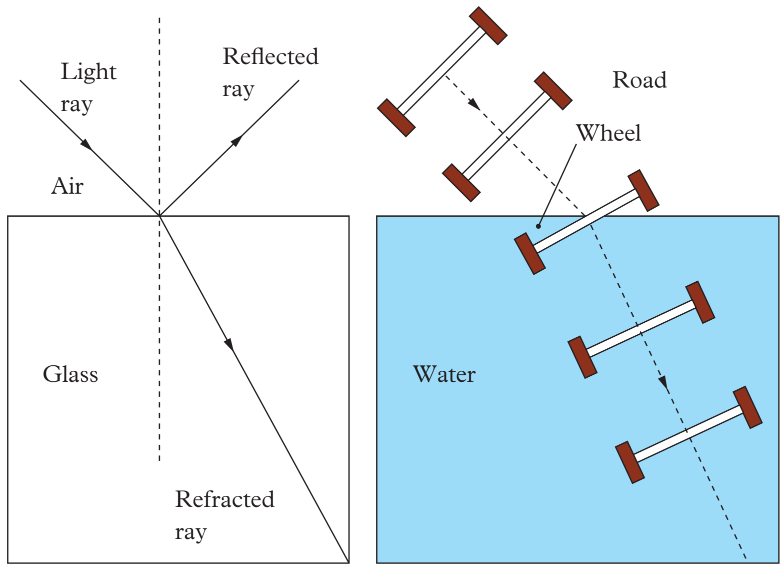


FIGURE 1 As the wheels of the car enter the water, they slow down and swerve towards the normal.

The ratio of the velocity of light in air to the velocity of light in a different medium is constant. This constant is called the **absolute refractive index** (n) of the material. It is denoted by the symbol n, where v_a is the velocity of light in air and v_m is the velocity of light in the medium.

$$n = \frac{v_a}{v_m}$$

If light travels through two media with similar absolute refractive indices, the amount of refraction will be minimal; that is, the light will bend less. The larger the difference between the two absolute refractive indices, the greater the amount of refraction; that is, the light will bend more. The speed of light through various media and their absolute refractive indices can be seen in Table 1.

absolute refractive index
the ratio of the velocity of light in air to the velocity of light in a different medium

TABLE 1 The velocity of light in various media of different refractive indices

Medium	Velocity of light in the medium, v ($\times 10^8$ m s^{-1})	Absolute refractive index of the material, n
Air	3.00	1.00
Ice	2.31	1.30
Water	2.26	1.33
Sea water (3.5% salt)	2.24	1.34
Ethyl alcohol	2.21	1.36
Fused quartz	2.05	1.46
Perspex	2.00	1.49
Benzene	2.00	1.50
Crown glass	1.97	1.52
Light flint glass	1.90	1.58
Heavy flint glass	1.82	1.65
Zircon	1.58	1.90
Diamond	1.24	2.42

angle of refraction
the angle between the normal and the direction of propagation of a refracted wave

Snell's law
when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index

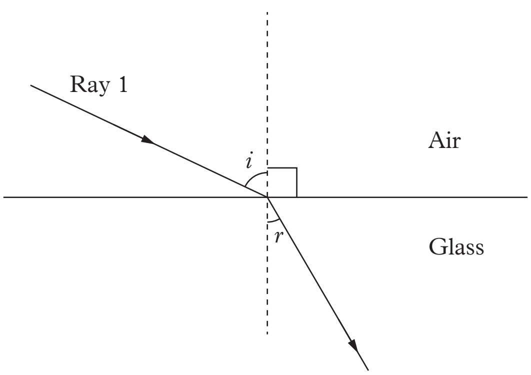


FIGURE 2 As light goes from air to glass, it bends towards the normal.

TABLE 2 Data for Figure 2

$\angle i°$	$\angle r°$	$\frac{\sin i}{\sin r}$
40	25	1.52
50	31	1.49
60	35	1.51

What is Snell's law?

In 1621, Dutch mathematician Willebrord Snell (1580–1626) discovered that the refractive index of a substance can be found using the angle of incidence and **angle of refraction**. Snell found that if the angle of incidence was changed, the angle of refraction also changed in such a way that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is always a constant for a particular material. This constant is the absolute refractive index of the material. The relationship between these angles is known as **Snell's law**:

$$\frac{\sin i}{\sin r} = n$$

For example, imagine a ray of light entering a block of glass from air at an angle of incidence i and an angle of refraction r, as shown in Figure 2. Pairs of readings could be taken for angle i and angle r, as shown in Table 2. The ratio of values of $\sin i$ to $\sin r$ is constant at about 1.50. Therefore, the refractive index of glass using the symbol n_{a-g}, $n_{a\rightarrow g}$, n_{ag} or just n_g is 1.5.

The refractive indices given in Table 1 are the absolute refractive indices – the refractive indices obtained when a light ray travels from air to the material. If we know the value of the absolute refractive index and the angle of incidence, we can determine the angle of refraction. Note that when the angle of incidence is 0°, the angle of refraction is also 0°. That is, there is no refraction when the incident ray approaches along the normal to the surface.

Worked example 14.6A

Calculating the angle of refraction

Light from a light box is shone onto a block of Perspex at an angle of 35° to the normal. **Calculate** the angle of refraction (2 s.f.). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply Snell's law. The question is worth 2 marks, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$\frac{\sin i}{\sin r} = n_{\text{Perspex}}$ $n_{\text{Perspex}} = 1.49$, $i = 35°$, $r = ?$
Step 3: Substitute the known values into the formula and find the angle of refraction.	$\frac{\sin 30°}{\sin r} = 1.49$ $\sin r = \frac{\sin 35°}{1.49}$ $= 0.385$ (1 mark) $r = \sin^{-1}(0.385)$ $= 22.641$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	23° (2 s.f.) (1 mark)

Your turn

Light strikes an air to water interface at an angle of 35° to the surface and enters the water. If the index of refraction from air to water is 1.33, **calculate** the angle of refraction (2 s.f.). (2 marks)

What is reciprocal law?

The absolute refractive indices in Table 1 are for light going from air to the material (such as glass, which is $n_{a\to g}$). But what is the refractive index of light passing from glass to air $n_{g\to a}$, as shown at the second surface in Figure 3?

Because of the reversible nature of light, $\angle r_1 = \angle i_2$, and $\angle i_1 = \angle r_2$.

Therefore, at surface 2:

$$n_{g\to a} = \frac{\sin i_2}{\sin r_2} = \frac{1}{\frac{\sin r_2}{\sin i_2}} = \frac{1}{\frac{\sin i_1}{\sin r_1}}$$

$$n_{g\to a} = \frac{1}{n_{a\to g}}$$

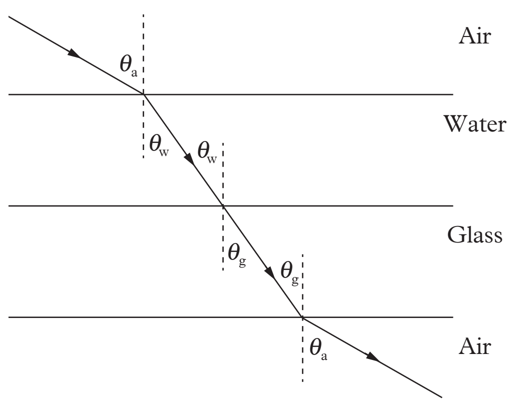


FIGURE 3 Because of the reciprocal law, light returns to its original angle after passing through different substances and emerging back into air.

This is called the **reciprocal law**.

In general, the refractive index of light going from a material to air is the reciprocal of the absolute refractive index of the material:

$$n_{m\to a} = \frac{1}{n_{a\to m}} = \frac{1}{n_m}$$

reciprocal law
the refractive index for light passing from medium 1 to medium 2 is the reciprocal of the refractive index of light passing from medium 2 to medium 1

Worked example 14.6B

Calculating refractive index using the reciprocal law

Calculate the refractive index of light going from glass to air, given that the value from air to glass is 1.50 (3 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the reciprocal law. The question is worth 1 mark, so we must gather the correct information, correctly apply the formula and complete the calculation.
Step 2: Select the correct formulas and gather any data required.	$n_{g\to a} = \frac{1}{n_g}$ $n_g = 1.50$, $n_{g\to a} = ?$
Step 3: Substitute the known values into the formula and find the refractive index going from glass to air.	$n_{g\to a} = \frac{1}{1.50}$ $= 0.667$
Step 4: Finalise your answer and make sure you have included the correct units and significant figures.	0.667 (3 s.f.) (1 mark)

Your turn

Calculate the refractive index of light going from air to diamond, given that the value from diamond to air is 0.413 (3 s.f.). (1 mark)

What is relative refractive index?

FIGURE 4 The pencils in the glass show light refraction.

If a ray of light passes from one medium to another, such as from water to glass, the ratio of the sine of the angle of incidence in water (n_w) to the sine of the angle of refraction in glass (n_g) is also a constant:

$$\frac{\sin\theta_a}{\sin\theta_w} = n_w \text{ and } \frac{\sin\theta_a}{\sin\theta_g} = n_g$$

$$\frac{\sin\theta_w}{\sin\theta_g} = \frac{n_g}{n_w} = n_{w\to g}$$

In general, the **relative refractive index** for light passing from medium 1 to medium 2 is given by the formula:

$$n_{1\to2} = \frac{n_2}{n_1}$$

where $n_{1\to2}$ is the relative refractive index for light going from medium 1 to medium 2, n_2 is the absolute refractive index for medium 2, and n_1 is the absolute refractive index for medium 1. The symbol $n_{1\to2}$ is also written as n_{12}.

relative refractive index
the ratio of the velocity in one medium to the velocity of light in a different medium; symbol n, $n_{1\to2}$, or n_{12} to indicate the passage from medium 1 to medium 2

We can now create a more general form of Snell's law, which can be used for light passing between any two media using θ_1 for the angle of incidence, and θ_2 for the angle of refraction:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

It can then be rearranged into a more useful form:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Snell's law has now been expanded to say that when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index from the first to the second medium. In general, for the refraction of any kind of wave incident on a boundary separating two media, the angles of incidence θ_1 and refraction θ_2 are related using this equation.

Worked example 14.6C

Calculating the angles of refraction for two different media

A ray of light passes from water ($n = 1.33$) to glass ($n = 1.50$) with an angle of incidence in water of 25°. **Calculate**

a the angle of refraction (2 s.f.) (2 marks)

b the angle the ray in the glass makes with the boundary of the water and glass (2 s.f.). (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the extended Snell's law. The questions are worth 2 marks and 1 mark respectively, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. Write the subscripts in to show the nature of each medium (w = water, g = glass).	$n_1 \sin\theta_1 = n_2 \sin\theta_2$ $n_w \sin\theta_w = n_g \sin\theta_g$ $n_w = 1.33$, $\theta_w = ?$, $n_g = 1.50$, $\theta_g = ?$
Step 3: Substitute the known values into the formula and find θ_g.	**a** $1.33 \sin 25° = 1.5 \sin\theta_g$ $\frac{1.33 \sin 25°}{1.50} = \sin\theta_g$ $0.3747 = \sin\theta_g$ (1 mark) $\theta_g = \sin^{-1}(0.3747)$ $= 22.01$
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures. Sense check your answer; the angle should be less than the angle of incidence if going from a less (optically) dense medium to a more dense medium.	22° (1 mark)
Step 5: Find the angle between the ray and the surface, which is the complement of the angle between it and the normal.	**b** $90° - 22° = 68°$ (1 mark)

Your turn

A ray of light in glass ($n_g = 1.50$) strikes a boundary with glycerine ($n_{gly} = 1.46$) at an angle of incidence of 40.0°. **Calculate**

a the angle of refraction in glycerine (3 s.f.) (2 marks)

b the angle the ray makes with the surface of the glass (3 s.f.). (1 mark)

What is the relationship between velocity and wavelength?

So far, we have looked at the relationship between refractive index and the angles of incidence and refraction. But because we are considering light in terms of the wave model, we can also consider the effect that different media have on the velocity and wavelength of the light.

We know that the refractive index of light in a particular medium (n_m) depends on its speed in that medium (v_m) compared with its speed in air (v_a). This is shown by the formula:

$$n_m = \frac{v_a}{v_m}$$

speed of light
electromagnetic waves such as light have a speed of $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$ in a vacuum; other waves have speeds determined by the nature of the medium

In air, the speed of light – an electromagnetic wave – can be regarded as the **speed of light** in a vacuum: $c = 3 \times 10^8\,\mathrm{m\,s^{-1}}$.

We can use the wave equation to express this ratio in terms of wavelength as well. Velocity can be replaced by the product of frequency and wavelength. However, frequency doesn't change when light is refracted. You'll know this from your experiments with springs, in which the wavelength and velocity of a wave will change when it passes into a heavier spring, but its frequency will remain constant. The formula for light then becomes:

$$n_\mathrm{m} = \frac{v_\mathrm{a}}{v_\mathrm{m}} = \frac{f \times \lambda_\mathrm{a}}{f \times \lambda_\mathrm{m}} = \frac{\lambda_\mathrm{a}}{\lambda_\mathrm{m}}$$

In summary:

$$n_{12} = \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

Worked example 14.6D

Determining the changes to velocity and wavelength when light is refracted

Red laser light has a wavelength of 665 nm and a speed of $3 \times 10^8\,\mathrm{m\,s^{-1}}$ in air. It passes into glass of refractive index 1.50. **Determine** its

a frequency in air (1 mark)
b frequency in the glass (1 mark)
c speed in glass (1 mark)
d wavelength in nanometres in glass. (1 mark)

Think	Do
Step 1: Look at the cognitive verbs and mark allocation to determine what the questions are asking you to do.	"Determine" means to establish after a calculation. We need to apply the wave equation, and Snell's law using velocities. The questions are worth 1 mark each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$v = f\lambda$ $v = 3 \times 10^8\,\mathrm{m\,s^{-1}},\ \lambda = 665\,\mathrm{nm}$ $n_\mathrm{ag} = \frac{n_\mathrm{g}}{n_\mathrm{a}} = \frac{\sin i}{\sin r} = \frac{v_\mathrm{a}}{v_\mathrm{g}} = \frac{\lambda_\mathrm{a}}{\lambda_\mathrm{g}}$ $n_\mathrm{ag} = 1.50$
Step 3: Substitute the known values into the formula and find the intensity. Make sure you complete any necessary conversions. Finalise your answer for part **a**.	**a** $v = f\lambda$ $3 \times 10^8 = f \times (665 \times 10^{-9})$ $f = 4.5 \times 10^{14}\,\mathrm{Hz}$ (1 mark)
Step 4: Recognise that the frequency doesn't change during refraction, only the speed and wavelength. Finalise your answer for part **b**.	**b** $4.5 \times 10^{14}\,\mathrm{Hz}$ (1 mark)
Step 5: Select the relationship for refractive index and speed. Substitute the known values into the formula and find the speed of light in the second medium (glass). Finalise your answer for part **c** and check that it is not greater than velocity in air ($3 \times 10^8\,\mathrm{m\,s^{-1}}$).	**c** $n_\mathrm{ag} = \frac{v_\mathrm{a}}{v_\mathrm{g}}$ $1.50 = \frac{3 \times 10^8}{v_\mathrm{g}}$ $v_\mathrm{g} = 2.0 \times 10^8\,\mathrm{m\,s^{-1}}$ (1 mark)
Step 6: Select the relationship for wavelength and refractive index. Substitute the known values into the formula and find the wavelength of the second medium (glass). Finalise your answer for part **d**.	**d** $n_\mathrm{ag} = \frac{\lambda_\mathrm{a}}{\lambda_\mathrm{g}}$ $1.50 = \frac{665}{\lambda_\mathrm{g}}$ $\lambda_\mathrm{g} = 443\,\mathrm{nm}$ (1 mark)

Your turn

A green laser produced light with a wavelength of 532 nm and a speed of $3 \times 10^8\,\mathrm{m\,s^{-1}}$ in air. It passes into Perspex of refractive index 1.46. **Determine** its

a frequency in air (1 mark)
b frequency in the Perspex (1 mark)
c speed in Perspex (1 mark)
d wavelength in nanometres in Perspex. (1 mark)

Study tip

Snell's law relates many different variables such as angles, velocity and wavelength. If you are given the frequency, you'll need to calculate the wavelength to use Snell's law.

How does dispersion of light produce colours?

We know that white light is made up of all of the colours of the rainbow, but how is it that drops of water can cause the colours to separate out? The phenomenon is known as **dispersion**, from the Latin "dis" = "away", and "spargare" = "to scatter". Different colours have different wavelengths, and so will have slightly different speeds in transparent substances such as water and glass. These differences in wavelength and speed give rise to different refractive indices in particular media.

If white light is shone onto the surface of a block of glass, the angle of refraction for each colour will be slightly different and the colours will separate slightly. If this occurs at a second surface, such as the second surface of a prism as shown in Figure 5, the effect is increased and results in a visible separation of the colours of light. The colour pattern formed is called a **spectrum** (from Latin meaning "image"). Violet light is refracted the most and red the least.

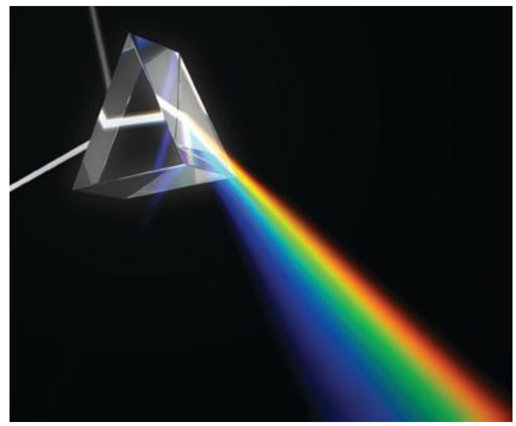
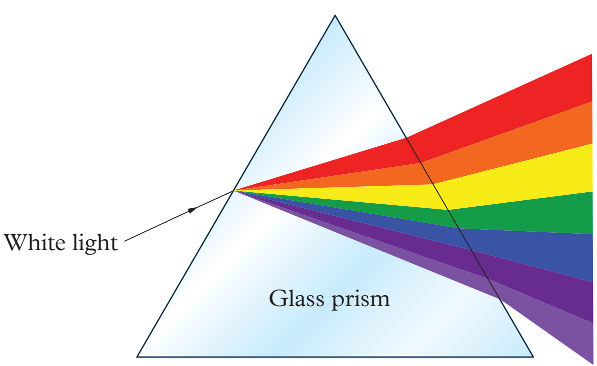


FIGURE 5 A continuous spectrum produced by the refraction of white light by a prism



	n	λ (nm)
Red	1.515	665
Orange	1.516	630
Yellow	1.517	600
Green	1.521	550
Blue	1.523	470
Indigo	1.533	425
Violet	1.538	400

FIGURE 6 Because the different colours of light have different refractive indices, velocities and wavelengths in a given medium, they separate when passing through a prism and create a spectrum. The refractive index and wavelength in air (in nanometres) of representative colours is shown.

dispersion
the separation of a ray upon refraction into distinct rays of different colours; observed as the splitting of white light into a rainbow

spectrum
the range of frequencies of electromagnetic radiation and their respective wavelengths, divided into spectral regions such as infrared (IR), visible, ultraviolet (UV), X-rays, and gamma rays

Worked example 14.6E

Calculating the angles of refraction during dispersion

A beam of white light in air strikes a glass interface with an angle of incidence of 45.0°. **Calculate** the difference in the angle between the dispersed red and violet rays in the glass. The refractive indices for red and violet light in glass are 1.515 and 1.538, respectively. Express your answer to 2 s.f. (5 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the extended Snell's law. The question is worth 5 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required.	$n = \frac{\sin i}{\sin r}$ $i_{red} = 45.0°$, $n_{red} = 1.515$ $i_{violent} = 45.0°$, $n_{violet} = 1.538$
Step 3: Substitute the known values into the formula and find the angle of refraction for the red light.	$1.515 = \frac{\sin 45.0°}{\sin r_{red}}$ $\sin r_{red} = 0.4667$ (1 mark) $r_{red} = \sin^{-1}(0.4667)$ $= 27.82°$ (1 mark)
Step 4: Substitute the known values into the formula and find the angle of refraction for the violet light.	$1.538 = \frac{\sin 45.0°}{\sin r_{violet}}$ $\sin r_{violet} = 0.4598$ (1 mark) $r_{violet} = \sin^{-1}(0.4598)$ $= 27.37°$ (1 mark)
Step 5: Finalise your answer by subtracting the angles to find the difference. Make sure you have included the correct units and significant figures.	$27.82 - 27.37 = 0.45°$ (2 s.f.) (1 mark)

Your turn

A beam of white light in air strikes a diamond interface with an angle of incidence of 25.0°. **Calculate** the angle between the dispersed red and blue rays in the diamond. The refractive indices for red and blue light in diamond are 2.412 and 2.428 respectively. Express your answer to 2 s.f. (5 marks)

Real-world physics

Laura Bassi's contributions to the modern understanding of colour and optics

Although Isaac Newton's work on colour separation in prisms and the mixing of colours to reform white light in 1672 was ground-breaking and formed the foundation of optics, our modern understanding of such phenomena is largely due to the work of Émilie du Châtelet and Laura Bassi (1711–1778). Châtelet – as we learnt in Module 11 – translated Newton's works on motion, and Italian physicist Bassi promoted his theories on colour and optics.

FIGURE 7 Portrait of Laura Bassi (1711–1778)

By then, science was becoming a more legitimate pursuit for exceptional women. However, they were excluded from lecturing at the universities, and were not allowed a role in scientific organisations in countries such as Britain and France.

In 1732, Bassi became the second woman to receive a university degree and the first to be offered an official teaching position at any university in Europe. She became one of the first scholars in Italy to teach Newtonian natural philosophy, beginning with her lectures on the less controversial teaching of a "Course in the experiments of Newton regarding light and color" in the late 1730s and continuing with the course in experimental physics that she conducted in her home.

Bassi is one of the most interesting natural philosophers of the early modem period. During her long tenure as a professor at the University of Bologna (Italy) and one of the most prominent members of Italy's leading scientific society, she played a central role in the introduction of new forms of learning into the university science curriculum. Among her contemporaries, few – with the exception of Newton – enjoyed an equivalent degree of institutional recognition and public acclaim.

Apply your understanding

1 Professor Bassi carried out experiments on the "refrangibility" of light of different colours in which she observed the bending of light as it passed from one medium to another. **Propose** the current term for "refrangibility". (1 mark)

2 Some of Bassi's physics colleagues mocked her by saying all she was going to do was repeat Newton's experiments in the dark. This was not true, but **predict** whether a dark room would have any effect on the dispersion of white light through a prism. (2 marks)

3 Bassi was interested in the study of the aurora borealis (the Northern Lights) because it combined her two areas of interest: light and electricity. **Propose** a research question from the claim on space.com that "Auroras tell us many things about Earth's upper atmosphere, including its density, composition, flow speeds, and the strength of electrical currents flowing." (1 mark)

What is apparent depth?

To a fish or diver underwater, a tree on the shore would appear to be up in the air and objects would appear to be in different positions from where they actually are (Figure 8). This apparent difference in position is due to refraction. Certain fish can shoot down insects by squirting a high-pressure jet of water from their mouths towards their prey. These fish must take account of refraction to enable them to aim from under the water and hit the insect.

Similarly, if you look at people standing in a swimming pool, their legs look short even though their top half looks normal. This is because the light from their legs refracts as it passes from water to the surface. We see objects in water as being closer to the surface than they really are. In other words, their **apparent depth** is less than their real depth.

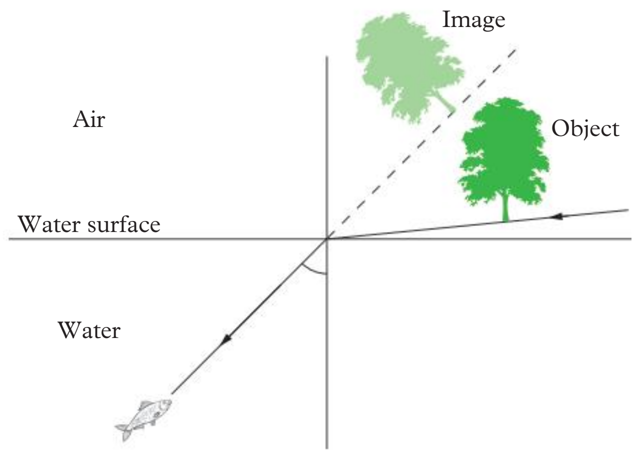


FIGURE 8 Because of refraction, objects will appear to be at positions that differ from their true positions.

apparent depth the depth (or height) of the image of an object when it is observed from a different medium (e.g. air from water, or water from air); a consequence of the refraction of light

Worked example 14.6F

Calculating refractive index using apparent depth

An archerfish is underwater and can see a bug 2.5 m up a tree that is 1.8 m away, as shown in the diagram. A ray of light from the bug strikes the water and refracts at an angle of 27°. **Calculate** the refractive index of the water (n_{air} = 1.00) (2 s.f.). (3 marks)

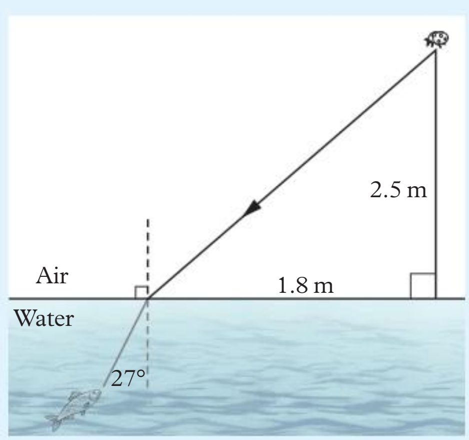


FIGURE 9 An archerfish views the bug from under the water.

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply SOHCAHTOA and the extended Snell's law. The question is worth 3 marks, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. We have the opposite (O) and adjacent (A), and want to find the angle, so the relevant ratio is TOA.	$\tan\theta = \frac{O}{A}$ O = 2.5 m, A = 1.8 m, $\theta = i = ?$ $n = \frac{\sin i}{\sin r}$ $r = 27°$, $n = ?$
Step 3: Substitute the known values into the formula to find the angle of incidence.	$\tan\theta = \frac{2.5}{1.8}$ $\theta = \tan^{-1}(1.3889)$ $= 54.25°$ (1 mark)
Step 4: Find the angle of incidence by subtracting the angles.	$i = 90 - 54.25$ $= 35.75°$ (1 mark)
Step 5: Substitute the known values into the formula to find the refractive index.	$n = \frac{\sin 35.75°}{\sin 27°}$ $= 1.287$
Step 6: Finalise your answer and make sure you have included the correct units and significant figures.	1.3 (2 s.f.) (1 mark)

Your turn

An archerfish is 2.0 m away horizontally from a tree as shown in Figure 10. It can spot a bug on a branch that is a distance *d* from the ground. The ray of light from the bug to the water is refracted at an angle of 27°. However, the ray appears to come from a position higher up in the tree, a distance *h* above the ground. **Calculate** the distance *d* (3 s.f.). The refractive index of water is 1.33. (3 marks)

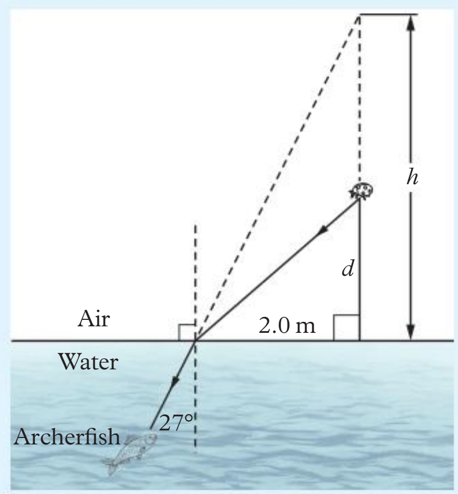


FIGURE 10 An archerfish spies a bug in the tree.

Check your learning 14.6

Check your learning 14.6: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** Snell's law in the context of the passage of light from water to glass. (3 marks)

2 **Describe** dispersion and account for its cause. (2 marks)

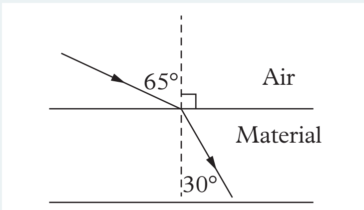
3 **Calculate** the index of refraction for light going from air ($v = 3 \times 10^8\,\mathrm{m\,s^{-1}}$) to a material in which its speed is

a $2.6 \times 10^8\,\mathrm{m\,s^{-1}}$ (2 marks)

b $1.8 \times 10^8\,\mathrm{m\,s^{-1}}$. (2 marks)

4 **Calculate** the speed of light in a medium whose refractive index is
  a 1.5 (2 marks)
  b 2.4 (2 marks)
  c 1.3. (2 marks)

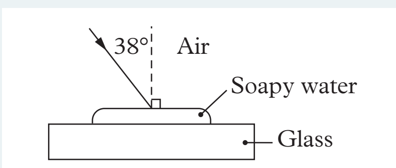
5 **Determine** the refractive index of the material shown in the image. (2 marks)



6 **Calculate** the refractive index for light passing from water (n = 1.33) to crown glass (n = 1.52). (2 marks)

Analytical processes

7 A drop of soapy water ($n_{\text{soapy water}}$ = 1.38) was placed onto a block of glass (n_g = 1.5), as shown in the figure. A ray from a laser was shone onto the water at an angle of 38°.



Determine the
  a angle of refraction in the soapy water (3 marks)
  b angle of refraction in the glass (3 marks)
  c angle at which the ray exited from the glass (3 marks)
  d relative refractive index of light going from soapy water to glass. (2 marks)

Knowledge utilisation

8 **Predict** whether rays of light bend towards the normal when going from
  a glass to water (1 mark)
  b glass to diamond (1 mark)
  c alcohol to water (1 mark)
  d Perspex to heavy flint glass. (1 mark)

9 Rays of red and violet light enter a rectangular piece of glass from air at 60° to the surface. The refractive indices for air to glass are n_{red} = 1.515, and n_{violet} = 1.538.
  a **Construct** a labelled ray diagram. (4 marks)
  b **Calculate** the angle between the two rays in the glass. (3 marks)

10 A glass block 5 cm thick is placed in water at the bottom of a fish tank. A beam of light in the water strikes the glass block at an angle of 55° to its upper surface. Use n_w = 1.33, n_g = 1.51.
  a **Construct** a labelled ray diagram to show the path of the light in the glass. (2 marks)
  b **Calculate** the angle of refraction and show this on the diagram (3 s.f.). (2 marks)

Practical

Lesson 14.7
Refractive properties of a transparent substance

Learning intentions and success criteria

oxforddigital

This practical lesson is available on Oxford Digital. It is also provided as part of a printable resource that can be used in class.

Video demonstration

Lesson 14.8
Total internal reflection

Learning intentions and success criteria

Key ideas

→ The critical angle is the angle of incidence that causes the angle of refraction to be 90°.

→ Total internal reflection occurs when the critical angle is exceeded.

critical angle the angle of incidence (symbol θ_c) for light in a more optically dense medium for which the angle of refraction in the less optically dense medium is 90°

total internal reflection the phenomenon whereby all energy is reflected inside a medium due to the incident angle of the wave being greater than the critical angle

What is total internal reflection?

Have you noticed all of the sparkling colours from a diamond ring? Have you ever seen a mirage on a hot road that looks like water? These are two examples of a phenomenon called total internal reflection.

As you know, a ray of light bends towards the normal when going from a less dense to a more dense medium. The opposite is also true. Rays will bend away from the normal when going from a more dense to a less dense medium. This results in an odd situation as the angle of incidence increases, as shown in Figure 1. There comes a stage at which the angle of refraction is 90° (Figure 1D). The angle of incidence that produces this is called the **critical angle** (θ_c).

If the critical angle is exceeded, the ray of light is entirely reflected from the surface at an angle equal to the angle of incidence (Figure 1E). This is called **total internal reflection** and occurs when light travels from a more optically dense medium to a less optically dense medium, and the angle of incidence is greater than the critical angle. As its name suggests, the ray of light only is reflected internally, back into the original medium.

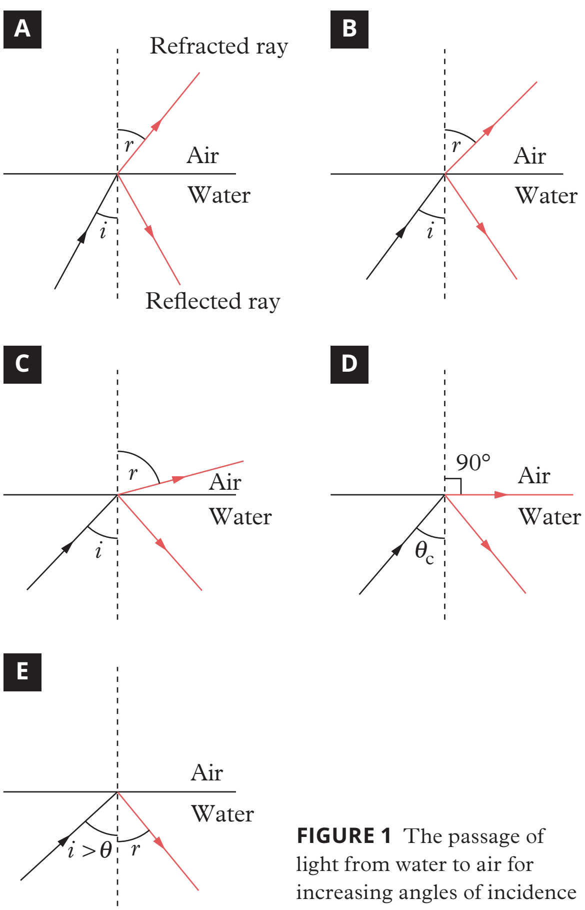


FIGURE 1 The passage of light from water to air for increasing angles of incidence

For a ray of light going from water to air:

$$\frac{\sin\theta_w}{\sin\theta_a} = n_{w\rightarrow a} = \frac{1}{n_w}$$

When the angle of incidence θ_w is equal to the critical angle θ_c, the refracted angle $\theta_a = 90°$, and $\sin 90° = 1$. Then, when the less dense medium is air:

$$\sin\theta_c = \frac{1}{n_w}$$

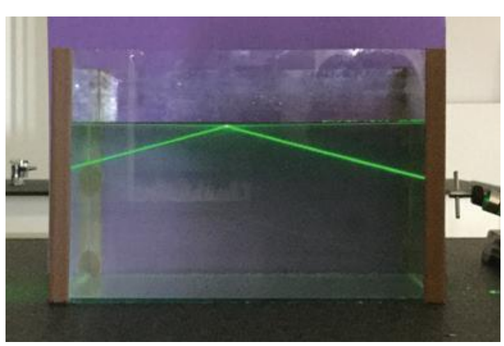


FIGURE 2 A green laser beam enters the fish tank of water, but the angle of incidence is too large for it to escape out into the air at the top. Hence, the light totally reflects off the underside of the water surface. This is total internal reflection.

Worked example 14.8A

Calculating the critical angle

Calculate the critical angle for a light ray passing from light flint glass (n = 1.58) to

a air (n = 1.00) (3 s.f.) (2 marks) **b** water (n = 1.33). (2 marks)

Think	Do
Step 1: Look at the cognitive verb and mark allocation to determine what the question is asking you to do.	"Calculate" means to determine or find a number or answer by using mathematical processes. We need to apply the extended Snell's law and the critical angle formula. The questions are worth 2 marks each, so we must gather the correct information, correctly apply the formulas and complete the calculations.
Step 2: Select the correct formulas and gather any data required. Write the subscripts in to show the nature of each medium (a = air, g = glass).	$n_1 \sin\theta_1 = n_2 \sin\theta_2$ $\sin\theta_c = \frac{1}{n_g}$ For **a**: $n_g = 1.58$, $\theta_g = \theta_c = ?$, $n_a = 1.00$, $\theta_a = 90°$ For **b**: $n_g = 1.58$, $\theta_g = \theta_c = ?$, $n_a = 1.33$, $\theta_a = 90°$
Step 3: For part **a**, the light is moving from a more dense medium into a less dense medium, so we can use the critical angle formula. This is because $n_a = 1.0$ and $\sin 90°$ is also 1.0:	**a** $\sin\theta_c = \frac{1}{1.58}$ $\sin\theta_c = 0.6329$ (1 mark) $\theta_c = \sin^{-1}(0.6329)$ $= 39.27$
Step 4: Finalise your answer for part **a** and make sure you have included the correct units and significant figures.	39.3° (1 mark)
Step 5: For part **b**, the less dense medium is not air, so we need to use the full formula in which medium 1 is the flint glass and medium 2 (the less dense medium) is water. Rearrange the equation before substitution so as to give $\sin\theta_c$ as the subject.	**b** $n_g \sin\theta_g = n_w \sin\theta_w$ $1.58 \sin\theta_c = 1.33 \sin 90°$ $1.58 \sin\theta_c = 1.33$ $\sin\theta_c = 0.8418$ (1 mark) $\theta_c = \sin^{-1}(0.8418)$ $= 57.33$
Step 6: Finalise your answer for part **b** and make sure you have included the correct units and significant figures.	57.3° (1 mark)

Your turn

The core of an optical fibre cable has a refractive index of 1.55. The cladding around it is made of a substance with a lower value, typically 1.45. **Calculate** the critical angle for light striking the interface from the core side (2 s.f.). (2 marks)

Total internal reflection can be demonstrated easily by using a semicircular block of glass and a light box (Figure 3). The block is placed on a sheet of white paper and a ray from a light box is directed from the top onto the centre of the semicircular block. The ray entering the glass is along a radius and is perpendicular to the surface; therefore, no refraction occurs at the first surface.

Refraction occurs at the second surface and the ray bends away from the normal. As the angle of incidence at this surface is increased, the angle of refraction also increases. When the angle of incidence is approximately 42°, the refracted beam will be along the straight surface of the block of glass – that is, the angle of refraction is 90°. If the angle of incidence is made slightly greater, the refracted beam disappears because the light beam is reflected back inside the block of glass at an angle equal to the angle of incidence.

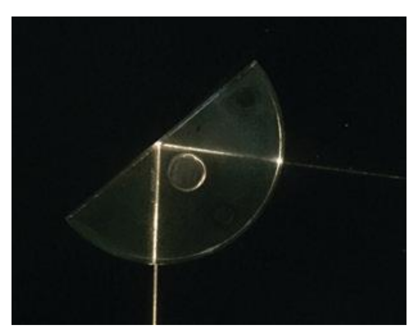


FIGURE 3 Total internal reflection produced by light striking the boundary between glass and air

How is total internal reflection used in optical fibres?

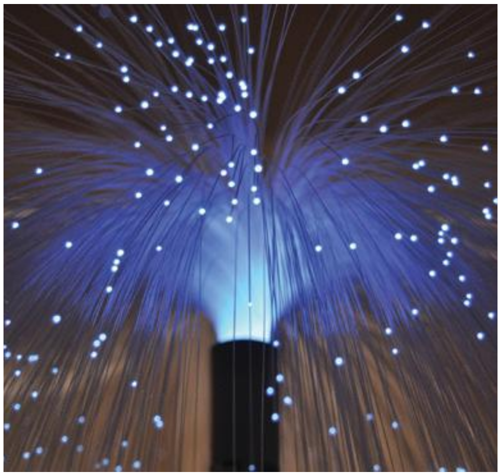


FIGURE 4 Optical fibre lamp

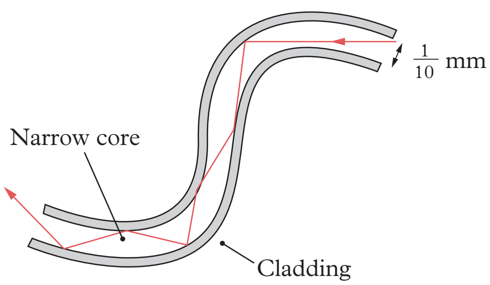


FIGURE 5 An optical fibre consists of a thin glass fibre of higher refractive index than the outside cladding layer. Thus, total internal reflection is used to reflect light pulses along the length of the fibre.

One of the major uses of total internal reflection is in optical fibres. Fibre optics is a branch of optics dealing with the transmission of light through fibres or thin rods of glass, or through some other transparent material of high refractive index. Light is admitted at one end of a fibre and travels through the fibre with very low loss, even if the fibre is curved.

An optical fibre (Figure 5) consists of a very pure glass fibre as thin as a hair (0.125 mm) with a layer of cladding around the outside to protect it from damage and moisture.

The cladding has a lower refractive index than the inside material, thus creating a situation in which light propagating in the core is travelling in a more dense material than in the outside layer. Light is totally internally reflected if it strikes the boundary between the two media at an angle greater than the critical angle. Light is reflected along the length of the fibre, which can be bent into any shape as long as it is not kinked. Once kinked, the surface cracks allow light to refract out.

The medical profession was the first to make use of optical fibres. Surgeons use bundles of fibres to look inside a person's stomach and lungs without surgery. A bundle of fibres is introduced into the stomach via the throat. Light is shone down some of the fibres and reflected light from the stomach is transmitted back via other fibres.

The telecommunications industry was one of the first large commercial users of optical fibres. Digital electrical signals are converted into light pulses and transmitted along optical fibre cable by switching light-emitting or laser diodes on and off. At the other end, these optical digital pulses are converted back into electrical signals by phototransistors.

Challenge

Colourful bacon

Have you noticed the green iridescent colours that sometimes appear on bacon and corned meat? This is not necessarily rotting meat! The appearance is caused by microscopic droplets of oil and water of differing refractive indices on the surface causing the interference of light. If it goes really green, that's the bacteria breaking down the oxygen transport protein (myoglobin) to produce green compounds. Heat will show the difference as it will make the oil droplets go away but not the green rot. Why is there green iridescence and not red or violet? (4 marks)

Check your learning 14.8

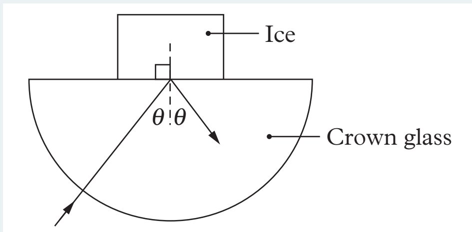
Check your learning 14.8: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Explain** the conditions for total internal reflection to occur. (2 marks)

2 **Describe** how an optical fibre transmits a light signal over long distances with a low loss of energy. (3 marks)

3 A block of ice ($n_{ice} = 1.30$) is placed on top of a semicircular block of crown glass as shown. **Determine** at what minimum angle all incident light on the boundary between the two surfaces would be reflected. (3 marks)



4 A ray of light travels from one medium to another. It is found that total internal reflection occurs when the incident angle is greater than 54°. If the refractive index of the first medium is 1.49, **calculate** the refractive index of the second medium. (2 marks)

Analytical processes

5 A light ray passes from one medium to another. **Determine** whether it is possible for total internal reflection to take place and **explain** why.

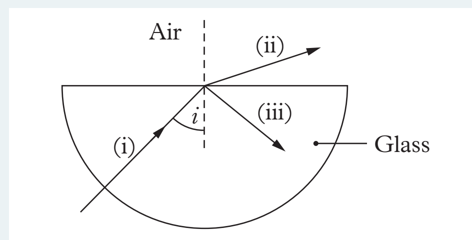
a Air to glass (2 marks)
b Diamond to air (2 marks)
c Water to glass (2 marks)
d Flint glass to air (2 marks)
e Ice to a vacuum (2 marks)
f Crown glass to Perspex (2 marks)

6 Optical fibres have a less optically dense layer surrounding the fibre in order to produce total internal reflection. A fibre has a refractive index of 1.70 and the outside cladding layer has a refractive index of 1.48.

a **Calculate** the minimum angle at which light incident on the boundary is totally internally reflected. (3 marks)
b **Determine** the speed of light in the fibre. (2 marks)

Knowledge utilisation

7 Students investigating total internal reflection in a semicircular block of glass notice that there is a faint reflected beam before total internal reflection occurs. **Discuss** the intensity of beams (i), (ii) and (iii) in as shown in the figure, as the angle of incidence increases. (4 marks)



Lesson 14.9
Lenses

Key ideas

→ Convex lenses cause rays of light to converge, whereas concave lenses cause rays of light to diverge.
→ Ray diagrams are used to show the path of light through lenses.
→ Depending on the position of an object observed through a lens, the nature, location, orientation and size of its image may differ.

Learning intentions and success criteria

What are lenses?

Lenses play a major part in everyday life and in the scientific world. They are present in glasses, contact lenses, phones, cameras, microscopes, telescopes and photocopiers, to name a few. Simple hand lenses are used in science classes for mineral identification and for looking at cells and crystals.

Lenses are transparent devices that refract light. Different shaped lenses refract light differently. Lenses were made of glass; now, most lenses are made of plastic to reduce the weight.

FIGURE 1 *Anableps* is a Central American fish that has two retinas per eye and egg-shaped lenses. It swims just below the surface of the water with its large eyes protruding half above and half under the water. Because of the difference in refraction that occurs when light passes from air to the eye, and from water to the eye, images occur at different distances from the lens, and thus two retinas and different eye positions confer a survival advantage.

What shapes do lenses come in?

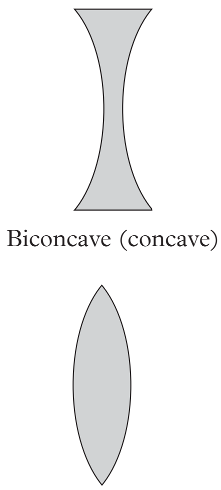


FIGURE 2 Shapes of two common lens types – concave and convex

The two main lens shapes are concave and convex (Figure 2). The earliest spectacles reminded their makers of the seeds called lentils, hence the term "lens", from the Latin for "lentil".

Incident rays of light shining on a lens always bend towards the thickest part. Recall the refraction of light through a prism (Figure 3). Light is refracted towards the normal at the first surface and away from the normal at the second surface. The overall effect is that light always bends towards the thickest part of the prism.

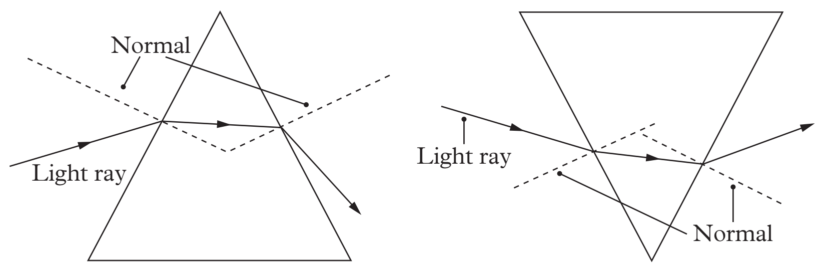


FIGURE 3 Light through a prism always refracts towards the thickest part of the prism.

A lens can be thought of as a system of prism-like blocks of slightly different shapes so that light rays are refracted at both sides of the lens, which results in the bending of light rays towards the thickest part. Light rays shining on a **convex lens** bend towards the centre, thus focusing or **converging** the light. For this reason, a convex lens is also called a converging lens (Figure 4A). Light incident on a **concave lens** spreads or **diverges** the light, so a concave lens is also called a diverging lens (Figure 4B).

convex lens
a lens that is thicker in the middle than at the edges that will cause rays to converge; also called converging lens

converging
the bending of light rays together

concave lens
a lens that is thicker at the edges than in the middle that will cause rays to diverge, and images formed will be virtual, erect and enlarged; also called diverging lens

diverging
the bending of light rays away from each other

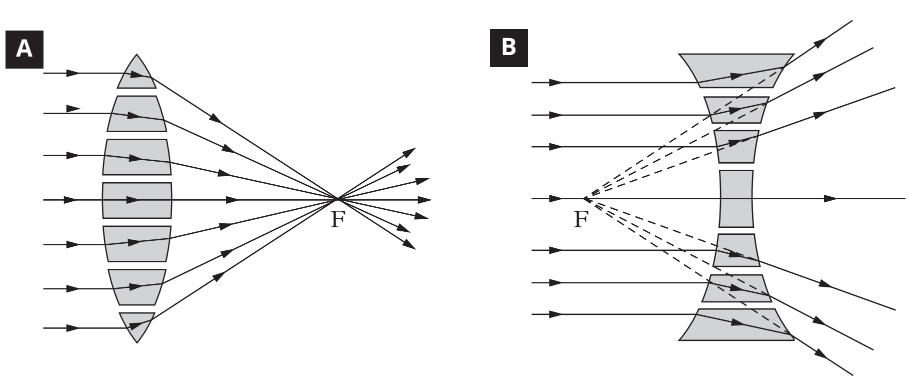


FIGURE 4 Lenses can be considered to be made up of prism-like blocks, so light will always refract towards the thickest part of the lens. (A) The convex lens converges light. (B) A concave lens is a diverging lens.

What are the features of lenses?

The surfaces of curved lenses look like parts of the circumference of a circle. We can use simple geometry to represent lenses.

Each face of the lens can be drawn using a compass. The centre of the circle that produces the curved surface is called the **centre of curvature**. Each face can have a different curvature. However, for our discussions, we will use lenses whose sides have the same radius of curvature. Figure 5 shows the main features of lenses.

Study tip

Remember lens shapes as "con**cave** goes in like a cave".

centre of curvature
the centre of the circle that produces the curved surface of a lens

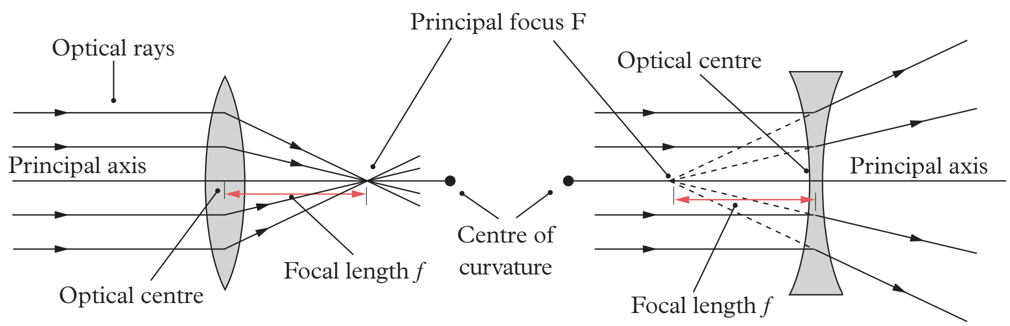


FIGURE 5 The main terms associated with lenses

The line from the centre of curvature through the optical centre of the lens is called the **principal axis**. If rays of light parallel to the principal axis are incident on a convex lens, the rays converge to a point on the other side of the lens called the **principal focus** (F). Since lenses can be used either way around, they have two focal points – one on either side of the lens. If rays of light parallel to the principal axis are incident on a concave lens, they diverge. However, if these rays are traced back, they appear to come from a point on the same side of the lens as the light originates. This is a virtual focus. The distance from the focal point to the optical centre of the lens is the **focal length** (f).

Thicker lenses have a shorter focal length, as shown in Figure 6.

principal axis
the line from the centre of curvature through the optical centre of the lens

principal focus
a point at which incident rays of light parallel to the principal axis converge on the other side of a converging lens, or from which the rays appear to have diverged for a diverging lens

focal length
the distance between the centre of a lens and its principal focus

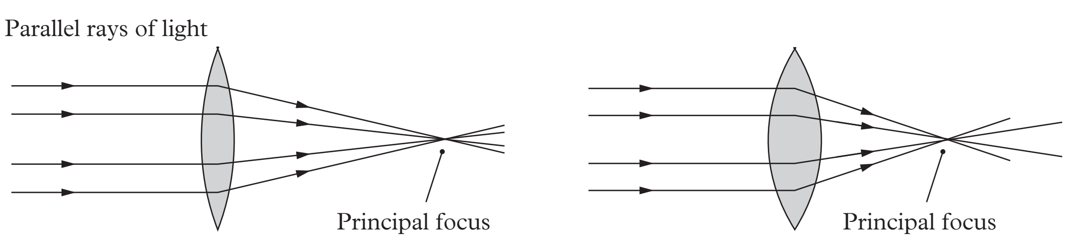


FIGURE 6 Thick lenses have shorter focal lengths than thin lenses and therefore are more powerful.

How are ray diagrams used to show images through lenses?

If you look through a magnifying glass (a convex lens) at an object, you can see the object. You are actually only seeing the image of the object. This can be easily verified if you look at an object a long distance away while holding the lens at arm's length. The image is inverted (upside-down).

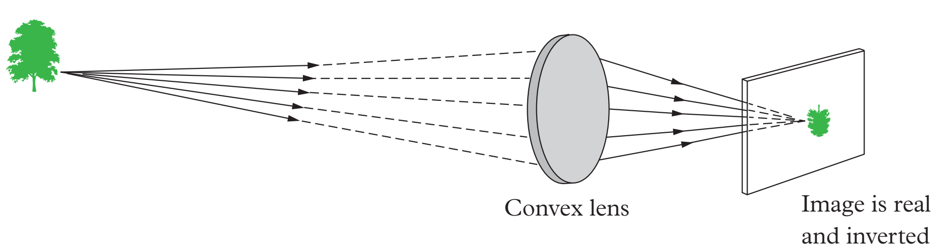


FIGURE 7 Images of distant objects are inverted, indicating that when you look through a lens, you are observing the image and not the object itself.

Ray diagrams can be drawn to find the position and nature of an image. Although refraction occurs at both sides of the lens, we simplify the drawing of ray diagrams by drawing a line through the centre of the lens and have all refractions occur at this line.

Any number of rays can be drawn to determine the position and nature of the image, but an accurate ray diagram often requires the use of protractors, calculations and measurements of the angles of refraction at both surfaces. For this reason, three rays are most commonly used to simplify the drawing of ray diagrams:

1. The ray parallel to the principal axis that refracts through the principal focus for a convex lens and appears to come from the focus for the concave lens.
2. The ray through the focus that refracts parallel to the principal axis for the convex lens. For a concave lens, the ray that is lined up with the focus on the opposite side refracts parallel to the principal axis.
3. The ray through the centre of the lens that continues unchanged in direction.

To find the position of an image requires the use of two rays – the third ray can be used to double-check the position.

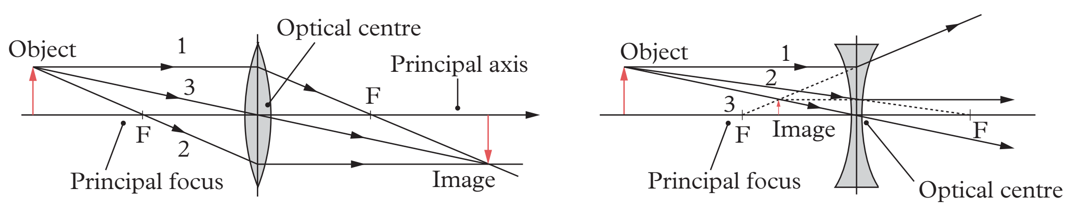


FIGURE 8 Three rays are used to find the image produced by a lens: a ray parallel to the principal axis (1), a ray through the focal point (2), and a ray through the optical centre of the lens (3). You can represent the lens by just a straight vertical line.

Challenge

Mirrors and lenses in water

A concave mirror and a convex lens are placed in water. Do their focal lengths change? Why or why not? (2 marks)

Characteristics of the image

When you draw a ray diagram, you will be expected to state the nature, location, orientation and size of an image:

- **Nature** – whether the image is real (rays pass through the image) or virtual (rays only appear to pass through the image)
- **Location** – where the image is in relation to the lens, usually stated in centimetres in front of the lens (same side as the object) or behind the lens (opposite side to the object); also stated in relation to the focal length of the optical device (e.g. $>2f$, f)
- **Orientation** – the appearance of an image with respect to the object stated as upright (erect) or inverted
- **Size** – the height of an image as measured perpendicular to the principal axis; stated qualitatively relative to the object such as bigger (enlarged or magnified) or smaller (diminished) compared with the object

What do images look like through convex lenses?

Figure 9 shows some examples of ray diagrams. The object has been placed at various positions with respect to the convex lens: greater than $2f$, at $2f$, between $2f$ and F, and between F and the lens. The ray diagrams show the nature, location and orientation of the image.

Figure 9A When the object is further than $2f$, the image produced is real, inverted, smaller, and between F and $2f$ on the opposite side of the lens.

Figure 9B When the object is at $2f$, the image produced is real, inverted, the same size, and at $2f$ on the opposite side of the lens.

Figure 9C When the object is between $2f$ and F, the image produced is real, inverted, larger, and outside $2f$ on the opposite side of the lens.

Figure 9D When the object is between F and the lens, the image produced is virtual, upright, larger, and between F and the lens on the same side of the lens.

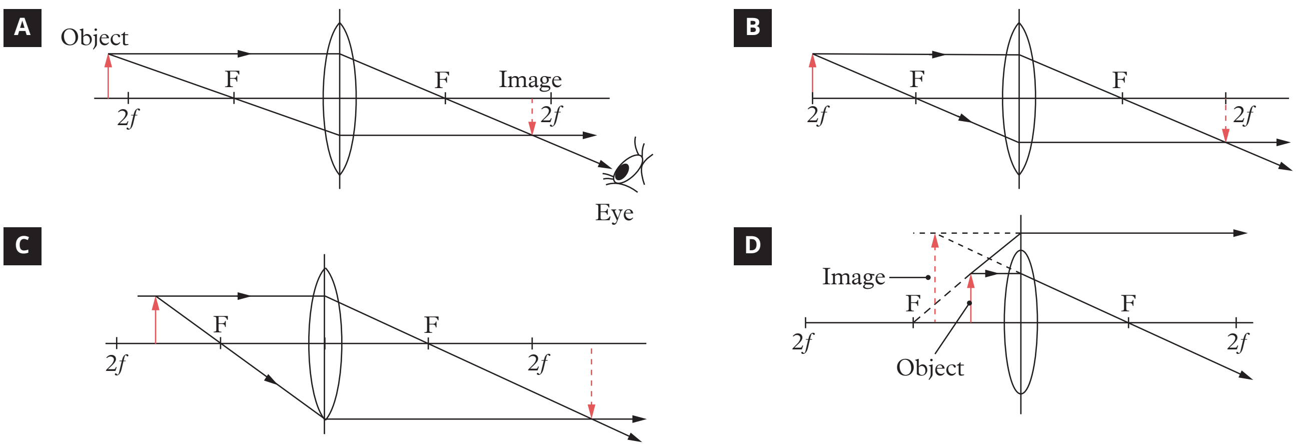


FIGURE 9 Ray diagrams for an object placed at various positions relative to a convex lens: (A) greater than $2f$, (B) at $2f$, (C) between $2f$ and F, and (D) between F and the lens

As an object moves towards F, the image moves away from the convex lens and increases in size. When the object is between F and the convex lens, a virtual image is formed.

What do images look like through concave lenses?

The same three rays can be used to find the position and nature of an image in a concave lens. However, two important rules must be remembered:

- The rays always bend towards the thickest part of the lens.
- The focal point (the point at which light rays parallel to the principal axis converge or appear to come from) is on the same side of the lens as the object.

Figure 10 shows the use of rays to find the position and characteristics of the image in a concave lens. The ray diagrams show the following:

Figure 10A When the object is at a distance greater than F from the concave lens, the image is virtual, upright, smaller, and between F and the lens on the same side of the lens as the object.

Figure 10B When the object is between F and the concave lens, the image produced is virtual, upright, smaller, and between the object and the lens on the same side of the lens.

Study tip

You will notice that whatever the distance of the object, even close to the lens, the image is virtual, upright, smaller and between the lens and F, on the same side as the object. Concave lenses always produce these types of images no matter where the object is placed.

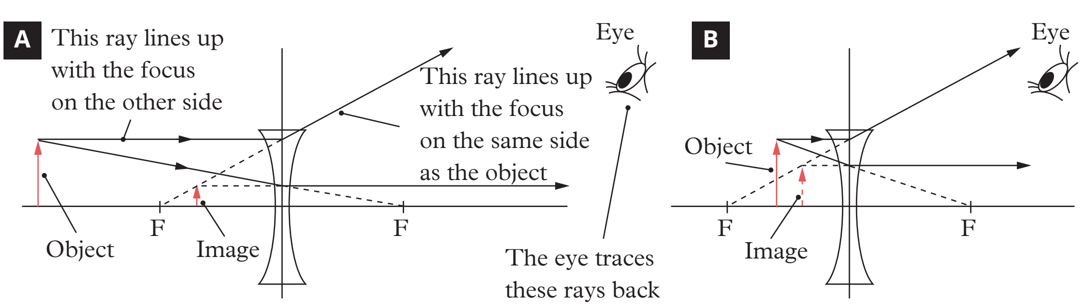


FIGURE 10 Ray diagrams for an object placed at various positions relative to a concave lens

Skill drill

Modifying an experiment involving images viewed through a convex lens

Science inquiry skills: Processing and analysing data (Lesson 1.7)

A convex lens with a focal length of 5 cm was positioned in a lens holder. Two one-metre rulers were laid end-to-end beside the lens, which was located at the point where the two rulers joined. A matchstick was used as an object, and students were directed to locate the image, capturing it on a sheet of white paper, if possible (i.e. if the image was real), as the object was moved towards the lens from a distance of 20 cm. For each position of the object, students were instructed to record the nature (real or virtual), location (distance, v), orientation (upright or inverted) and size (magnified, diminished or same size) of the image. The set of data recorded by students is shown in Table 3.

TABLE 3 Recorded data for convex lens experiment

Nature	Object distance, *u* (cm)	Image distance, *v* (cm)	Orientation	Size
Real	20	6.5	inverted	diminished
Real	15	7.5	inverted	diminished
Real	10	10	inverted	same
Real	8	13	inverted	enlarged
Real	6	30	inverted	enlarged
—	5	N/A	—	—
Virtual	4	–20	upright	enlarged
Virtual	3	–7.5	upright	enlarged
Virtual	2	–3.5	upright	enlarged
Virtual	1	–1	upright	enlarged

Practise your skills

1 **Identify** the focal length of the lens. **Justify** your answer. (2 marks)

2 **Propose** a modification to this experiment which would refine the data collected. (2 marks)

3 **Propose** a modification to this experiment which would extend its scope. (2 marks)

4 **Propose** a modification to this experiment which would redirect the aim of the investigation. (2 marks)

Check your learning 14.9

Check Your Learning 14.9: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Sketch** ray diagrams to represent a 1 cm high object placed 3 cm from

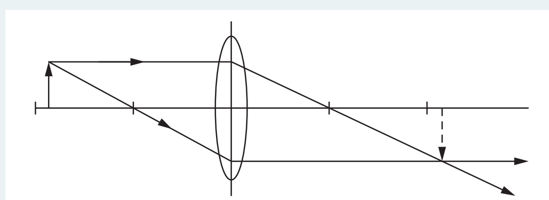
a a convex lens (f = 2 cm) (2 marks)

b a concave lens (f = 2 cm). (2 marks)

2 For the ray diagram shown in the figure

a **identify** the focal point, 2f, object, image, object height, optical centre, image distance, and object distance (8 marks)

b **describe** the location, orientation and size of the image. (3 marks)



3 A 2.0 cm high candle is placed 50 cm in front of a 20 cm focal length convex lens. **Sketch** a ray diagram to find the

a location of the image (1 mark)

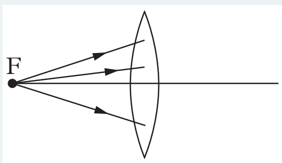
b height of the image (1 mark)

c location of the image of the candle if the candle is placed inside the focal point at a point 10 cm from the lens. (1 mark)

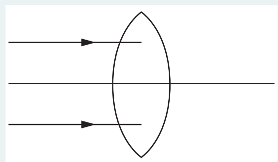
Analytical processes

4 **Determine** the path of light in each ray diagram.

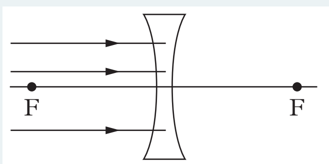
a (3 marks)



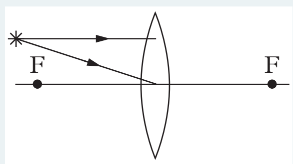
b (2 marks)



c (3 marks)



d (2 marks)



5 An object 5.0 cm high is placed 20.0 cm from a convex lens of focal length 15.0 cm. **Sketch** a ray diagram to scale to **determine** the nature, location, orientation and size of the image. (4 marks)

6 A 5.0 cm high object is placed 25.0 cm in front of a concave lens of 10.0 cm focal length.

a Use a ray diagram to **determine** the nature, location, orientation and size of the image (Use a scale of 1 cm = 5 cm). (4 marks)

b "Magnification" is defined as the ratio of image height to object height. **Determine** the magnification in this case and state whether it is equal to object distance/image distance. (2 marks)

Lesson 14.10
Diffraction and interference of light

Key ideas

→ The diffraction of light occurs when waves pass through a slit or bend behind a barrier.

→ Interference of light affects the observed diffraction patterns.

When does light diffract?

In Module 12, we saw that diffraction is the bending of waves as they pass through an opening (aperture) or around the edge of an object in their path. For light, if an object is placed in the path of the waves, a "shadow" is produced if the object is of the same size as the wavelength. This is due to the bending of light around the edges of objects. This produces diffraction "fringes" where the edges appear to be blurred when light is shone on them. Figure 1 shows the diffraction fringes produced by red light passing the edges of a razor blade. This explains why it is difficult to look at objects smaller than the wavelength of light (such as atoms) with a microscope. They just look blurred.

To observe this effect, the slit or the object in front of the waves has to be of the same size as the wavelength of the waves, and light waves have very short wavelengths.

Learning intentions and success criteria

Study tip

Both the wave model and the particle model are useful for describing some properties of light, such as how images form. However, diffraction and interference are two characteristics of light that can only be explained by the wave model of light.

How does interference affect diffraction patterns?

A striking example of the diffraction effect can be seen when light passes through two narrow slits side by side. For example, at night in rainy weather, scratches on a car's windscreen produce long shafts of light with black bands across them. This is a result of diffraction of the light as it passes through the slits and the interference of light afterwards.

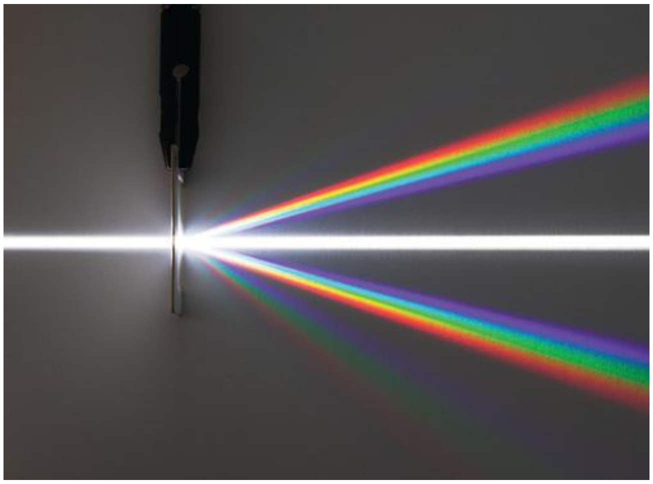


FIGURE 2 The diffraction pattern of white light passed through a narrow slit

FIGURE 3 The Christmas beetle (*Anoplognathus pallidicollis*) displays colourful iridescence, which can be explained by the thin film interference of light waves in its exoskeleton.

This pattern can be seen more clearly if a laser and commercially prepared narrow slits are used. If different colours of light are used, the pattern changes. If red light is used, the pattern spreads out more than when blue light is used. Recall the diffraction of water waves – the larger the wavelength compared with the slit, the more the pattern spreads out and the more noticeable the diffraction is. This suggests that the wavelength of red light is larger than that of blue light.

Diffraction of light is also produced when light passes through a single slit, but it is not as dramatic. Figure 2 shows the diffraction pattern produced on a screen when white light passes through a very narrow single slit.

These banding effects can be explained by constructive and destructive interference of the light passing through the slits. For example, a wavefront striking a slit becomes a new circular wave on the other side. With two slits, these two circular waves overlap and regions of constructive interference and destructive interference are produced. Constructive interference occurs when the waves are in phase and it is responsible for the bright light and colours, whereas destructive interference is due to the waves being out of phase and creates the dark regions. This is seen in Figure 4.

The first person to come to a theoretical understanding of how this diffraction and interference works was English academic Thomas Young (1773–1829).

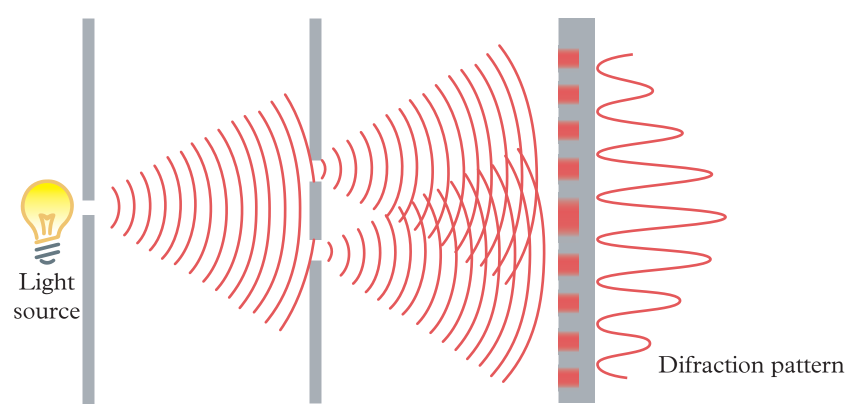


FIGURE 4 In Young's double-slit experiment, the overlap of light passing through separate slits causes a pattern with regions of constructive interference (light regions) and destructive interference (dark regions).

Real-world Physics

Michelson–Morley experiment

An early use of interference principles in a scientific experiment was in 1887 when American scientists A. A. Michelson (1852–1931) and E. W. Morley (1838–1923) measured the speed of light into two directions (north–south, and east–west) at right angles.

They were concerned that there was no experimental proof of the luminiferous aether, which was supposed to be the absolute frame of reference for light. They argued that as Earth moves around the Sun, it should be moving through an aether or "wind". If there was an aether, and a beam of light was shone in the same direction as Earth's movement through it, the velocity of light would be measured as greater compared to light travelling at right angles to the direction of motion of Earth through the aether. Similarly, if light was shone in the opposite direction to Earth's movement through the aether, the velocity should be measured as smaller. That seemed logical.

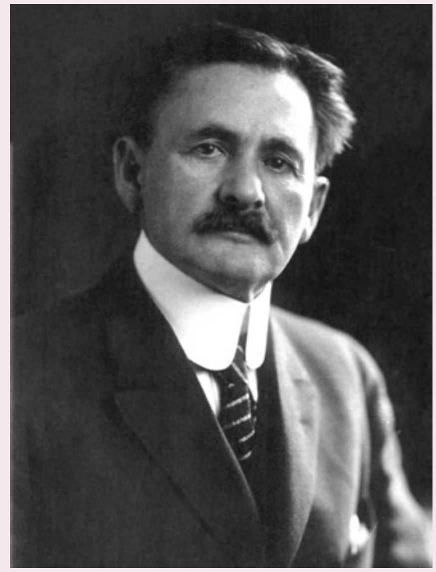


FIGURE 5 A. A. Michelson refuted the aether theory.

However, light travels so rapidly that direct measurement of its speed was not possible at the time. They were able to use an interferometer to measure the difference in the speed of light travelling with, against or across the aether. Figure 6 shows the path diagram for the interferometer. It was a huge instrument consisting of a source of coherent (single-wavelength) light and mirrors on a platform screwed to a massive granite stone block, floating in a pool of mercury so that it was stable but could be rotated.

They tried everything – they rotated it left and right; they did the experiment in the morning and afternoon, in summer and in winter–but there was no fringe shift. Trying to explain this "null" result was going to be difficult for physicists.

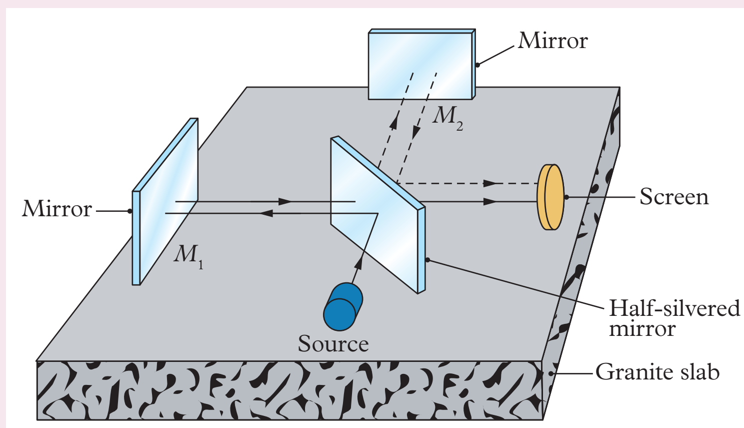


FIGURE 6 Light path in the Michelson–Morley experiment

All theories attempting to explain the Michelson–Morley "null" result were eventually replaced by the comprehensive theory proposed by Albert Einstein in 1905 – the special theory of relativity.

Apply your understanding

1 **Explain** the purpose of the Michelson–Morley experiment, and state whether their aim was achieved. (3 marks)

2 **Explain** why Michelson and Morley use "coherent" light for the experiment. In your response, **explain** the meaning of the term. (2 marks)

3 The interferometer used yellow light with a frequency of 5.09×10^{14} Hz. The light was sent along a path length of 11.0 m from light source to detector.

  a **Calculate** the wavelength of the light. (2 marks)

  b **Determine** how many wavelengths fit into the 11.0 m path length. (2 marks)

Check your learning 14.10

Check your learning 14.10: Complete these questions online or in your workbook.

Retrieval and comprehension

1 **Describe** how the wave model helps explain the phenomenon of diffraction. (2 marks)

2 **Describe** how the wave model helps explain interference of light. (3 marks)

Analytical processes

3 **Explain** whether blue or orange light would undergo more diffraction. Orange light has a longer wavelength than blue light. (2 marks)

4 **Predict** whether diffraction would occur if light with a wavelength of 1×10^{-7} m struck a slit of width 1 mm. **Justify** your prediction. (2 marks)

Knowledge utilisation

5 Using the image of single slit diffraction in Figure 2, **propose** evidence to demonstrate that the greater the wavelength, the greater the diffraction. (2 marks)

MODULE 14

Lesson 14.11
Review: Light

Summary

14.1
- Light is an electromagnetic wave that needs no medium for its propagation.
- The wave and particle models are used to explain the behaviour of light.

14.2
- Light is modelled as transverse waves composed of electric and magnetic fields.
- Polarisation controls the amount of light transmitted by only allowing waves oscillating in a specific direction.

14.3
- Intensity of light is the power transferred per unit area.
- The intensity of light is proportional to the square of the amplitude of the waves.
- The intensity of light decreases with distance in an inverse-square relationship.

14.4
- The first law of reflection states that the incident ray, reflected ray and normal are in the same plane.
- The second law of reflection states that the angle of incidence is the same as the angle of reflection.
- Ray diagrams show the paths of light as they reflect off plane mirrors.

14.5
- Practical: The law of reflection for images in a plane mirror

14.6
- Light is refracted when it passes from one medium to another. For a given angle of incidence, the amount of refraction depends on the refractive index of each medium.
- Snell’s law relates the angle of incidence, angle of refraction, velocity of light passing through two media, their wavelengths and refractive indices.
- Different wavelengths of light are refracted to different degrees, giving rise to dispersion.

14.7
- Practical: Refractive properties of a transparent substance

14.8
- The critical angle is the angle of incidence that causes the angle of refraction to be 90°.
- Total internal reflection occurs when the critical angle is exceeded.

14.9
- Convex lenses cause rays of light to converge, whereas concave lenses cause rays of light to diverge.
- Ray diagrams are used to show the path of light through lenses.
- Depending on the position of an object observed through a lens, the nature, location, orientation and size of its image may differ.

14.10
- The diffraction of light occurs when waves pass through a slit or bend behind a barrier.
- Interference of light affects the observed diffraction patterns.

Key formulas

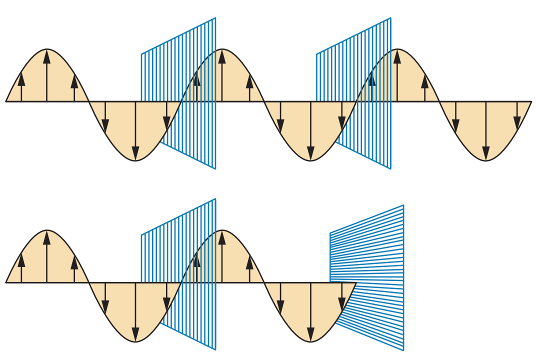
Power	$P = \frac{W}{t}$
Intensity	$I = \frac{P}{A}$
Intensity and distance	$I = \frac{P_S}{4\pi r^2}$ or $\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2}$ or $I \propto \frac{1}{r^2}$
Snell's law	$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$ or $n_1 \sin\theta_1 = n_2 \sin\theta_2$
Reciprocal law	$n_{m\rightarrow a} = \frac{1}{n_{a\rightarrow m}} = \frac{1}{n_m}$
Critical angle	$\sin\theta_c = \frac{1}{n}$

Review questions 14.11A Multiple choice

Review questions: Complete these questions online or in your workbook.

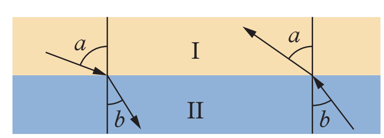
(1 mark each)

1 The diagram represents an electromagnetic wave that is undergoing



A polarisation.
B diffraction.
C dispersion.
D interference.

2 The diagram shows light as it passes between medium I and medium II. If the absolute refractive index of medium II is 1.33, the possible refractive index of medium I is



A 0.9.
B 1.0.
C 1.33.
D 1.5.

3 When light strikes substance X (from air) at an angle of incidence of 40°, the angle of refraction is measured at 29°. When light strikes substance Y (from air) at an angle of 40°, the angle of refraction is measured at 34°. Which one of the following is closest to the angle of refraction when light from substance Y strikes substance X at an angle of incidence of 40°?

A 5°
B 34°
C 67°
D 85°

4 An object 4.0 cm high is located 15 cm in front of a plane mirror. Which one of the following best describes the characteristics and the location of the image?

A Virtual, 4 cm high, upright, 15 cm behind the mirror

B Virtual, 4 cm high, inverted, 15 cm behind the mirror

C Real, 4 cm high, upright, 15 cm behind the mirror

D Real, <4 cm high, upright, <15 cm behind the mirror

5 The critical angle for a beam of light striking the interface between a certain type of glass and air is 41°. If the glass was placed in a liquid medium with an absolute refractive index of 1.3, the new critical angle would be

A <41°. **B** 41°.

C >41°. **D** 90°.

6 A light source has an intensity of 100 W m^{-2} at a distance of 0.5 m from the source. The intensity will be 50 W m^{-2} at a distance of

A 0.25 m.

B 0.71 m.

C 1.00 m.

D 1.41 m.

7 Decide which of the following choices completes the statement correctly. The image of an object reflected in a plane mirror is

A upside down.

B in front of the mirror.

C virtual.

D real.

8 Which statement describes what happens when light travels from a less dense medium into a more dense medium?

A It refracts towards the normal.

B It refracts away from the normal.

C It does not refract.

D It exhibits total internal reflection.

9 Light passes from air into a transparent substance with an absolute refractive index of 1.36. The angle of incidence is 30°. The angle of refraction is

A 20.0°. **B** 21.6°.

C 42.8°. **D** 51.6°.

10 Which statement describes the image of an object two focal lengths from a convex lens?

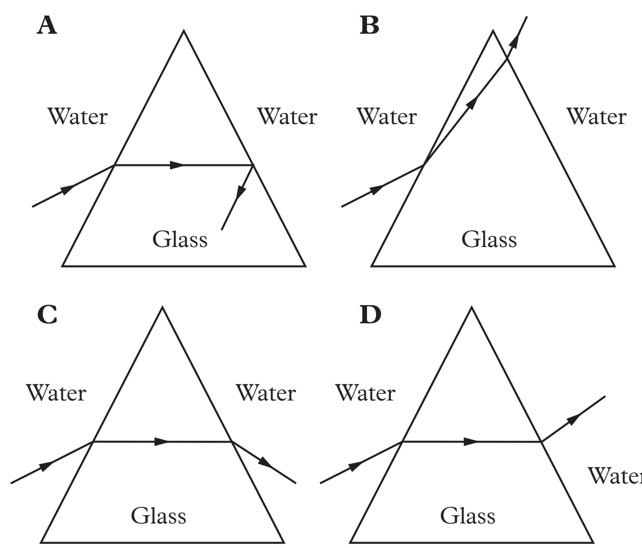
A Impossible to locate (no image)

B At a distance of 1 focal length, upright, enlarged and real

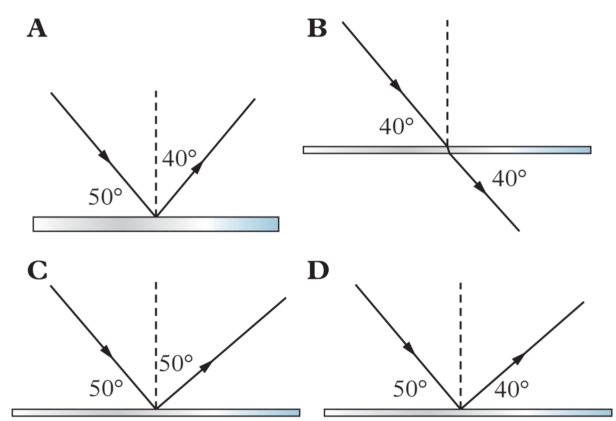
C At a distance of 2 focal lengths, inverted, same size and real

D At a distance of 2 focal lengths, upright, same size and virtual

11 Which one of the following diagrams best shows the path of a light ray for a glass prism (n_{glass} = 1.55) immersed in water (n_{water} = 1.33)?



12 Which one of the following best shows the path of a beam of light striking a plane mirror?



Review questions 14.11B Short response

Review questions: Complete these questions online or in your workbook.

Retrieval and comprehension

13 **Describe** the difference between unpolarised and polarised light. (1 mark)

14 **Identify** two properties of waves that are considered to be strictly wave characteristics. (2 marks)

15 **Explain** whether there is any one model for light that can explain all of its properties. (2 marks)

16 **Recall** the angle between the electric and magnetic wave planes in polarised light. (1 mark)

17 When a light ray goes from a less optically dense medium to a more optically dense medium, does the ray bend towards or away from the normal? **Sketch** a diagram to show your answer and **propose** two media that would demonstrate this. (3 marks)

18 **Recall** Snell's law and **describe** the meaning of the terms. (2 marks)

19 **Define** the term "dispersion" and **explain** what characteristic of light makes it happen. (2 marks)

20 **Sketch** ray diagrams for

- **a** a convex lens showing the images produced when an object is placed at the following distances
  - **i** $>2f$ (2 marks)
  - **ii** $2f$ (2 marks)
  - **iii** between F and $2f$ (2 marks)
  - **iv** F (2 marks)
  - **v** $<F$ (2 marks)
- **b** a concave lens when the object is at $2f$. (2 marks)

21 **Define** the term "diffraction" and give an example of this phenomenon. (2 marks)

22 A light source has an intensity of $20\,\mathrm{W\,m^{-2}}$ at a distance of 100 m from a source. **Calculate** its intensity at distances of

- **a** 200 m (2 marks)
- **b** 1.0 km. (2 marks)

23 A beam of light is incident on water ($n_{\text{water}} = 1.33$) at an angle of incidence of 35.0°.

- **a** **Calculate** the angle of refraction. (3 marks)
- **b** **Calculate** the angle the refracted ray makes with the surface of the water. (1 mark)

24 A small light 4.0 cm high is placed 25.0 cm in front of a concave lens of 10.0 cm focal length. **Sketch** a ray diagram to find the

- **a** position of the image (2 marks)
- **b** height of the image. (1 mark)

25 A candle 3.0 cm high is placed 5.0 cm in front of a convex lens of 20 cm focal length.

- **a** **Sketch** a ray diagram to find the image. (2 marks)
- **b** **Describe** the nature of the image. (5 marks)

26 A light ray strikes the surface of a block of fused quartz at an angle of 54° to the normal.

- **a** **Calculate** the angle of refraction. (3 marks)
- **b** **Calculate** the velocity of light in the quartz. (2 marks)

27 **Calculate** the absolute refractive index for light going from air to a medium in which the velocity of light is

- **a** $2.4 \times 10^8\,\mathrm{m\,s^{-1}}$ (2 marks)
- **b** $1.8 \times 10^8\,\mathrm{m\,s^{-1}}$. (2 marks)

28 The refractive indices of flint glass and turpentine are 1.65 and 1.50 respectively.

- **a** **Calculate** the refractive index for light passing from turpentine to flint glass. (2 marks)
- **b** If the angle of incidence in the turpentine is 49°, **calculate** the angle of refraction in the flint glass. (3 marks)

29 In each of the following cases, **sketch** a ray diagram to find the position and characteristics of the image.

- **a** A 2.0 cm high object is placed 10 cm in front of a 20 cm focal length convex lens. (3 marks)
- **b** A 5.0 cm object is placed 18 cm in front of a 6.0 cm focal length concave lens. (3 marks)
- **c** A 10 cm high object is placed 50 cm in front of a 25 cm focal length convex lens. (3 marks)

Analytical processes

30 **Contrast** the properties of light and sound waves. (1 mark)

31 **Determine** the value of the refracted angle when the incident ray of light is at the critical angle of 43.5°. (1 mark)

32 In air, the wavelength of red light is 665 nm and that of blue light is 470 nm. Use this information to

a **calculate** the frequency of red light and blue light (3 s.f.), using the exact value of 3.00×10^8 m s^{-1} for the speed of light in air (2 marks)

b **calculate** the wavelengths of red light and of blue light in glass (in nm) given that their refractive indices in glass are n_g(red) = 1.515 and n_g(blue) = 1.523 (3 s.f.) (2 marks)

c **determine** the velocity of red light and of blue light in glass (3 s.f.). (2 marks)

33 A light ray passes from the first medium to the second medium. **Determine** whether the light ray will bend away from or towards the normal. Use Table 1 in Lesson 14.6 to find values to help you decide.

a Air to water (1 mark)

b Glass to air (1 mark)

c Water to glass (1 mark)

d Diamond to glass (1 mark)

e Flint glass to crown glass (1 mark)

f Perspex to a vacuum (1 mark)

34 Given the absolute refractive indices of n_{air} = 1.00, n_{water} = 1.33 and n_{glass} = 1.52, **determine** which way light will bend (towards the normal or away from the normal) in each case, briefly justifying your decision.

a Air to glass (1 mark)

b Glass to air (1 mark)

35 "Total internal reflection always occurs when a light beam in a more dense medium strikes a boundary to a less dense medium." **Explain** whether this statement is accurate or not. (2 marks)

36 A wavefront approaches a fixed barrier at an angle of 30° to the barrier.

a **Determine** the

i angle of incidence (1 mark)

ii angle of reflection (1 mark)

iii angle the direction of propagation makes with the barrier. (1 mark)

b **Create** a labelled diagram to show these angles. (2 marks)

37 Light from a source has an intensity of 150 W m^{-2} at a distance of 100 m from the source. **Determine** how far from the source its intensity would be 100 W m^{-2}. (2 marks)

38 Light from a light box is directed at an angle of 30° onto a block of glass whose refractive index is 1.5, and then onto the surface of salty water whose refractive index is 1.4. **Determine** in which case the light will bend more. (5 marks)

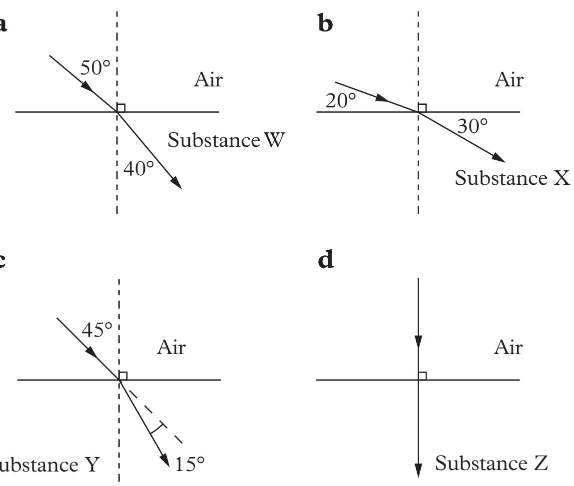
39 The absolute refractive indices of medium A and medium B are 1.78 and 1.20 respectively.

a **Calculate** the speed of light in each medium. (2 marks)

b **Determine** which substance is the most optically dense. (1 mark)

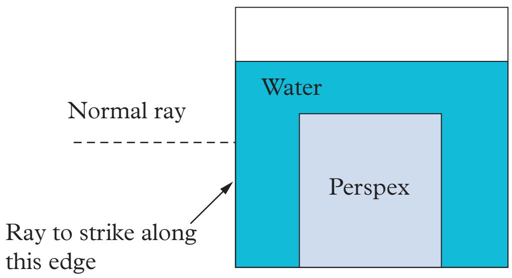
40 In each of the four cases shown, a light ray travels from air to the substance. Use the diagrams to **determine** the refractive index of the substances. (2 marks each)

a **b** **c** **d**

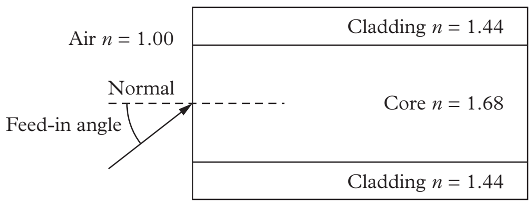


41 The index of refraction for glass is different for different colours of light. The refractive index for blue light (λ = 430 nm) passing from air into flint glass is 1.650 and for red light (λ = 680 nm) it is 1.615. A beam containing blue and red light is shone onto a block of flint glass at an angle of 52°. **Determine** the angle between the blue and the red rays in the glass. (5 marks)

42 The figure represents a block of Perspex (refractive index 1.49) submerged in water (refractive index 1.33) in a large glass container. A beam of light is shone onto the edge of the container, at an angle of incidence of 30°. **Determine** the path of the light beam through the water and through the Perspex and back into the air. Draw the path accurately on the diagram. (Disregard any refraction caused by the glass.) (4 marks)



43 **Consider** the following optical fibre cable. The initial feed-in of light occurs from air into the core material.



A design engineer claims that a feed-in angle of 40° would allow total internal reflection to occur.

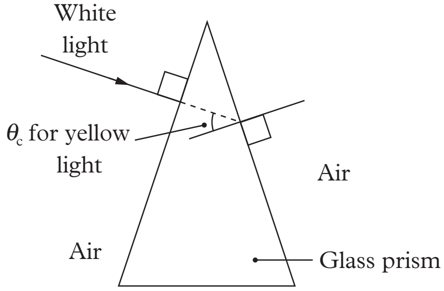
a **Determine** whether the engineer is correct. Support your argument through quantitative analysis. (6 marks)

b Regardless of whether you supported the engineer or not, **determine** what range of feed-in angles would allow total internal reflection to occur. (7 marks)

44 An object 5.0 cm high is placed 1.8 cm in front of a convex lens. An image 6.8 cm high is produced on a screen. **Use** a ray diagram to **determine** the focal length of the lens. (3 marks)

45 An object 6 cm high is placed 8 cm in front of a convex lens with a focal length of 5 cm. **Create** a ray diagram and use it to **determine** the nature, location, orientation and size of the image. Show any calculations you use. (5 marks)

46 A beam of white light is shone onto a glass prism such that the angle with the second surface is the critical angle for yellow light. **Analyse** what occurs to the beam of white light. (5 marks)

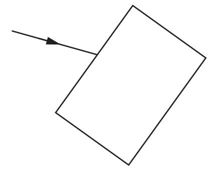


Knowledge utilisation

47 **Predict** what happens to the intensity of light if the distance from the source is doubled. (1 mark)

48 **Determine** and **sketch** the path of light in each of the diagrams, when a ray of light passes from air to a block of glass ($n_g = 1.5$). The critical angle for glass in air is 41.8°. (2 marks each)

a



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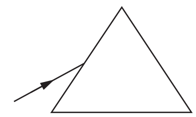

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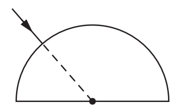

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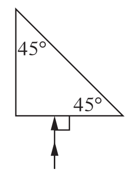

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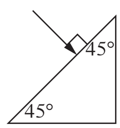

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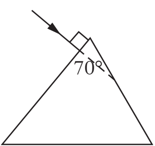

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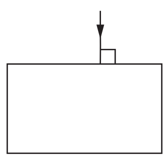

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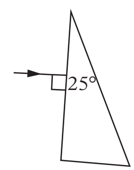


49 On a sunny morning, the intensity of the sunlight was measured to be 350 W m^{-2} (3 s.f.). A science student takes a hand lens with a diameter of 10.0 cm out into the sunlight.

a **Calculate** the amount of power falling on the area of the lens. (2 marks)

b **Determine** the intensity when the sunlight is focused onto a spot 1.00 cm in diameter. (1 mark)

c **Determine** whether the piece of paper the spot is focused on is likely to catch fire, given that a light intensity of 100 W cm^{-2} is required to ignite paper. (3 marks)

Data drill

Investigating refraction

A student conducted an experiment to determine the refractive index of a transparent substance. A laser was used to shine incident rays at various angles to the centre of the curvature of a semicircular Perspex block. The position of the refracted ray was marked, and the angle of refraction measured.

Angles of incidence i and refraction r were measured using a standard student protractor. The procedure was repeated to gather the raw data shown in Table 1.

TABLE 1 Results from the refraction experiment

Angle i (°)	Angle r_1 (°)	Angle r_2 (°)	Angle r_{av} (°)	δ (r)	sin i	sin r_1	sin r_2	sin r_{av}	δ (sin r)
10.0	6.5	6.0	6.3	0.25	0.174				0.004
20.0	12.5	15.5	14.0	1.50	0.342	0.216	0.267	0.242	
30.0	18.5	21.0	19.8	1.25	0.500	0.317	0.358	0.338	0.021
40.0	24.5	27.0	25.8	1.25	0.643	0.415	0.454	0.434	0.020
50.0	32.5	29.5	31.0	1.50	0.766	0.537	0.492	0.515	0.022
60.0	34.0	37.0	35.5	1.50	0.866	0.559	0.602	0.581	0.021

Apply understanding

1 **Calculate** the values of sin $r_{1,}$ sin r_2 and sin r_{av} for the incident angle of 10.0°. (2 marks)

2 **Calculate** the uncertainty for the mean $\delta\bar{x}$ of sin r for the incident angle of 20.0°. (2 marks)

Analyse data

3 **Identify** any trends, or relationships related to Snell's law. **Justify** your answer. (4 marks)

4 **Identify** any possible sources of systematic error and random error, and **justify** by referring to the data. (2 marks)

Interpret evidence

5 **Draw a conclusion** and **justify** if the experiment can be used to accurately determine the refractive index of Perspex (the accepted value is 1.49). (5 marks)

Module 14 checklist: Light

Quizlet: Revise key terms online to test your understanding

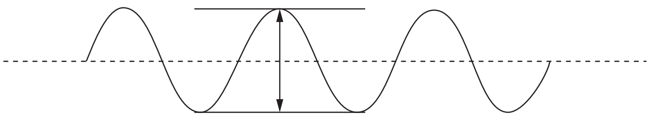
UNIT 2

Topic 2 review

Multiple choice

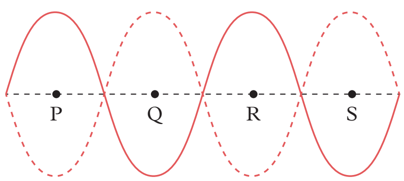
(1 mark each)

1 The arrow in this wave diagram represents



A wavelength.
B the amplitude.
C twice the amplitude.
D twice the wavelength.

2 A standing wave is generated on a spring by shaking one end sideways. Three stages of its motion are shown in the diagram. Which statement best identifies one wavelength, and two points in phase?



A PQ is one wavelength, P and R are in phase.
B PQ is one wavelength, Q and S are in phase.
C PR is one wavelength, Q and R are in phase.
D PR is one wavelength, P and R are in phase.

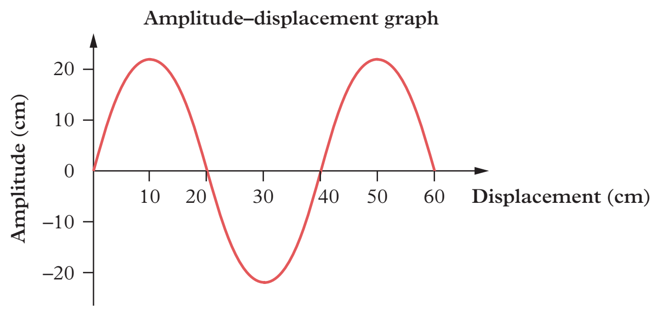
3 Which of the following produces standing waves?

A Identical waves travelling in opposite directions in a medium
B Superposition of different wave forms in the same medium
C Superposition of identical wave forms in different media
D Inverse waves crossing over each other as they pass through a medium

4 Which is the best term for the time for two successive crests to pass a point?

A Period
B Frequency
C Amplitude
D Wavelength

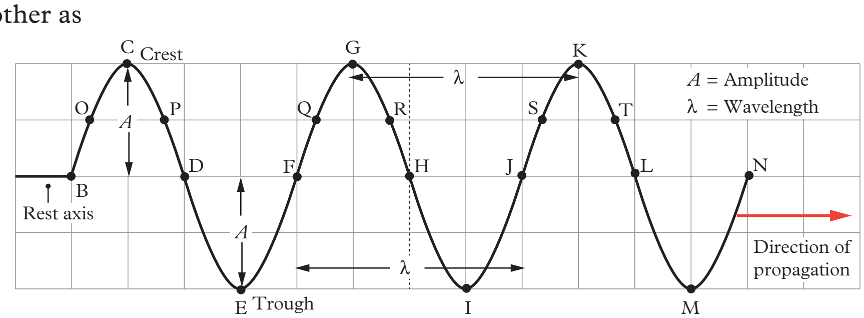
5 The period of the wave in the figure shown is 2 seconds. Its velocity is



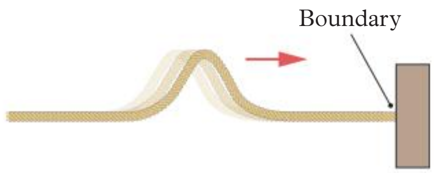
A $10\,cm\,s^{-1}$.
B $20\,cm\,s^{-1}$.
C $40\,cm\,s^{-1}$.
D $60\,cm\,s^{-1}$.

6 A diagram of a wave is shown. Which of the following represents the wavelength?

A CE
B BD
C CG
D DF



7 Consider the figure.



Which of the diagrams A–D correctly shows the nature of the wave after reflection?

A

B

C

D

8 The lowest frequency that a piano can produce is 27.5 Hz. What is the wavelength of the sound from this string on a day when the temperature is 20°C? (The speed of sound is related to temperature by the formula:

$$v(\text{sound}) = 331 + 0.6T$$

where T is the temperature in °C.)

A 8 cm

B 12.00 m

C 12.47 m

D 343 m

9 The velocity of a wave in a guitar string was measured to be 200 m s^{-1}. The string was plucked in its fundamental mode and the wavelength was noted as 2.0 m. What is the frequency of the string, and the next harmonic?

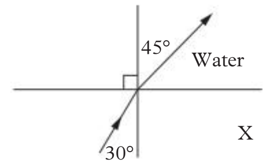
A 100 Hz, 200 Hz

B 100 Hz, 300 Hz

C 400 Hz, 800 Hz

D 400 Hz, 1200 Hz

10 A beam of light in medium X enters water with an angle of incidence of 30°, as shown in the figure. The angle of refraction into the water is 45°. What is the refractive index of medium X? Note: $n_{\text{water}} = 1.33$.



A 0.47

B 0.94

C 1.5

D 1.88

11 The fundamental of an open tube of a certain length is 233 Hz. If the length of the tube is doubled, what is the fundamental frequency?

A 58 Hz

B 116.5 Hz

C 233 Hz

D 466 Hz

12 A light has an intensity of 100 W m^{-2} at a distance of 0.5 m from the source. At what distance will the intensity be 50 W m^{-2}?

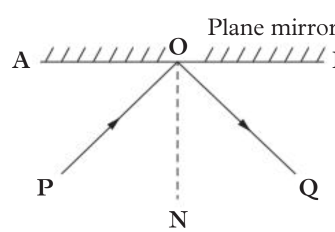
A 0.25 m

B 0.71 m

C 1.00 m

D 1.41 m

13 A ray of light is reflected off a plane mirror so that the angle between the incident and reflected rays is 90°.



If the plane mirror is rotated by 10° about O in the anticlockwise direction, then the angle between the incident and reflected rays will be

A 70°.

B 80°.

C 100°.

D 110°.

14 Light passes from air into a transparent substance with an absolute refractive index of 1.36. The angle of incidence is 30°. What is the angle of refraction?

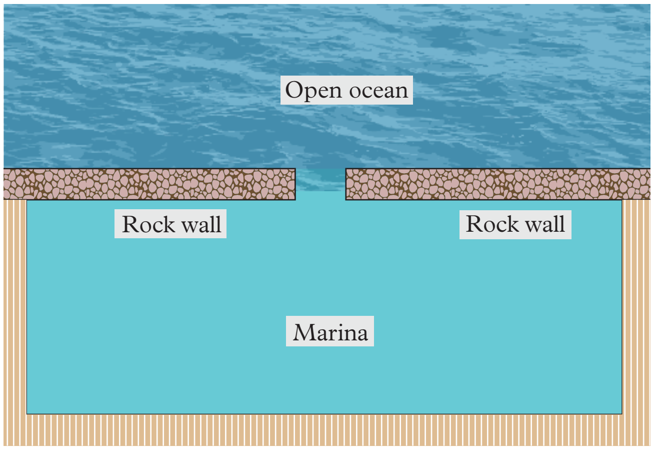
A 20.0°
B 21.6°
C 42.8°
D 51.6°

15 Which of the following describes the image of an object two focal lengths from a convex lens?

A No image formed
B At a distance of 2 focal lengths, inverted, same size and real
C At a distance of 2 focal lengths, upright, same size and virtual
D At a distance of 1 focal length, upright, enlarged and real

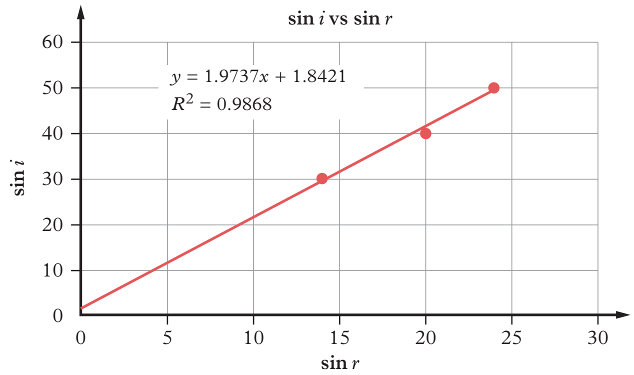
Short response

16 The entrance to a boat anchorage (marina) is between two rock walls. The wave pattern in the ocean outside the marina is shown. **Sketch** the expected wave pattern inside the marina. **Explain** the pattern you have drawn. (3 marks)



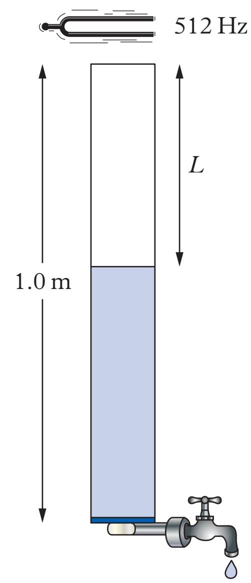
17 Students experimenting with an unknown transparent substance used a light box to produce a ray of light. They shone the ray onto the unknown substance at various angles and measured the angles of refraction. Their results are given in the table. A graph of the sine of the angles is also shown.

Angle of incidence, i (degrees)	30.0	40.0	50.0
Angle of refraction, r (degrees)	14	20	24



Determine the refractive index using information provided in the graph (2 d.p.). **Explain** your reasoning. (3 marks)

18 A vertical tube 1.0 m in length is filled with water. The water is slowly let out by a tap at the bottom of the tube while a tuning fork of frequency 512.0 Hz is sounded and held over the top of the tube. (Note: the speed of sound in air is $340.0\,m\,s^{-1}$.) Given that an observer is solely interested in any resonance (loud) sound coming from the tube due to the vibration of the tuning fork, **determine** and **explain** what the observer will hear from the time the tube starts to empty until it is empty of water. **Use** both calculations and diagrams to **justify** your explanation. (6 marks)



19 A trombone can be modelled as an open pipe 270 cm long. Given the information in the table, **determine** what happens to the frequency of a trumpet's third harmonic as the temperature varies. Include some calculations to **justify** your answer. (3 marks)

Temperature (°C)	Speed of sound (m s^{-1})
0	331
15	340
20	343
25	346

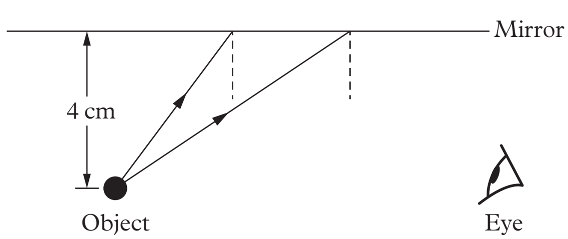
20 On a sunny morning, the intensity of the sunlight was measured to be 350 W m^{-2}. A science student takes a hand lens with a diameter of 10.0 cm out into the sunlight.

a **Calculate** the power of the sunlight falling on the area of the lens. (2 marks)

b **Calculate** the intensity when the sunlight is focused onto a spot 1.00 cm in diameter (3 s.f.). (3 marks)

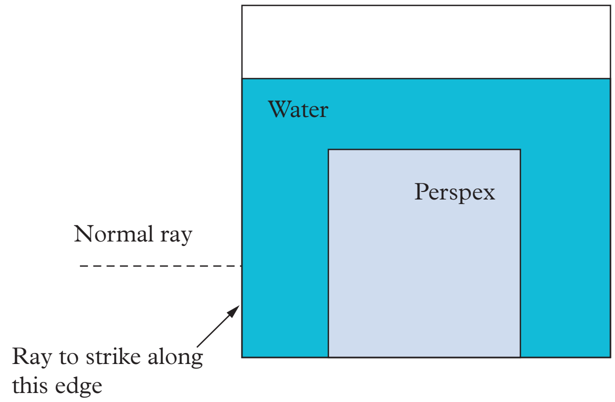
c **Determine** whether the piece of paper the spot is focused on is likely to catch fire, given that a light intensity of 100 W cm^{-2} is required to ignite paper. (1 mark)

21 An object is placed 4 cm in front of a plane mirror as shown.



Determine the location of the image as viewed by the eye and complete the ray diagram. (3 marks)

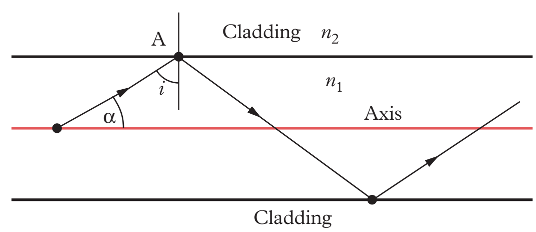
22 The figure represents a block of Perspex (refractive index 1.49) submerged in water (refractive index 1.33) in a large glass container. A beam of light is shone onto the edge of the container, at an angle of incidence of 30°. **Determine** the path of the light beam through the water and through the Perspex and back into the air. **Sketch** the path accurately on the diagram. (Disregard any refraction caused by the glass.) (4 marks)



23 A ray of light is shone through a semicircular block of crown glass (refractive index 1.52). The ray is positioned so that it is directed along a radius of the semicircle, striking the straight edge of the glass block at the centre of curvature. **Determine** the critical angle for crown glass (i.e. the angle at which light reaching the interface between the glass and the air will refract along the surface of the glass). (4 marks)

24 An object 6 cm high is placed 8 cm in front of a convex lens with a focal length of 5 cm. **Construct** a ray diagram and use it to **determine** the nature, location, orientation and size of the image. (7 marks)

25 An optical fibre consists of a core made of glass of refractive index $n_1 = 1.5$. It is through this core that light travels along the fibre. The core is surrounded by another layer of glass of lower refractive index n_2, which is called the "cladding".



a **Evaluate** this arrangement and **deduce** what the refractive index n_2 of the cladding needs to be so that the critical angle at the core–cladding interface is 80°. (3 marks)

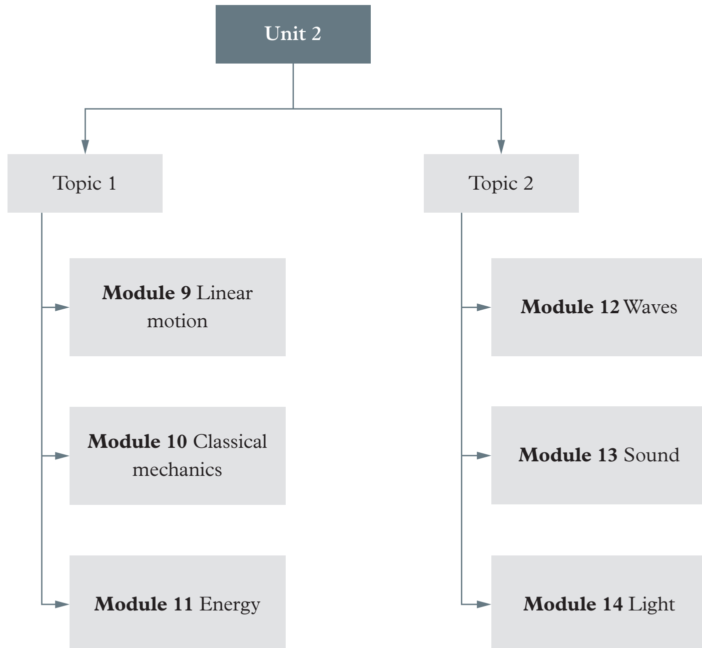
b α is the angle made by the ray with the axis of the fibre. **Determine** the values of α for which the incident angle i is larger that the critical angle found in part **a**. **Justify** your statement with reasoned mathematical argument. (4 marks)

TOTAL MARKS
/61

UNIT 2 Review

Part A – Revisit and revise

Part A of the Unit review asks you to reflect on your learning and identify areas in which you need more work.



Part B – Exam essentials

Now that you have completed your revision for Unit 2, it is time to learn and practise some of the skills you'll need to answer exam questions like a pro! Our expert authors have created the following advice and tips to help you maximise your results on the end-of-year examination.

Exam tip 1: Watch out for the cognitive verbs: explain vs describe.

When a question asks you to "explain" some content, you need to describe and elaborate on it in a logical sequence. The "describe" part often just involves a definition of the main concepts. To avoid losing marks in an "explain" question, you need to add an "elaboration" in which you link the concepts together in terms of any scenario presented.

See it in action

Read the real exam question and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 1 (3 marks)

Many engines work by heating a fluid that turns a rotor or other moving element.

Explain how this is an application of the first law of thermodynamics and why this process could be considered inefficient.

Source: *QCAA 2022 Physics Alternative Sequence Paper 2* © State of Queensland (QCAA)

Complete response

Accurately describes the first law of thermodynamics [1 mark]

Explains the conversion of thermal energy to kinetic energy [1 mark]

The first law of thermodynamics recognises that a change in internal energy can be expressed as a change of thermal energy of work being done. Engines use this principle by converting the thermal energy of the heated fluid to the kinetic energy of the moving element, such that the internal energy of the system is approximately constant. The process is inefficient because the system is not closed and heat lost to the environment reduces the total useful energy of the system.

Explains inefficiency as loss of energy from the system [1 mark]

Incomplete response

Accurately describes the first law of thermodynamics [1 mark]

Explains inefficiency as loss of energy from the system [1 mark]

The first law of thermodynamics states that when energy passes, as work or heat, into or out of a system, the system's internal energy changes in accordance with the law of conservation of energy. Efficiency means the ratio of useful work performed by a machine or in a process to total energy expended or heat taken in. It has the formula: $\eta = \frac{\text{work out}}{\text{work in}} \times 100\%$

When an engine is inefficient it means that the energy in the fuel doesn't all end up as work but some energy is lost as heat to the environment, so it has to be inefficient.

Explains the conversion of chemical energy to work but fails to describe a heat engine as having a constant temperature and how the thermal energy from the "heating of a fluid" is converted to kinetic energy of the engine [0 marks]

Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the marking guide to mark the response.

QUESTION 2 (3 marks)

Contrast the properties of light and sound waves.

Sound waves are longitudinal, which means the particles vibrate in the direction of propagation, whereas light waves are transverse so the particles vibrate at right angles to the direction of propagation. Light travels much faster than sound. Both sound and light can be modelled as waves and they both carry energy from one place to another.

Source: *QCAA 2022 Physics Alternative Sequence Paper 2* © State of Queensland (QCAA)

Marking guide

Question 3	• identifies differences between the – nature of the waves [1 mark] – relative speed of the waves [1 mark] – requirement of a medium [1 mark]

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Exam tip 2: Double-check that your answer is what has been asked for.

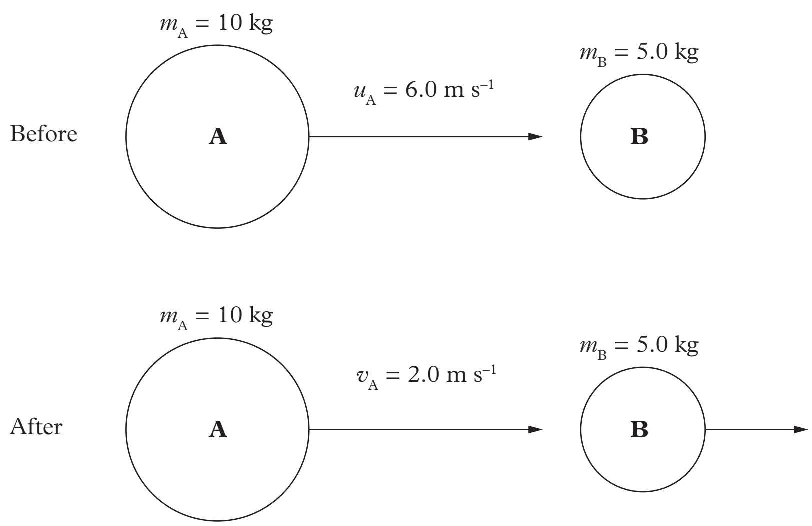
Students tend to develop an automatic approach to questions and assume they understand what the question calls for. The calculations may be perfectly correct but have not produced the result requested. You may get some marks for correct working if it is a part of the solution.

See it in action

Read the real exam question and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 27 (6 marks)

Object A collides with stationary Object B.



b) Determine the change in momentum experienced by Object B during the collision in kg m s^{-1} (to the nearest whole number). Show your working. [*4 marks*]

Source: *QCAA 2022 Physics Alternative Sequence Paper 1* © State of Queensland (QCAA)

Complete response

$p_{initial} = p_{final}$ — Recognises the scenario relates to conservation of momentum [1 mark]

$p_{initial} = m_A u_A + m_B u_B$

$= 10 \times (+6.0) + 5 \times 0$

$= +60$ kg m s^{-1} — Determines the total momentum before the collision [1 mark]

$p_{final} = m_A v_A + m_B v_B$

$+60 = 10 \times (+2.0) + p_B$

$p_B = +60 - (+20)$

$= +40$ kg m s^{-1}

$\Delta p_B = +40 - 0$

$= +40$ kg m s^{-1} — Determines the correct change of momentum [1 mark]

Determines the final momentum of B [1 mark]

Incomplete response

$p_{initial} = p_{final}$

Recognises the scenario relates to conservation of momentum [1 mark]

$p_{initial} = m_A u_A + m_B u_B$

$= 10 \times (+6.0) + 5 \times 0$

$= +60\ kg\ m\ s^{-1}$

Determines the total momentum before the collision [1 mark]

$p_{final} = m_A v_A + m_B v_B$

$+60 = 10 \times (+2.0) + 5v_B$

$v_B = \dfrac{+60 - (+20)}{5}$

$= +8\ m\ s^{-1} = +8.0\ m\ s^{-1}$

Fails to determine the correct change of momentum; determines the correct final velocity of B instead [0 marks]

Calculates the final velocity of B instead of final momentum [0 marks]

Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the marking guide to mark the response.

QUESTION 26 (3 marks)

Two closed-ended pipe instruments of different lengths produce different natural frequencies. Explain why the longer instrument produces a lower natural frequency.

Longer pipes allow longer wavelength resonances to form. According to the wave equation $v = f\lambda$, the longer the wavelength, the smaller the frequency.

Source: *QCAA 2022 Physics Alternative Sequence Paper 1* © State of Queensland (QCAA)

Marking guide

Question 26	• identifies that the natural frequency of the instrument is related to the frequency of standing waves inside the closed-ended pipe [1 mark] • explains the relationship between the length of the instrument and the wavelength of standing waves [1 mark] • explains the relationship between wavelength and frequency [1 mark]

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Exam tip 3: Understand what the formulas mean.

You have been provided with a copy of the QCAA Formula and data book. This contains all the formulas and constants you need for the course.

- Often in exams, you will see questions that ask you to state the correct formula for a particular concept– for example "mass–energy equivalence". There are lots of formulas containing m and E so you need to understand the differences.
- Usually, you'll be awarded 1 mark for just "identifying the relevant scenario" and this means writing down the correct formula.

For the wave motion topic, the formulas for sound in pipes and strings are tricky, so you need to:

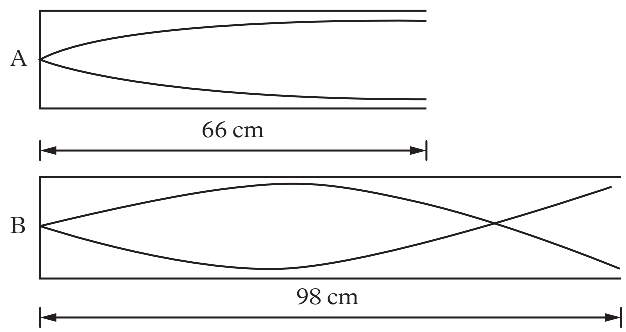
- distinguish between formulas for open and closed pipes
- identify that the correct formula for strings is the same as for an open pipe.

See it in action

Read the real exam question and see how the tip has made a difference between a response that has scored full marks and a response for which marks have been lost.

QUESTION 6 (4 marks)

A student must choose between the two closed-ended pipes shown. The standing wave formed in each pipe travels at the speed of sound.



Determine which pipe will produce a note with a frequency of 265 Hz.

Source: *QCAA 2022 Physics Alternative Sequence Mock Paper 2* © State of Queensland (QCAA)

Complete response

Indicates an understanding of the physical scenario in relation to standing waves in closed pipes [1 mark]

Indicates an understanding of harmonics and the relationship between frequency and wavelengths [1 mark]

To create a frequency of 265 Hz requires a wavelength of $\lambda = \frac{v}{f} = \frac{346}{265} = 1.31\text{ m} = 131\text{ cm}$.
Pipe A gives a fundamental frequency and the wavelength is 4 times the length of the pipe, which equals $4 \times 66 = 264$ *cm. This is too long a pipe length. Pipe B is giving a higher harmonic. The pipe wavelength is:* $\lambda = \frac{4}{3} \times L = \frac{4}{3} \times 98 = 131\text{ cm}$. *Therefore, the correct pipe to use is Pipe B.*

Arrives at a consequentially correct solution [1 mark]

Provides pertinent mathematical operation(s) correctly performed [1 mark]

Incomplete response

Indicates an understanding of the physical scenario in relation to standing waves in closed pipes [1 mark]

To create a frequency of 265 Hz requires a wavelength of $\lambda = \frac{v}{f} = \frac{346}{265} = 1.31\text{ m} = 131\text{ cm}.$

Pipe A gives a fundamental frequency ($n = 1$) so we can apply the closed pipe formula:

$L = n\frac{\lambda}{2}$, $\lambda = \frac{2L}{n} = \frac{2 \times 66}{1} = 132\text{ cm}$

Pipe B is giving a 3rd harmonic ($n = 2$). The wavelength is:

$L = n\frac{\lambda}{2}$, $\lambda = \frac{2L}{n} = \frac{2 \times 66}{2} = 66\text{ cm}$

Provides non-pertinent mathematical operation(s); is able to substitute into the chosen equation [1 mark]

Therefore, the correct pipe to use is Pipe A.

Arrives at wrong solution [1 mark]

Indicates a misunderstanding of harmonics and the relationship between frequency and wavelengths; has used the open pipe formula instead of the closed pipe formula [0 marks]

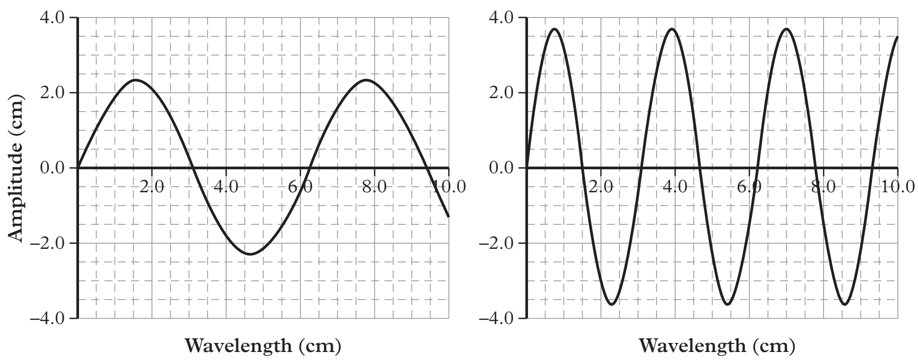
Think like an assessor

To maximise your marks on an exam, it can help to think like a QCAA assessor. Consider how many marks each question is worth and what information the assessor is looking for.

A student has given the following response in a practice exam. Imagine you are a QCAA assessor and use the marking guide to mark the response.

QUESTION 8 (7 marks)

Two continuous transverse waves travelling in opposite directions in the same medium are shown.



A barrier is placed between the two waves, resulting in each reflecting back along its original path.

b) Explain what will happen to each wave as a result of adding the barrier. [*5 marks*]

Each wave is reflected back in the opposite direction from which it came. Both waves are inverted upon reflection and they undergo constructive and destructive interference as the original wave and reflected wave superimpose with each other to form a standing wave. They don't have to have the sample amplitude to interfere.

Source: *QCAA 2022 Physics Alternative Sequence Paper 2* © State of Queensland (QCAA)

Marking guide

Question 8b	• identifies a change in the direction of the waves [1 mark] • identifies the inversion of waves at a fixed boundary [1 mark] • describes interference between the original and reflected waves [1 mark] • explains the relevance of the same wavelength of interfering waves [1 mark] • identifies the formation of a standing wave [1 mark]

Fix the response

Consider where you did and did not award marks in the above response. How could the response be improved? Write your own response to the question to receive full marks from a QCAA assessor.

Part C – Exam practice

Now it is time to put the tips and advice you've learnt into practice while you complete these exam-style questions! During the examination, you will most likely be asked multiple choice questions, short response questions, and more complex, multi-part short response questions. The questions here, in Part C, give you practice at these types of questions.

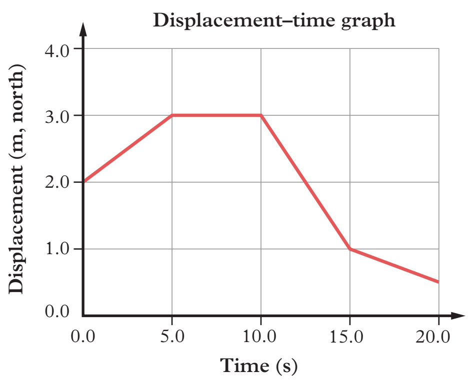
Multiple choice

(1 mark each)

1 Which of the following is a vector quantity?

A Speed
B Energy
C Newtons
D Momentum

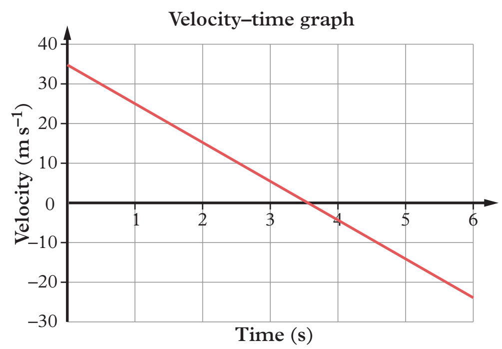
2 The graph shows the motion of an object.



During which interval does the object have the fastest velocity?

A 0.0–5.0 s
B 5.0–10.0 s
C 10.0–15.0 s
D 15.0–20.0 s

3 The graph is a velocity–time graph for the motion of an object.



The acceleration and distance covered in the 6 seconds is

A $-9.8\,m\,s^{-2}$, 31.3 m.
B $-9.8\,m\,s^{-2}$, 91.3 m.
C $+9.8\,m\,s^{-2}$, 386 m.
D $-1.8\,m\,s^{-2}$, 177 m.

4 An object moves east for 100.0 m from the starting point in a time of 20.0 s, then west 120.0 m in a time of 60.0 s. What is the average speed and the average velocity of the object for this period?

A $2.75\,m\,s^{-1}$, $0.25\,m\,s^{-1}$ west
B $2.75\,m\,s^{-1}$, $2.75\,m\,s^{-1}$ west
C $2.75\,m\,s^{-1}$, $0.25\,m\,s^{-1}$ east
D $4.0\,m\,s^{-1}$, $0.25\,m\,s^{-1}$ west

5 If the initial velocity of an object is $+1\,\mathrm{m\,s^{-1}}$ and it accelerates at $+10\,\mathrm{m\,s^{-2}}$, the distance it would cover in time t would be

A $5t^2$.

B $10t^2$.

C $5t^2 + t$.

D $10t^2 + t$.

6 A 2 kg object is dropped from a height of 12 m near the surface of the Earth. What is its impact speed when it strikes the ground?

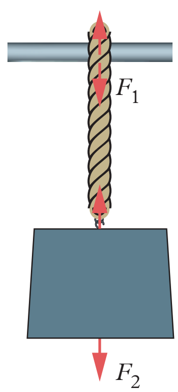
A $8\,\mathrm{m\,s^{-1}}$

B $11\,\mathrm{m\,s^{-1}}$

C $15\,\mathrm{m\,s^{-1}}$

D $235\,\mathrm{m\,s^{-1}}$

7 An object is held stationary by a rope tied to an overhead support.



The forces F_1 and F_2 in order are

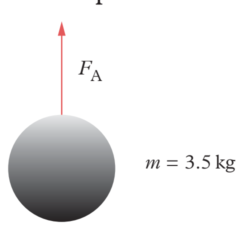
A gravity, weight.

B friction, weight.

C tension, weight.

D weight, tension.

8 An object of mass 3.5 kg is hanging at rest from a rope when it is subjected to an applied force F_A that causes it to accelerate upwards at $2.0\,\mathrm{m\,s^{-2}}$.



The magnitude of the applied force is

A 7.0 N.

B 27 N.

C 41 N.

D 45 N.

9 Which example describes one of Newton's laws of motion?

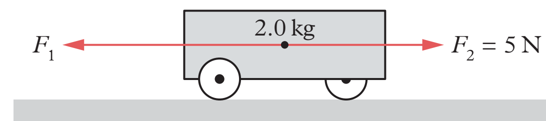
A The acceleration of an object must always be uniform.

B The normal reaction force equals the weight of the object.

C The normal force for a box on a table and its weight make a third law pair.

D In the absence of a net force, an object maintains a constant velocity.

10 The diagram shows the horizontal force vectors acting on a collision trolley of mass 2.0 kg. The vector arrows are drawn to scale.



The magnitude of its acceleration is most likely to be

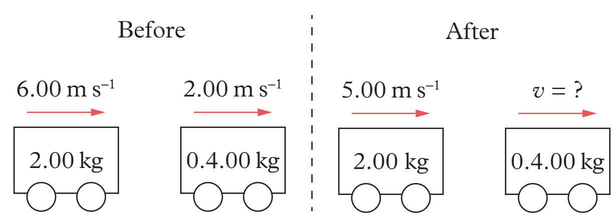
A $1.2\,\mathrm{m\,s^{-2}}$.

B $2.4\,\mathrm{m\,s^{-2}}$.

C $3.7\,\mathrm{m\,s^{-2}}$.

D $6.2\,\mathrm{m\,s^{-2}}$.

11 A cart of mass 2.00 kg moving at $6.00\,\mathrm{m\,s^{-1}}$ collides with a cart of mass 0.400 kg moving in the same direction at $2.00\,\mathrm{m\,s^{-1}}$. After the collision, both carts continue in the same direction, with the 2.00 kg cart moving at $5.00\,\mathrm{m\,s^{-1}}$. What is the speed of the other cart, and the type of collision?



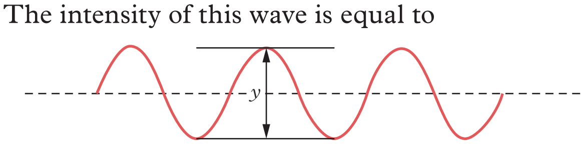
A $7.00\,\mathrm{m\,s^{-1}}$, elastic

B $9.17\,\mathrm{m\,s^{-1}}$, elastic

C $7.00\,\mathrm{m\,s^{-1}}$, inelastic

D $9.17\,\mathrm{m\,s^{-1}}$, inelastic

12 The arrow in this diagram has a length y.
The intensity of this wave is equal to



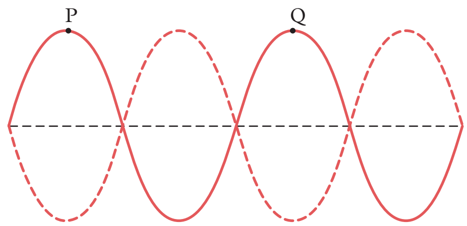
A $\left(\frac{1}{2}y\right)^2$.

B $\frac{1}{2}y$.

C $\frac{1}{2}y^2$.

D y^2.

13 A standing wave is generated on a spring by shaking one end sideways. Three stages of its motion are shown in the diagram.



Points P and Q are

A 1λ apart, $\frac{1}{2}\lambda$ out of phase.

B $1\frac{1}{2}\lambda$ apart, in phase.

C 1λ apart, in phase.

D 2λ apart, in phase.

14 A 10,000 Hz sound wave and a 3,000 Hz sound wave arrive separately at a 10 cm gap in a wall. Which of the following best describes the diffraction of the waves through the gap?

A The diffraction is greater for the 10,000 Hz wave.

B The diffraction is greater for the 3,000 Hz wave.

C There is no diffraction as the gap is too large.

D The diffraction is the same for both waves.

15 A pipe closed at one end has a 340 Hz tuning fork held next to it as the length of the pipe is changed. What is the length of the shortest air column producing the resonance if the speed of the sound is 340 m s^{-1}?

A 25 cm

B 50 cm

C 75 cm

D 100 cm

16 A guitar string 50 cm long was plucked in its fundamental mode and the velocity of the wave in the string was measured to be 200 m s^{-1}. The frequency of the string, and the next harmonic are

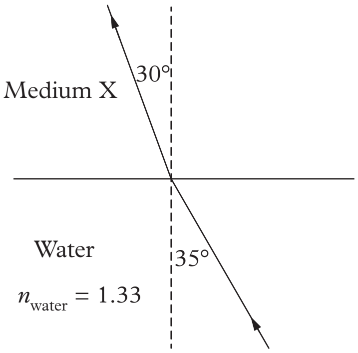
A 100 Hz, 200 Hz.

B 100 Hz, 300 Hz.

C 200 Hz, 400 Hz.

D 400 Hz, 800 Hz.

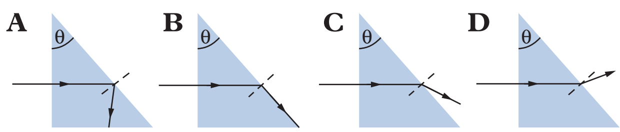
17 A beam of light in water enters medium X with an angle of incidence of 35°, as shown in the figure. The angle of refraction is 30°. What is the absolute refractive index of medium X?



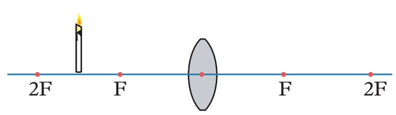
A 1.14   **B** 1.16

C 1.53   **D** 1.55

18 A beam of light strikes a glass prism from air at 90°. The prism is a right-angled triangle and the other angle is θ, as shown in the figures. Angle θ is less than the critical angle for glass–air boundary. Which of the following diagrams shows the path of the ray?



19 An object is placed in front of a converging lens at a point between F and 2F, as shown in the figure.



The image is

A real, inverted and magnified.

B virtual, upright and magnified.

C virtual, upright and diminished.

D real, inverted and diminished (smaller).

20 The lowest frequency that a standard guitar can produce is 84 Hz. What is the wavelength of the sound on a day when the temperature is 30°C? The speed of sound is related to temperature by the formula v(sound) = 331 + 0.6T, where T is the temperature in °C.

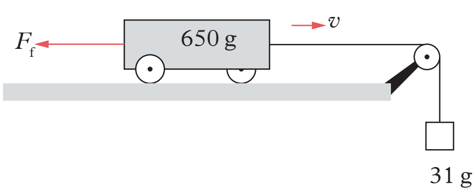
A 0.24 m   **B** 0.27 m

C 3.72 m   **D** 4.15 m

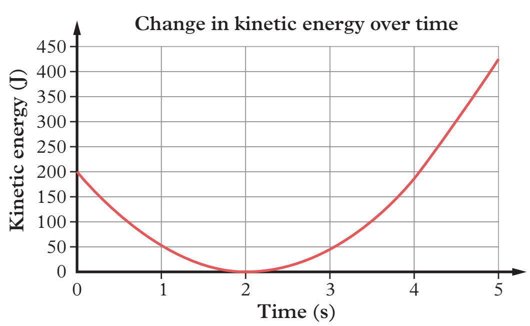
Short response

21 A 2 kg book rests on a table. A person puts a paperweight on top of the book and the book now experiences a normal force of 25 N. **Determine** the mass of the paperweight. (3 marks)

22 A three-wheeled cart of mass 650 g is at rest and a mass of 31 g is attached to it and allowed to hang vertically. The cart begins to accelerate at 0.25 m s^{-2} to the right, as shown. **Determine** the friction force on each wheel. Assume the string has negligible mass and friction. (4 marks)



23 A 1 kg rock was thrown vertically upwards from the top of the cliff and landed at the base below 5.0 s later. A graph of the rock's kinetic energy over time is shown.



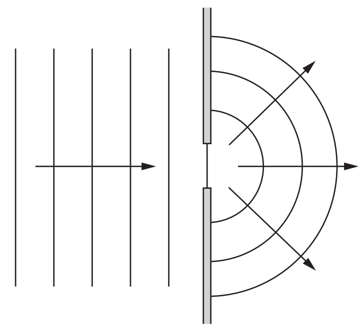
a **Calculate** the rock's maximum height from the top of the cliff (2 s.f.). (3 marks)

b **Determine** the height of the cliff (2 s.f.). (3 marks)

24 In an experiment, a student let a 150 g steel ball bearing fall through oil in a measuring cylinder. As it fell, it experienced a downward force due to gravity and an opposing drag force of 1.10 N. **Calculate** the total work done on the object as it falls 15.0 cm through the oil (2 s.f.). Show your working. (4 marks)

25 Two objects travelling in opposite directions undergo an elastic collision. Object X on the left has a mass $2m$ and is travelling at speed u to right. Object Y on the right has a mass m and is travelling at u to the left. **Calculate** the velocities of both X and Y after the collision (2 s.f.). Show your working. (5 marks)

26 The figure shows water waves in a ripple tank moving towards and passing through a gap in a barrier. Every second, four waves pass through the gap. The waves have a wavelength of 0.020 m.



a **Calculate** the speed of the water waves and give the unit (2 s.f.). (2 marks)

b **Recall** the name of the wave phenomenon shown in the diagram. (1 mark)

27 Two closed-ended pipe instruments of different lengths produce different natural frequencies. **Explain** why the longer instrument produces a lower natural frequency. (4 marks)

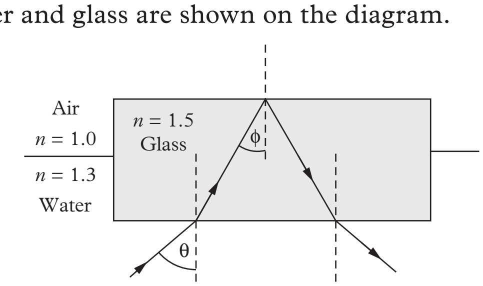
28 **Explain** "critical angle" in terms of the refraction and reflection of light. (3 marks)

29 Musical wind instruments can be modelled as closed pipes or open pipes. For example, a flute can be treated as a resonant pipe open at both ends, and an organ can be treated as a pipe closed at one end. Assume the speed of sound = 346 m s^{-1}.

a Suppose the fundamental frequency of the flute was 300.0 Hz. **Determine** the length of the open tube that represents the flute (3 s.f.). (4 marks)

b **Determine** the length of the organ pipe if it has the same fundamental frequency at the same temperature (3 s.f.). (2 marks)

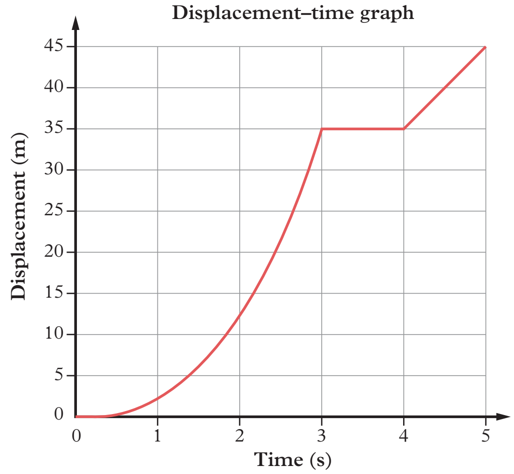
30 A glass block is partly submerged in water as shown in the diagram. Light from a laser is shone up through water and is incident on the bottom of the glass block at an angle (θ), such that the light is at the critical angle (ϕ). The refractive indices of water and glass are shown on the diagram.



a **Determine** the critical angle ϕ and the incident angle θ (2 s.f). (4 marks)

b A substance of refractive index 1.25 is poured on top of the glass plate. **Determine** the critical angle now (2 s.f.). (2 marks)

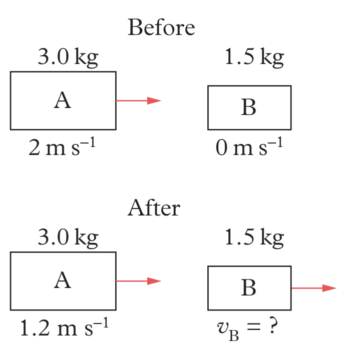
31 A radio-controlled car is being driven in a straight line along a flat path. Its displacement at each second is shown on the graph.



a **Determine** the instantaneous velocity at the 1.5 second mark (2 s.f.). (3 marks)

b **Determine** its acceleration from 4 to 5 seconds. (1 mark)

32 Object A travelling at $2\,m\,s^{-1}$ collides with stationary object B as shown.

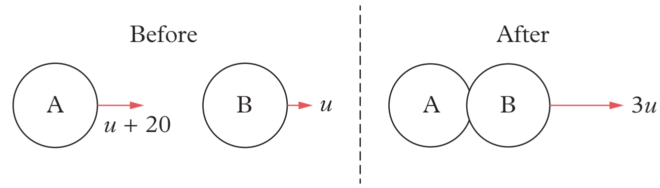


a Object A experiences a force of 24 N during the interaction. **Determine** the acceleration it would have undergone during this time, including the direction of the acceleration (2 s.f). (3 marks)

b **Determine** the change in momentum for object B. (3 marks)

c **Determine** whether the collision was elastic. (4 marks)

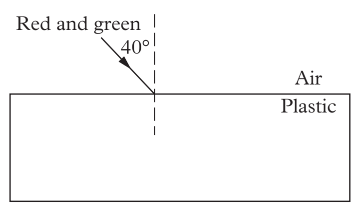
33 Two objects A and B each with a mass of 2 kg move to the right, as shown in the diagram. Object B moves at a velocity u and object A is travelling $20\,m\,s^{-1}$ faster than B. After collision, they remain joined and continue on at a velocity $3u$.



a **Calculate** the velocity of the combined mass. (4 marks)

b Assuming energy lost in the collision was transformed entirely into heat, **calculate** the rise in temperature of the combined object. The specific heat capacity of steel is $460\,J\,kg^{-1}\,K^{-1}$. (5 marks)

34 A narrow beam of light consists of a mixture of red and green wavelengths. It is shone on a rectangular plastic block with an incident angle of 40°, as shown in the figure. In the plastic, the refractive index for red light is 1.515 and the refractive index for green light is 1.521.



a **Construct** labelled lines to show an approximate path of the red and green rays in the block and in the air after they exit the block. (2 marks)

b The block is 5 cm thick. **Determine** the distance between the two rays as they strike the bottom of the block. (5 marks)

35 **Contrast** the properties of water waves and light waves. (3 marks)

36 The intensity of monochromatic light is measured to be $48\,W\,m^{-2}$ at a distance, r, from the source.

a **Describe** the meaning of intensity using the scenario above. (2 marks)

b **Calculate** the intensity of the light at a distance that is four times further away from the source (2 s.f.). (3 marks)

c **Determine** the distance from the source at which the light would have one-quarter its original intensity (2 s.f.). (3 marks)

TOTAL MARKS /104

MODULE

15 Practical manual

Introduction

This is a guide to all practicals included in the QCAA Senior Physics Syllabus. The practicals in this module have been trialled, and safety instructions are provided; however, it is the legal obligation of the teacher to perform their own risk assessments prior to participating in any practical activity. These practicals are not prescriptive and schools may adapt them to their own needs.

For this module, safety hazards will be highlighted at the top of each practical. When undertaking practical experiments, you should always wear lab coats, safety glasses and enclosed footwear, and have long hair tied back. Below is a summary of general safety cautions:

- → Burns – hot water and hotplates can cause burns in the lab. These can be avoided by not moving boiling water and avoiding splashing, as well as leaving heated samples to cool before using them. It is also important to ensure that each member of your group is aware that a hotplate is on, and once you have finished with it, use a hazard sign to warn others that it may still be hot.
- → Electrical cords – always keep electrical cords away from water and hot metal surfaces.
- → Electric shock – electrical equipment can cause electric shocks, and cause serious or fatal injury. When using electrical equipment make sure that there are no exposed wires.
- → Glass – glass can shatter and cut you. Be careful when you are using thermometers, conical flasks, beakers or other glassware in the lab. Make sure you handle each item with care. Do not use your hands to pick up broken glass.
- → Ionising radiation – exposure to ionising radiation can be extremely dangerous. You should have a risk management plan in place suitable for use with radioactive sources. This plan could include Queensland Health's "Radioactive Substances used for Science Activities" and "The Radiation Protection Series" published by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA). Other control measures can also be used: you'll find them listed in the relevant practicals.
- → In the event that an injury or accident does happen, make sure you tell your teacher immediately.

Please familiarise yourself with your school's safety procedures including the location of first aid kits, safety equipment, chemical waste disposal, and the set-up and pack-down of practical stations. If you are unsure of any steps in a practical, check with your teacher for the best course of action.

Along with guidance for completing data collection and analysis for any practical you encounter in your senior Physics course, Module 1 Physics toolkit is a good reference for how to keep safe in the laboratory.

Full lessons for this module are available on Oxford Digital. They are also provided as part of a printable resource that can be used in class.

Unit 1 Practicals

Lesson 2.2	Heating water on a hotplate – graphing and analysing data
Lesson 2.7	Precision and accuracy of thermometers
Lesson 2.10	Specific heat capacity of liquids – on a hotplate
Lesson 3.4	Specific heat capacity of a metal – by calorimetry
Lesson 3.5	Mixture of two liquids – calorimetry
Lesson 5.3	Shielding effects from a radioactive source
Lesson 5.4	Intensity and distance from a radioactive source
Lesson 7.7	Finding resistance using current and voltage across an ohmic resistor
Lesson 7.8	Ohmic and non-ohmic resistors
Lesson 8.3	Investigating series and parallel circuits
Lesson 8.5	Circuits for real-life purposes – using a fuse for protection

Unit 2 Practicals

Lesson 9.6	Displacement–time and velocity–time graphs for a ball on an incline
Lesson 9.9	Acceleration due to gravity by linearising time–displacement graphs
Lesson 10.10	Linear elastic collision between trolleys – conservation of momentum
Lesson 12.4	Longitudinal and transverse waves on springs
Lesson 13.2	Fundamental and harmonic wavelengths in pipes
Lesson 13.3	Speed of sound in air using a closed-end pipe over water
Lesson 14.5	The law of reflection for images in a plane mirror
Lesson 14.7	Refractive properties of a transparent substance

Glossary

A

absolute error
the difference between the observed (measured) value and the accepted (true) value

absolute refractive index
the ratio of the velocity of light in air to the velocity of light in a different medium

absolute uncertainty
the dispersion (spread) of values around the mean, $\delta\bar{x}$, reported by half the range of the measurements; an indicator of the precision of measurements

absolute zero
the lowest temperature that is theoretically possible, at which the motion of particles which constitutes heat would be minimal; zero on the Kelvin scale (0 K)

acceleration
the rate of change in the velocity of an object (symbol: a; SI unit: m s^{-2})

accuracy
the difference between the observed (measured) value and a currently accepted value of a quantity

adhesion
the tendency of dissimilar surfaces to cling to one another by electromagnetic forces

air resistance
the force that acts in the opposite direction to an object moving through the air; also known as the drag force

alpha decay
a type of radioactive decay caused by an excess of mass in a nuclide, releasing a $^{4}_{2}\text{He}$ nucleus (two protons, two neutrons)

alpha radiation
composite particle consisting of two protons and two neutrons (symbol: α or $^{4}_{2}\text{He}$) emitted from the nucleus of some radionuclides

alternating current
electric current that periodically reverses direction and changes its magnitude continuously with time, in contrast to direct current which flows only in one direction

ammeter
a device for measuring the rate of flow of charge (current) in a circuit

amplitude
the distance of a point in a wave from the rest position (equilibrium position) to the crest position, which is half the vertical distance from a trough to a crest

angle of incidence
the angle between the normal and the direction of propagation of an incident wave

angle of reflection
the angle between the normal and the direction of propagation of a reflected wave

angle of refraction
the angle between the normal and the direction of propagation of a refracted wave

anomaly
a false data point often the result of a faulty observation or wrong equipment

antineutrino
an elementary subatomic particle without electrical charge and with negligible mass; electron antineutrinos are associated with beta negative decay

antinode
the point where there is maximum amplitude of vibration; further displacement from equilibrium

antiparticle
a particle with the same mass but opposite charge to its corresponding particle; a positron is an antiparticle of the electron, and vice versa

apparent depth
the depth (or height) of the image of an object when it is observed from a different medium (e.g. air from water, or water from air); a consequence of the refraction of light

applied force
an external force applied to an object; it can be a push or a pull

artificial transmutation
the process in which an isotope is intentionally made to change into an isotope of another element by being bombarded with particles that cause a nuclear process

atom
the basic unit of matter; the smallest particle of a chemical element that can exist

atomic number
the number of protons in an element's nucleus, Z; in a neutral atom, the number of protons will be equal to the number of electrons surrounding the nucleus

B

balanced forces
two forces acting in opposite directions on an object, and equal in size; they do not cause a change in the motion of an object

best estimate
the a value closest to the true value, usually found by taking repeated measurements and averaging

beta negative decay
a type of radioactive decay caused by an excess of neutrons in a nuclide, releasing an energetic electron ($^{0}_{-1}\text{e}$) and associated electron antineutrino ($\bar{\nu}_e$)

beta negative radiation
a stream of energetic electrons (symbol: β^- or $^{0}_{-1}\text{e}$) emitted from the nucleus of some radionuclides, always accompanied by the emission of electron antineutrinos

beta positive decay
a type of radioactive decay caused by an excess of protons in a nuclide, releasing a positron ($^{0}_{+1}\text{e}$) and associated electron neutrino (ν_e)

beta positive radiation
stream of energetic positrons (symbol: β^+ or $^{0}_{+1}\text{e}$) emitted from the nucleus of some radionuclides, always accompanied by the emission of electron neutrinos

bibliography
a full list of all resources used in some research, provided at the end of a report or submitted along with another form of presentation

binding energy
the energy needed to overcome the forces holding a nucleus together to disassemble it into constituent particles

binding energy per nucleon
the binding energy divided by the number of nucleons in the nucleus of an atom

boiling point
the temperature at which a liquid changes into a vapour by boiling

boundary
a change in the media, such as between springs of different weights, or an interface between two different materials; e.g. air and glass; deep water and shallow water; light and heavy springs

C

calibration
the configuration of an instrument against standard values to ensure that it measures a true value

calorimetry
the science of measuring the amount of heat transferred between objects or in a chemical reaction

Celsius scale
a temperature scale that takes the temperature at which pure water freezes as 0°C and its boiling point as 100°C

centre of curvature
the centre of the circle that produces the curved surface of a lens

chain reaction
a series of nuclear fissions, each initiated by a neutron produced in a preceding fission

change in momentum
the difference between the initial momentum and final momentum; a vector quantity

charge
a physical property of an object that causes it to experience a force when placed in an electric field; it can be negative, such as on an electron, or positive, such as on a proton

circuit
a closed loop of conducting material through which electric charge can flow

closed circuit
a complete electrical circuit in which charge can flow; switch is "on"

cognitive verb
a task word that requires you to perform a specific cognitive task

collision
when two or more objects hit each other

compression
a region in a longitudinal wave where the particles are forced closer together in the direction of propagation; where they are closest together

concave lens
a lens that is thicker at the edges than in the middle that will cause rays to diverge, and images formed will be virtual, erect and enlarged; also called diverging lens

condensation
a physical process in which a gas undergoes a phase change to become a liquid

conduction
a process in which heat is directly transferred or transmitted through a substance due to a temperature difference between neighbouring regions, without movement of any matter

conductor
a substance that allows free movement of charge through it

confounding factor
an uncontrolled variable that has a systematic effect on the value of the dependent variable; if a confounding variable exists, then the validity is diminished and should be addressed in the evaluation

constant force
one that has the same magnitude and direction for the duration of an interaction; also known as uniform force

constant velocity
motion where the speed and direction of the object relative to the observer is not changing; this includes an object at rest (no acceleration)

constructive interference
the interference of two or more waves superposing to produce a resultant wave with increased amplitude

contact force
a force where the object and the action producing the force touch each other

controlled variable
a variable that is kept constant (controlled) in an investigation

convection
a transfer of heat caused by the movement within a fluid of the hotter and less dense material, which rises, and the colder, more dense material, which sinks under the influence of gravity

convection current
the pathway in which fluid (liquid or gas) particles flow as they heat up (become less dense) and cool down (become more dense)

conventional current
the direction in which positive charges flow; opposite to electron flow

converging
the bending of light rays together

convex lens
a lens that is thicker in the middle than at the edges that will cause rays to converge; also called converging lens

coulomb
a measure of electric charge; one coulomb (C) is the charge on 6.24×10^{18} elementary charges

crest
the highest part or point of a wave; the point of maximum positive displacement

critical angle
the angle of incidence (symbol θ_c) for light in a more optically dense medium for which the angle of refraction in the less optically dense medium is 90°

D

data points
a set of measurements of a dependent variable made by manipulating an independent variable through a range of variations using exactly the same methodology, conditions and materials

decay series
a sequence of nuclides formed by successive radioactive decays until a stable decay product, the end product, is formed

decimal places
positions of the digits to the right of a decimal point; abbreviated as d.p. The number 3.14159 has five decimal places

dependent variable (DV)
the variable (often denoted by y) that responds to the independent variable; it "depends" on the independent variable

destructive interference
the interference of two or more waves superposing to produce a resultant wave with reduced amplitude

deuteron
the nucleus of a deuterium atom consisting of a proton and a neutron; (symbol: ${}^{2}_{1}H$)

diffraction
a phenomenon in which, if a wavefront is partially blocked by an obstacle, the unblocked part of the wavefront diffracts (bends) into the region behind the obstacle

direct current
electrical current in which the flow of charge is in one direction only

directed line segment
an arrow representing a vector in which the arrowhead represents the spatial direction of the vector, and the length represents the magnitude

direction of propagation
the direction of energy flow for a wave

directly proportional
relationship that is linear and the line goes through the origin (0, 0)

dispersion
the separation of a ray upon refraction into distinct rays of different colours; observed as the splitting of white light into a rainbow

displacement
(for wave motion) the distance between a particle's position and the equilibrium position

displacement
(linear motion) a vector quantity representing a change in position irrespective of the path actually taken between two points (symbol: s; SI unit: metre; symbol: m); displacement (change in position) = final position – initial position

displacement–time graph
depicts the displacement of an object as a function of time, the gradient of which is the instantaneous velocity

dissipate
to lose energy (and hence, for a wave, amplitude) over time

distance
the total length of the pathway taken between the origin and the destination point; symbol d

disturbance
a displacement from the equilibrium position of a vibrating system

diverging
the bending of light rays away from each other

drag force
the force acting to oppose the motion of any object moving with respect to a surrounding fluid; symbol F_D

dynamic friction
a force that acts between surfaces in motion relative to each other; also known as sliding or kinetic friction

E

efficiency
the ratio of useful work produced by a machine or in a process compared to total energy expended or heat taken in; often expressed as a percentage (symbol: η)

elastic collision
a collision in which kinetic energy is conserved

elastic potential energy
potential energy stored as a result of deformation of an elastic object, such as the stretching of a spring

electric current
the rate of motion of electric charge carriers from one part of a conductor to another (symbol: I; SI unit: ampere; unit symbol: A)

electrical potential
the amount of work needed to move a unit (1 C) of charge from one point to another, or the electrical potential energy per unit of charge (symbol: V; SI unit: volt; unit symbol: V).

electrical potential energy
the energy stored in a charge and circuit system, or the capacity of the charge carriers to do work due to their position in an electrical circuit (symbol: U; SI unit: joule; unit symbol: J).

electrical resistance
opposition to the flow of current in a circuit or component measured as the ratio of the voltage applied to the current that flows through it

electromagnetic radiation
radiant energy consisting of electromagnetic waves, propagated at the speed of light in a vacuum

electromagnetic wave
wave that does not require a medium for transmission and travels at the speed of light in a vacuum; include long wavelength radio waves through to short wavelength gamma rays (called the electromagnetic spectrum)

electromotive force
a difference in potential that tends to give rise to an electric current (symbol: EMF; SI unit: volt; unit symbol: V)

electron
a subatomic particle of mass 1,836 times lighter than a proton with a −1 elementary electric charge; present in all atoms

electron flow
the direction of electron motion in a conductor from negative to positive

electron volt (eV)
a unit of energy defined as the work done on an electron to move it through an electrical potential difference of 1 V; equal to 1.60×10^{-19} J

electrostatic repulsion
the phenomenon of two like charged particles repelling each other

element
a chemical substance that cannot be broken down into other substances by chemical reactions

elementary charge
the magnitude of the electric charge carried by a single electron or single proton

elementary particle
a particle whose substructure is unknown

energy
a measure of the ability of a system to do work and supply heat; energy is conserved in any interaction (symbol: W; SI unit: joule; unit symbol: J)

energy transfer diagram
a diagram that summarises all the energy transfers taking place in a process: the thicker the line or arrow, the greater the amount of energy involved

energy–time graph
a graph that depicts the kinetic and potential energy of an object as a function of time

equilibrium position
the natural or resting position assumed by a medium if no disturbance is travelling through it

ethics
the principles that govern how we behave or conduct activities

explosion
when a single object separates into two or more fragments

extraneous variable
a variable other than the independent variable that may cause changes in the value of the dependent variable

extrapolation
the prediction of values beyond the range of data points by extending the trendline

F

Fahrenheit scale
a temperature scale that takes the temperature at which a salt–water mixture freezes into ice as 0°F, and Daniel Fahrenheit's body temperature as 100°F

first law of reflection
the incident ray, the reflected ray and the normal to the surface of the mirror all lie in the same plane

first law of thermodynamics
a law that states that during an interaction between a system and its surroundings, the amount of energy gained by the system must be exactly equal to the amount of energy lost by the surroundings; $\Delta U = Q + W$

fixed end
a boundary condition where the medium at a boundary is fixed in place so it cannot move

focal length
the distance between the centre of a lens and its principal focus

force
a push or pull between objects that may cause an object or both objects to change speed and/or the direction of their motion or change their shape (symbol: F; SI unit: newton; unit symbol: N)

force–displacement graph
a graph depicting the force acting on an object as a function of displacement, with the area under the curve representing work done

force–time graph
a graph that depicts the force acting on an object as a function of time, with the area under the curve being equal to the change in momentum (impulse)

forced convection
the movement caused within a fluid generated by an external source such as a pump, fan or suction device

forced vibration
the tendency of one object to be forced into vibrational motion by an adjoining or interconnected object

free convection
the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, more dense material to sink under the influence of gravity; this consequently results in transfer of heat

free end
a boundary condition where the medium at the boundary is free to move

free-body diagram
a diagram used to show the relative magnitude and direction of all forces acting on an object in a given situation; also called a force diagram

free-fall motion
any motion of a body where gravity is the only force acting upon it

freezing
a physical process in which a liquid undergoes a phase change to become a solid

frequency
the number of oscillations of a wave source per unit of time; when time is in seconds, the unit is hertz (Hz)

friction
the force that resists motion between two surfaces in contact

fundamental harmonic
the minimum frequency at which a vibrating medium will form a standing wave; the lowest natural frequency produced by an object or musical instrument; also called the fundamental frequency or first harmonic

G

gamma decay
a type of radioactive decay in which an unstable atomic nucleus dissipates energy by emitting gamma radiation

gamma radiation
extremely high-frequency electromagnetic radiation (symbol: γ) emitted from the nucleus of some radionuclides

gradient
the slope of a graph

gravitational force
a force that acts through a gravitational field between objects with mass

gravity
a fundamental interaction that causes mutual attraction between all things with mass

H

half-life
the time taken for half of the atoms in a sample of the material to undergo radioactive decay (symbol: $t_{\frac{1}{2}}$)

half-scale division
half of the smallest division of a scale

heat
energy that is spontaneously transferred from one object to another due to a difference in temperature between the objects (symbol: Q; SI unit: joule; unit symbol: J)

heat engine
a device that receives heat from a high temperature source and converts part of this heat into work, transferring the remaining waste heat to a low temperature "sink"; it works by heating a fluid that turns a rotor or other moving element

heavy positive ion
the positively charged ion that remains after radiation has caused the removal of an electron

hypothesis
a considered opinion, theory or statement, based on research and evidence, about something that is yet to be tested

I

impulse
a vector quantity defined as the product of a force and the time interval over which the force acts; it is the change in momentum of an object during the time

incident wave
an approaching wave

independent variable (IV)
a variable (often denoted by x) whose variation does not depend on that of another

inelastic collision
a collision in which total kinetic energy is not conserved

inertia
the tendency of an object to resist a change in its motion

instantaneous speed
speed as measured over a very small period (an instant) of time

instantaneous velocity
rate of change of displacement over an instant of time

insulator
a substance that does not allow free movement of charge through it

intensity
(of radiation) the average power per unit area ($W\,m^{-2}$) carried by radiation; the number of counts per second registered on a Geiger counter (of waves) the average power per unit area carried by a wave

intermolecular force
a force between particles of a substance

internal energy
the total microscopic potential energy and microscopic kinetic energy of the particles in a system (symbol: U; units: joules; symbol: J)

interpolation
the prediction of values between data points using a trendline

ion
an atom that has lost or gained electrons

ionisation
the process by which an atom or molecule acquires a negative or positive charge by gaining or losing electrons

ionisation ability
a measure of the ability of radiation to remove electrons from a particle as it passes through it

ionising radiation
radiation that can remove an electron from an atom and create a heavy positive ion and free electron

isolated system
one that cannot exchange either matter or energy with its surroundings; also called a closed system

isotope
a form of an element with the same number of protons but different number of neutrons; nuclides with the same atomic number but different mass numbers

K

Kelvin scale
a temperature scale that takes absolute zero as 0 K and the melting point of ice as 273 K

kinetic energy
the energy due to the motion of an object, including the motion of particles in a substance (symbol: E_k; SI unit: joule; unit symbol: J)

Kirchhoff's current law
electric charge is conserved at all points in an electrical circuit; for example, at any node in an electrical circuit, electric charge is conserved such that the sum of the electric currents flowing into a node is equal to the sum of electric currents flowing out of that node

Kirchhoff's voltage law
the energy inputs in a circuit equal the sum of energy outputs from loads in the circuit such that the directed sum of the electrical potential differences around any closed network is zero; $\Sigma V = 0$

L

law of conservation of charge
the net amount of charge produced in any transfer process is zero

law of conservation of electric charge
the total electric charge of an isolated system remains constant regardless of changes within the system

law of conservation of energy
a law that states the total energy of an isolated system remains constant

law of conservation of momentum
for two objects colliding in an isolated system, the total momentum before and after the collision is equal

law of reflection
the angle of incidence equals the angle of reflection; $\angle i = \angle r$

light
an electromagnetic wave that does not need a medium for its propagation

linearising
the process of transforming non-linear data by applying a mathematical function to one of the variables so that the relationship between the variables becomes closer to a straight line

longitudinal wave
a wave for which the direction of oscillation of particles is parallel to the direction of energy transfer

M

macroscopic energy
big or bulk forms of energy not at an atomic scale (symbol: E_{macro}; unit: joule; symbol: J)

magnitude
a quantitative measure of the size or amount of a physical quantity

mass
a characteristic of a body's resistance to change in motion; a measure of the amount of inertia

mass defect
the difference between the mass of a nucleus and the sum of the masses of the constituent particles of which it is made

mass–energy equivalence relationship
states that all objects having mass, or massive objects, have a corresponding intrinsic energy, even when they are stationary; related by $\Delta E = \Delta mc^2$

mass number
the total number of nucleons in an element's nucleus; the number of protons plus the number of neutrons; symbol: A

maximum trendline
a line of best fit of maximum gradient within the bounds of the error bars

mean
the average of multiple values

mechanical energy
the sum of potential energy and kinetic energy of an object; the energy associated with its motion and position

mechanical wave
wave that requires a medium for the transfer of energy

mechanical work
the transfer of energy to or from an object by the action of a force over a distance; $W = \Delta E$ and $W = Fs$

medium
an elastic substance such as air or water that allows for the transfer of energy in the form of a mechanical wave

melting
a physical process in which a solid undergoes a phase change to become a liquid

melting point
the temperature at which a solid changes into a liquid

microscopic energy
energy of the particles that make up a substance, including microscopic kinetic energy from the motion of particles and microscopic potential energy (symbol E_{micro}; unit: joule; symbol: J)

microscopic potential energy
the energy stored in the bonds within and between particles of a substance (symbol: $E_{p(micro)}$; SI unit: joule; unit symbol: J)

minimum trendline
a line of best fit of minimum gradient within the bounds of the error bars

mode
different standing wave patterns formed in strings and air columns (pipes)

momentum
a vector quantity, the product of an object's mass and its velocity

N

natural frequency
the frequency at which an object will vibrate when an imposed frequency or force is applied; it is independent of the size of the stimulus, depending solely upon the size, shape and composition of the object; also known as resonant frequency

natural radioactive decay
the process by which the nucleus of an unstable atom loses energy by emitting radiation

neutrino
an elementary subatomic particle very similar to an electron, but without electrical charge and with a very small mass (symbol: ${}^0_0\nu_e$ or ν_e)

neutron
a subatomic particle of about the same mass as a proton but without an electric charge; present in all atomic nuclei except those of ordinary hydrogen

neutron-induced nuclear fission
nuclear fission reaction induced by the bombardment of a nuclide with neutrons, often producing extra neutrons; also known as artificial transmutation

Newton's first law
an object maintains its state of rest or constant velocity motion unless it is acted on by an external unbalanced force; also known as the first law of motion

Newton's second law
the acceleration of an object is in the direction of the net external force acting on it, proportional to the size of the force and inversely proportional to the mass; also known as the second law of motion

Newton's third law
whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first; also known as the third law of motion

node
point in a medium that is not displaced as a wave is propagated through it

non-contact force
an action-at-a-distance force that acts on an object without coming physically in contact with it

non-ohmic
not following Ohm's law

normal
a line perpendicular to a surface, barrier or boundary

normal force
a contact force that acts at right angles to the surface

nuclear fission
a nuclear reaction in which a large unstable nucleus splits, forming two or more smaller, more stable nuclides and releasing neutrons and energy

nuclear fusion
a nuclear reaction in which two or more atomic nuclei combine to form one or more different, heavier nuclides and subatomic particles

nuclear model of the atom
a model that suggests that the atom consists of a small nucleus surrounded by electrons

nuclear radiation
radiation emitted by the subatomic particles in an atomic nucleus, such as alpha, beta or gamma rays

nuclear reaction
a reaction that alters the energy, composition or structure of an atomic nucleus

nuclear stability
a measure of the stability of an isotope determined from the neutron-to-proton ratio and the total number of nucleons in the nucleus

nucleon
proton or neutron found in the nucleus of an atom

nucleus
the positively charged central core of an atom, consisting of protons and neutrons and containing nearly all its mass

nuclide
a distinct kind of atom or nucleus characterised by a specific number of protons and neutrons

O

Ohm's law
electric current is proportional to voltage and inversely proportional to resistance

ohmic devices
those that follow Ohm's law

open circuit
an incomplete electrical circuit in which no charge can flow; switch is "off"

optical density
a measure of the relative speed of light in a medium; the higher the optical density, the slower the speed; quantified as absolute refractive index

oscillation
the back and forth repetitive motion of an object through a central equilibrium point

outlier
a value data point that is much smaller or larger than most of the other values in a set of data; often quantified as being greater than three standard deviations from the mean

P

parallel connection
one in which the components are connected along multiple paths

particle
a minute portion of matter, mainly atoms and molecules

particle model of light
uses photons to describe the behaviour of light, such as the photoelectric effect and atomic spectra

penetrating ability
the ability of each type of radiation to pass through matter

percentage error
the absolute error expressed as a percentage of the accepted (true) value

percentage uncertainty
an indicator of uncertainty in which the range of values for a measurement result (the absolute uncertainty) is expressed as a percentage of the observed measurement

period
the length of time one cycle or one event takes to occur; the length of time taken for one wavelength to pass a given point

phase
the position of a particle at a point in time on a waveform cycle; particles in phase have the same motion (velocity, amplitude and direction of movement) at that time

phase change
when a substance changes state, such as from solid to liquid

physics
the systematic study of energy and matter and how they interact with each other to explain observed phenomena

polarisation
(linear) a process in which the electric field in light oscillates in a fixed plane perpendicular to the direction of propagation, in contrast to an unpolarised wave that allows oscillations in all directions perpendicular to the direction of propagation

polariser
a device that allows only one component of the electric field to pass

positron
a particle of matter with the same mass as an electron but a positive charge

potential difference
the change in potential energy per unit charge between two defined points in a circuit, ΔV; the unit of electrical potential difference is the volt, V; sometimes referred to as the voltage

potential energy
the energy stored in an object due to its position relative to another object to which it is attracted by the force of gravity (symbol: E_p; SI unit: joule; unit symbol: J)

power
the rate at which work is done or the rate at which energy is transferred or transformed

power dissipation
a measure of the rate at which energy is lost from an electrical system

precision
the range of values found around the observed (measured) value; how close two or more measurements of the same object or phenomenon are to each other (i.e. the "uncertainty" of the measurement); the higher the uncertainty the lower the precision

primary data
first-hand data collected from an experiment designed to answer the specific research question

principal axis
the line from the centre of curvature through the optical centre of the lens

principal focus
a point at which incident rays of light parallel to the principal axis converge on the other side of a converging lens, or from which the rays appear to have diverged for a diverging lens

proton
a subatomic particle of about the same mass as a neutron with a +1 elementary electric charge; present in all atomic nuclei

proton–proton chain reaction
a series of nuclear fusion reactions in which four hydrogen nuclei (protons) are combined to form one helium nucleus

pulse
single disturbance produced in a medium by a source

Q

qualitative data
relating to the non-numerical information about a substance, an object or a phenomenon

quantitative data
relating to numerical information about a substance, an object or a phenomenon

R

radiation
the transfer of energy in the form of electromagnetic waves or moving subatomic particles

radioactive
substances which have nuclei with an excess of energy and spontaneously emit radiation to reduce excess energy

radioactivity
the loss of energy from an unstable atomic nucleus by radiation

radionuclide
an unstable isotope of an element that decays or disintegrates spontaneously, thereby emitting radiation

random error
error due to the limitations (uncertainty) of the measurement equipment and the uncontrollable effects of a method and environment on a measurement result

rarefaction
a region in a longitudinal wave where the particles are furthest apart

raw data
primary data that is collected but not yet processed or analysed

ray diagram
a representation of the possible paths light can take to get from a source or object to an observer or screen

rays
straight line paths followed by narrow beams of light along which light energy travels; lines depicting the direction of propagation perpendicular to the wavefront

real image
an image through which the rays of light from the object actually converge

reciprocal law
the refractive index for light passing from medium 1 to medium 2 is the reciprocal of the refractive index of light passing from medium 2 to medium 1

rectilinear propagation
the property of light that characterises it as travelling in a straight line in a uniform medium

reflected pulse
the wave being reflected; also known as the reflected wave

reflection
the process by which incident waves at a boundary change direction, returning into the same medium

refraction
the process in which incident waves at a boundary change direction and speed when passing into another medium

relative refractive index
the ratio of the velocity in one medium to the velocity of light in a different medium; symbol n, $n_{1\rightarrow 2}$, or n_{12} to indicate the passage from medium 1 to medium 2

reliability
the likelihood that another experimenter will obtain the same results (or very similar results) if they perform exactly the same experiment under the same conditions

replicate
a result for a data point obtained from repetition of a measurement using the same methodology, conditions and materials; also known as a trial

resistor
a device that reduces the flow of charge (current) in a circuit

resolution
the smallest division of a scale

resonance
the process in which the frequency of the external force matches the natural frequency of the vibrating object, resulting in an increase in the amplitude of vibration

resultant
the vector sum of two or more vectors

resultant force
a single force that has the same effect as all the forces acting on an object combined; also called net force, F_{net}

risk assessment
a system or document that evaluates any potential risks involved with a particular activity

rolling friction
friction between two surfaces rolling over each other; the smallest of all three types of friction

rotational motion
a form of kinetic energy in which a particle spins on its own axis

S

safety data sheet
a document that lists information relating to hazardous and non-hazardous materials

scalar quantity
a quantity that has a magnitude but no spatial direction

scale reading limitations
the inability of an instrument to resolve small measurement differences

scientific notation
a shorthand way of expressing very large or very small numbers in terms of a decimal number between 1 and 10 multiplied by a power of 10

second law of reflection
the angle of reflection is equal to the angle of incidence when both angles are measured with respect to the normal to the mirror

secondary data
second-hand data obtained from other sources

series
describes an electrical circuit in which components are connected along a single path, so the same current flows through all of the components

series connection
one in which the components are connected along a single path

significant figures
the digits of a number that are used to express it to the required degree of precision (abbreviated: s.f.)

simple wave
a wave that forms a strictly periodic pattern with one wavelength and one wave period and propagating in one direction, unlike real waves which are irregular and composites of simple waves

Snell's law
when light travels from one medium to another, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the refractive index

spatial direction
a direction in space

specific heat capacity
the thermal energy required to raise the temperature of 1 kg of a substance by 1°C or 1 K (symbol: c; unit: joules per kilogram per degree; unit symbol: $J kg^{-1} °C^{-1}$ or $J kg^{-1} K^{-1}$)

specific latent heat
the amount of energy required to change the phase of 1 kg of a substance

specific latent heat of fusion
the amount of energy required to change 1 kg of a substance from solid to liquid at its melting point (symbol: L_f; unit: joules per kilogram; unit symbol: $J kg^{-1}$)

specific latent heat of vaporisation
the thermal energy required to change 1 kg of a liquid into a vapour at its boiling point (symbol: L_v; unit: joules per kilogram; unit symbol: $J kg^{-1}$)

spectrum
the range of frequencies of electromagnetic radiation and their respective wavelengths, divided into spectral regions such as infrared (IR), visible, ultraviolet (UV), X-rays, and gamma rays

speed
the rate at which distance is covered

speed of light
electromagnetic waves such as light have a speed of $c = 3 \times 10^8 m s^{-1}$ in a vacuum; other waves have speeds determined by the nature of the medium

stable
characteristic of nuclides that are not radioactive and so (unlike radionuclides) do not spontaneously undergo radioactive decay; when such nuclides are referred to in relation to specific elements, they are usually termed stable isotopes

standard deviation
a measure of the amount of variation of a set of data values

standard operating procedure
step-by-step guide on how to operate a piece of equipment or an instrument correctly and safely

standing wave
wave with stationary vibration patterns formed due to the superposition of waves with particular frequencies

static friction
friction between surfaces stationary relative to each other; generally higher than dynamic friction

strong nuclear force
a force that acts over very small distances in the nucleus to hold the nucleons together against the repulsive electrostatic forces between the positively charged protons

superposition
when two or more waves overlap in space, the resultant wave is the algebraic sum of the individual waves

systematic error
an error that causes readings to deviate from the accepted value by a consistent amount and in the same direction each time a measurement is made; it is affected by the accuracy of a measurement process

T

temperature
the average kinetic energy of a system of particles, typically expressed according to a comparative scale, such as the Celsius temperature scale; what a thermometer measures

tension
the pulling force transmitted along a rope, string, cable or chain on an object

terminal velocity
the speed reached when an object falling through a fluid stops accelerating

thermal energy
the component of internal energy present in a system that determines its temperature (symbol, E_{th}; unit: joules; symbol: J)

thermal energy transfer
the process of transferring thermal energy from a hot object to a cooler one; also known as heat transfer

thermal equilibrium
a state in which there is no net exchange of thermal energy between any components of a system; the components have the same temperature and the same average kinetic energy

thermal expansion
the process by which heat causes an increase in the kinetic energy of particles, leading them to spread apart and occupy a larger volume

thermal radiation
the transfer of thermal energy in the form of electromagnetic waves in the infrared region

thermometer
a device used to measure temperature

third law force pair
an equal and opposite pair of forces involved when two objects interact; the force on one object is equal and opposite to the force acting on the other object; the forces cannot act on the same object; also called a ”third law pair”

total energy of the system
the sum of the energy present in a system, including microscopic and macroscopic kinetic and potential energy (symbol, E_{sys}; unit: joules; symbol: J)

total internal reflection
the phenomenon whereby all energy is reflected inside a medium due to the incident angle of the wave being greater than the critical angle

total momentum
the vector sum of individual momenta (plural of momentum)

translational motion
a form of kinetic energy in which a particle moves from place to place

transmission
the passage of a wave through a boundary between one medium and another

transmitted pulse
the pulse that has passed through a boundary between one medium and another

transmutation
the change of one chemical element into another by a nuclear reaction

transparent
a substance through which you can see clearly because it allows light to pass through without appreciable scattering

transverse wave
for a mechanical wave, the direction of oscillation of particles is perpendicular to the direction of energy transfer

trendline
a line of best fit which shows the general direction that a group of points seem to follow

trough
the lowest part or point of a wave; the point of maximum negative displacement

U

unbalanced forces
forces that cause a change in the motion of an object

uncertainty
the range of values for a measurement result, taking account of the likely values that could be attributed to the measurement result given the measurement equipment, procedure and environment

uniformly accelerated motion
motion for which the velocity is changing in magnitude or direction in a regular manner

V

validity
a measure of whether the investigation is sound and measures what it is intended to measure

vaporisation
a physical process in which a liquid undergoes a phase change to become a vapour (it can include evaporation or boiling)

variable force
one that has a change in magnitude or direction during an interaction; also known as non-uniform force

vector addition
two or more vector quantities can be combined to produce a single resultant vector

vector quantity
a quantity that has both magnitude and spatial direction

velocity
the rate of change of displacement of an object (symbol, v; SI unit, m s^{-1}).

velocity–time graph
depicts the velocity of an object as a function of time, the gradient of which is the acceleration, and the area under the curve is the displacement

vibrational motion
a form of kinetic energy in which particles vibrate in place

virtual image
an image through which the rays of light from the object do not actually converge but only appear to

volt
a unit of electrical potential or voltage, equivalent to 1 joule per coulomb of charge

voltage
a measure of electrical potential energy per unit charge, measured in joules per coulomb; often referred to as electrical potential

voltmeter
an instrument used for measuring electrical potential difference between two points in an electrical circuit

W

wave equation
a formula that relates the velocity of wave propagation through a medium to the frequency and wavelength of the disturbance; $v = f\lambda$

wave height
the vertical distance of a wave from the crest to the trough; equal to twice the amplitude

wave model of light
uses the characteristics of waves such as wavelength, frequency and speed to describe the behaviour of light such as interference, reflection and refraction

waveform diagram
a graph that shows displacement (amplitude) of a wave at a moment in time

wavelength
the minimum distance between two points on the wave in phase

weight
a measure of the force of gravity acting on an object

Z

zeroth law of thermodynamics
if two bodies are in thermal equilibrium with a third body, they are in thermal equilibrium with each other; energy will transfer from a system with higher temperature to a system with lower temperature until thermal equilibrium is reached

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Acknowledgements

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Appendix 1: Properties of the Nuclides

Z = atomic number = number of protons
A = atomic mass = number of protons plus neutrons
M = exact mass of the nuclide including electrons (in u)

Z		A	M	Z		A	M
–1	e	0	0.000549	37	Rb	90	89.914798
						93	92.922039
0	n	1	1.008665			96	95.934133
1	p	1	1.007276	38	Sr	88	87.905613
						90	89.907730
1	H	1	1.007825			93	92.914024
		2	2.014102			94	93.915356
		3	3.016050			96	95.921707
2	He	3	3.016029	39	Y	90	89.907144
		4	4.002603	40	Zr	94	93.906311
		6	6.018886	42	Mo	100	99.907472
		8	8.033934	47	Ag	107	106.905092
3	Li	6	6.015123			108	107.905950
		7	7.016003	48	Cd	113	112.904408
		8	8.022486	49	In	115	114.903879
		9	9.026790			116	115.905260
4	Be	6	6.019726	50	Sn	116	115.901743
		7	7.016929	52	Te	137	136.925599
		9	9.012183	54	Xe	135	134.907228
5	B	8	8.024607			139	138.918792
		10	10.012937			140	139.921646
		11	11.009305	55	Cs	130	129.906709
6	C	9	9.031037			135	134.905977
		10	10.016853			138	137.911017
		11	11.011434			141	140.920045
		12	12.000000	56	Ba	136	135.904576
		13	13.003355			141	140.914403
		14	14.003242			142	141.916432
7	N	12	12.018613			143	142.920625
		13	13.005738			144	143.922955
		14	14.003074	81	Tl	208	207.982019
8O		13	13.024815	82	Pb	206	205.974466
		16	15.994915			208	207.976652
		17	16.999132	83	Bi	212	211.991286
		18	17.999160	84	Po	212	211.988868
11	Na	22	21.994437			216	216.001915
		23	22.989769	86	Rn	220	220.011394
		24	23.990963			222	222.017578
12	Mg	23	22.994124	88	Ra	224	224.020212

Z		A	M	Z		A	M
13	Al	27	26.981539			226	226.025410
15	P	30	29.978314			228	228.031071
		31	30.973762	89	Ac	228	228.031022
		32	31.973908	90	Th	234	234.043601
16	S	32	31.972071	91	Pa	234	234.043307
		35	34.969032	92	U	233	233.039636
17	Cl	36	35.968307			234	234.040952
19	K	40	39.963998			235	235.043930
26	Fe	56	55.934936			236	236.045568
27	Co	60	59.933816			238	238.050788
28	Ni	60	59.930786			239	239.054293
		61	60.931056	93	Np	239	239.052939
		64	63.927967	94	Pu	239	239.052164
29	Cu	64	63.929764			240	240.053814
30	Zn	64	63.929142			241	241.056852
		65	64.929241	95	Am	239	239.053025
36	Kr	84	83.911498			241	241.056829
		90	89.919528				
		91	90.923806				
		92	91.926173				

Source: International Atomic Energy Agency

Appendix 2: Periodic table

Key:

6 **C** 12.01 Carbon

- 6 — Atomic number
- C — Chemical symbol
- 12.01 — Atomic mass
- Carbon — Name of element

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 **H** 1.0 Hydrogen																	2 **He** 4.0 Helium
2	3 **Li** 6.9 Lithium	4 **Be** 9.0 Beryllium											5 **B** 10.8 Boron	6 **C** 12.0 Carbon	7 **N** 14.0 Nitrogen	8 **O** 16.0 Oxygen	9 **F** 19.0 Fluorine	10 **Ne** 20.2 Neon
3	11 **Na** 23.0 Sodium	12 **Mg** 24.3 Magnesium											13 **Al** 27.0 Aluminium	14 **Si** 28.1 Silicon	15 **P** 31.0 Phosphorus	16 **S** 32.1 Sulfur	17 **Cl** 35.5 Chlorine	18 **Ar** 39.9 Argon
4	19 **K** 39.1 Potassium	20 **Ca** 40.1 Calcium	21 **Sc** 45.0 Scandium	22 **Ti** 47.9 Titanium	23 **V** 50.9 Vanadium	24 **Cr** 52.0 Chromium	25 **Mn** 54.9 Manganese	26 **Fe** 55.8 Iron	27 **Co** 58.9 Cobalt	28 **Ni** 58.7 Nickel	29 **Cu** 63.5 Copper	30 **Zn** 65.4 Zinc	31 **Ga** 69.7 Gallium	32 **Ge** 72.6 Germanium	33 **As** 74.9 Arsenic	34 **Se** 79.0 Selenium	35 **Br** 79.9 Bromine	36 **Kr** 83.8 Krypton
5	37 **Rb** 85.5 Rubidium	38 **Sr** 87.6 Strontium	39 **Y** 88.9 Yttrium	40 **Zr** 91.2 Zirconium	41 **Nb** 92.9 Niobium	42 **Mo** 96.0 Molybdenum	43 **Tc** (97) Technetium	44 **Ru** 101.1 Ruthenium	45 **Rh** 102.9 Rhodium	46 **Pd** 106.4 Palladium	47 **Ag** 107.9 Silver	48 **Cd** 112.4 Cadmium	49 **In** 114.8 Indium	50 **Sn** 118.7 Tin	51 **Sb** 121.8 Antimony	52 **Te** 127.6 Tellurium	53 **I** 126.9 Iodine	54 **Xe** 131.3 Xenon
6	55 **Cs** 132.9 Caesium	56 **Ba** 137.3 Barium	57 to 71	72 **Hf** 178.5 Hafnium	73 **Ta** 180.9 Tantalum	74 **W** 183.8 Tungsten	75 **Re** 186.2 Rhenium	76 **Os** 190.2 Osmium	77 **Ir** 192.2 Iridium	78 **Pt** 195.1 Platinum	79 **Au** 197.0 Gold	80 **Hg** 200.6 Mercury	81 **Tl** 204.4 Thallium	82 **Pb** 207.2 Lead	83 **Bi** 209.0 Bismuth	84 **Po** (210) Polonium	85 **At** (210) Astatine	86 **Rn** (222) Radon
7	87 **Fr** (223) Francium	88 **Ra** (226) Radium	89 to 103	104 **Rf** (267) Rutherfordium	105 **Db** (270) Dubnium	106 **Sg** (269) Seaborgium	107 **Bh** (270) Bohrium	108 **Hs** (270) Hassium	109 **Mt** (278) Meitnerium	110 **Ds** (281) Darmstadtium	111 **Rg** (281) Roentgenium	112 **Cn** (285) Copernicium	113 **Nh** (286) Nihonium	114 **Fl** (289) Flerovium	115 **Mc** (290) Moscovium	116 **Lv** (289) Livermorium	117 **Ts** (294) Tennessine	118 **Og** (294) Oganesson

Metals

Rare earth elements
Lanthanide series

57 **La** 138.9 Lanthanum	58 **Ce** 140.1 Cerium	59 **Pr** 140.9 Praseodymium	60 **Nd** 144.2 Neodymium	61 **Pm** (145) Promethium	62 **Sm** 150.4 Samarium	63 **Eu** 152.0 Europium	64 **Gd** 157.3 Gadolinium	65 **Tb** 158.9 Terbium	66 **Dy** 162.5 Dysprosium	67 **Ho** 164.9 Holmium	68 **Er** 167.3 Erbium	69 **Tm** 168.9 Thulium	70 **Yb** 173.1 Ytterbium	71 **Lu** 175.0 Lutetium

Actinide series

89 **Ac** (227) Actinium	90 **Th** 232.0 Thorium	91 **Pa** 231.0 Protactinium	92 **U** 238.0 Uranium	93 **Np** (237) Neptunium	94 **Pu** (244) Plutonium	95 **Am** (243) Americium	96 **Cm** (247) Curium	97 **Bk** (247) Berkelium	98 **Cf** (251) Californium	99 **Es** (252) Einsteinium	100 **Fm** (257) Fermium	101 **Md** (258) Mendelevium	102 **No** (259) Nobelium	103 **Lr** (260) Lawrencium

Metals
- Alkali metal
- Alkaline earth metal
- Lanthanide
- Actinide
- Transition metal
- Post-transition metal

Non-metals
- Diatomic non-metal
- Polyatomic non-metal
- Noble gas

Other
- Metalloid
- Unknown chemical properties

Notes

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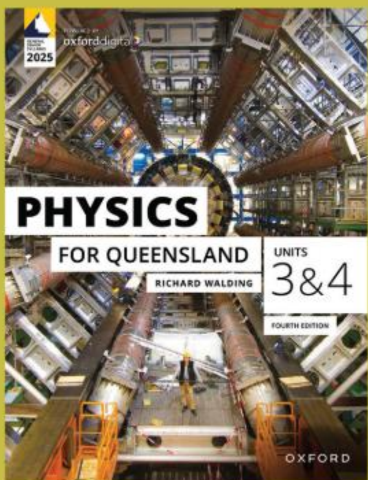

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