NELSON

QCE Physics

UNITS

1

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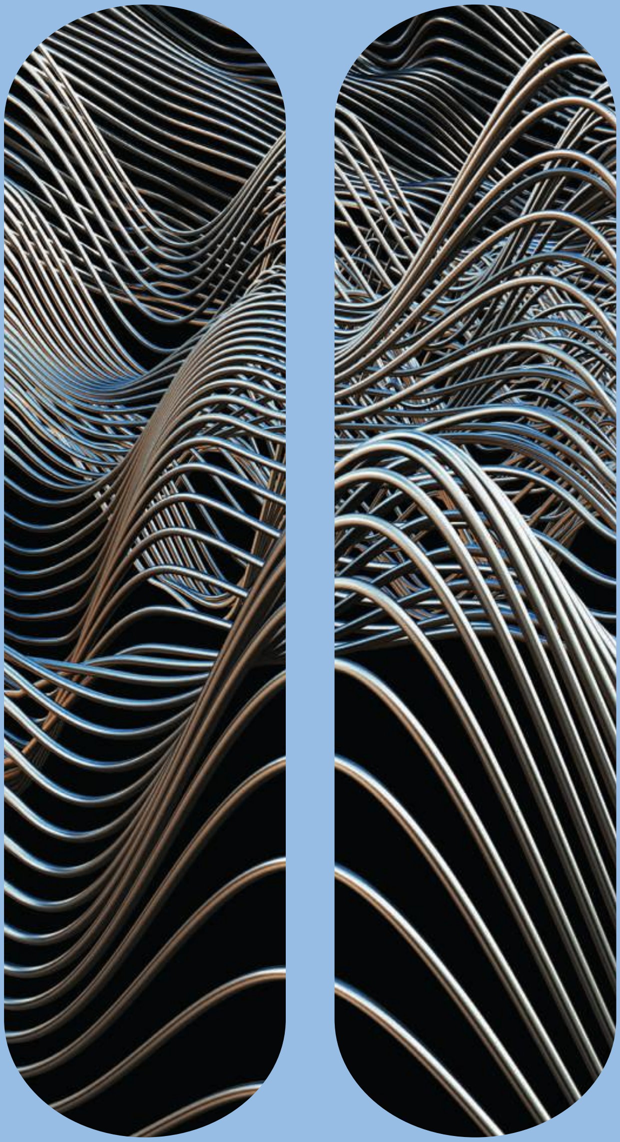

Scott Adamson
Shanee Conran
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NELSON

QCE Physics

UNITS
1
2

LEARNING DISCOVERY

SOUND WAVES

Some waves are made to be surfed, others are made to be heard. The beautiful sounds around us are in fact, intricate patterns of particles oscillating through space and time.

Scott Adamson
Shanee Conran
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Nelson QCE Physics Units 1 & 2
1st Edition
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TOPIC 1: LINEAR MOTION AND FORCE

TOPIC 2: WAVES

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The following people have contributed to the review of the Nelson QCE Physics series: Matt Cardus and George Higgins.

ACKNOWLEDGEMENTS

The publisher would like to acknowledge the authors for their expertise and devotion to supporting teachers and students engaging in Physics around Queensland.

ABOUT THIS BOOK

Nelson QCE Physics Units 1 & 2 is a comprehensive textbook specifically tailored to align with the 2025 QCAA Physics General Senior Syllabus. It has been thoughtfully developed to empower students by providing a strong foundation in essential concepts and equipping them with the necessary skills to excel in their studies. Emphasising the importance of making connections between topics and practising exam techniques, this edition is designed to support students in unlocking their full potential and achieving success in their journey.

AT THE BEGINNING OF THE BOOK

- An online chapter to support the development of students' science inquiry skills for application throughout the syllabus

AT THE BEGINNING OF UNIT

- Unit introductions are an overview of the key content in the unit

UNIT 1

Thermal, nuclear and electrical physics

Topic 1: Heating processes

Topic 2: Ionising radiation and nuclear reactions

Topic 3: Electrical circuits

UNIT OBJECTIVES

AT THE BEGINNING OF EACH CHAPTER

- Chapter introduction to set the context of the upcoming key content
- List of syllabus dot points being covered in the chapter
- List of student resources available on Nelson MindTap

CHAPTER 1 Kinetic particle model and heat transfer

SYLLABUS DOT POINTS

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.

Physics 2025 v1.1 General Senior Syllabus © QCAA 2024

Introduction

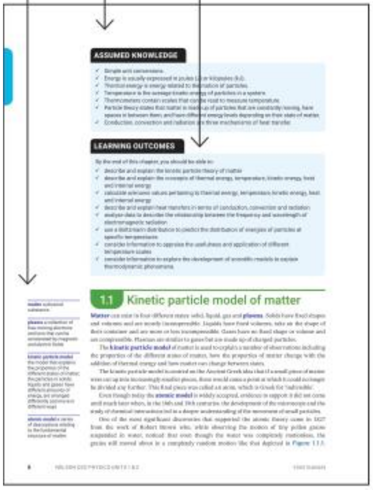
Worksheet

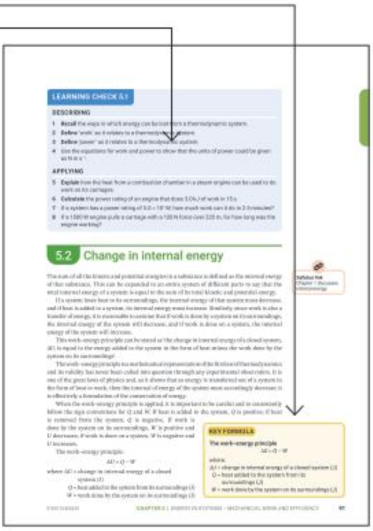
Nelson MindTap

4 NELSON QCE PHYSICS UNITS 1 & 2 9780170483629

IN EACH CHAPTER

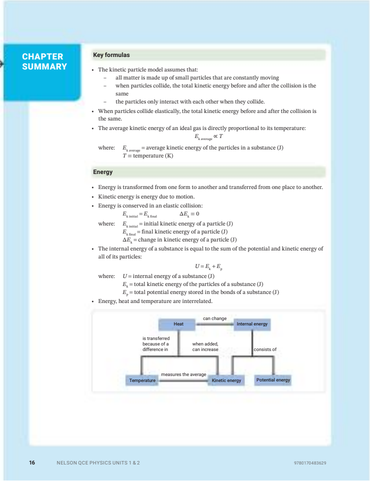
- **Assumed knowledge** – knowledge and skills students are expected to know coming into the chapter that relate to the chapter content
- **Learning outcomes** – highlights the key outcomes from chapter
- **Key terms** – defined in situ to help students deconstruct scientific language
- **Learning check** – written to the developmental levels highlighted in the syllabus objectives
- **Key formulas** – important formulas to remember
- **Syllabus links** – highlighting links to other areas in the syllabus to help students make connections
- **Practicals** – syllabus-aligned practicals with guided instructions on the materials, procedure, collection and analysis of results, and discussion





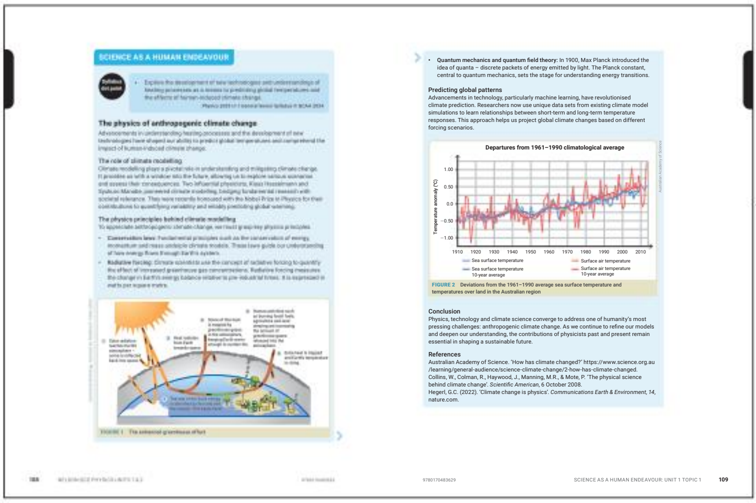
AT THE END OF EACH CHAPTER

- **Chapter summary** – visual summaries to help summarise key concepts
- **Chapter exam** – exam-style questions to help students develop exam skills, including deliberate practice in data analysis and making connections across content



AT THE END OF EACH TOPIC

- **Science as a Human Endeavour** – a deep dive on the evolution of science and how it has contributed to and influenced society



SCIENCE AS A HUMAN ENDEAVOUR

The physics of anthropogenic climate change

- **Quantum mechanics and quantum field theory:** In 1900, Max Planck introduced the idea of quanta – discrete packets of energy emitted by light. The Planck constant, central to quantum mechanics, sets the stage for understanding energy transitions.

Predicting global patterns
Advancements in technology, particularly machine learning, have revolutionised climate prediction. Researchers now use unique data sets from existing climate model simulations to learn relationships between short-term and long-term temperature responses. This approach helps us project global climate changes based on different forcing scenarios.

FIGURE 2 Deviations from the 1961–1990 average sea surface temperature and temperatures over land in the Australian region

Conclusion
Physics, technology and climate science converge to address one of humanity's most pressing challenges: anthropogenic climate change. As we continue to refine our models and deepen our understanding, the contributions of physicists past and present remain essential in shaping a sustainable future.

References
Australian Academy of Science. 'How has climate changed?' https://www.science.org.au/learning/general-audience/science-climate-change/2-how-has-climate-changed.
Collins, W., Colman, R., Haywood, J., Manning, M.R., & Mote, P. 'The physical science behind climate change'. *Scientific American*, 6 October 2008.
Hegerl, G.C. (2022). 'Climate change is physics'. *Communications Earth & Environment, 14*, nature.com.

9780170483629 SCIENCE AS A HUMAN ENDEAVOUR: UNIT 1 TOPIC 1 109

AT THE END OF THE BOOK

- **Glossary** provides explanations of all terms introduced in the text.
- **Answers** provide complete answers for student reference.

GLOSSARY

A

absolute refractive index a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light

absolute uncertainty the magnitude of the difference between the observed/measured value and the true value

absolute zero the theoretical lowest possible temperature; −273.15°C on the Celsius scale or 0 K on the absolute or kelvin scale

acceleration the rate of change of velocity (vector); magnitude of rate of change of speed (scalar) with respect to time

accepted value the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

accuracy the degree to which the result of a measurement, calculation or specification conforms to the correct value or a standard

action-at-a-distance forces a non-contact force

activity a measure of the magnitude of radioactive emissions; the number of emissions per second, measured in the SI unit Bq

alpha particle a particle made up of two neutrons and two protons; a helium nucleus

alternating current (AC) current that changes direction periodically, typically 50 oscillations per second (50 Hz)

amplitude the maximum displacement of a particle in a wave from its mean position; units: m

analyser material that allows or stops polarised electromagnetic radiation

angle of incidence the angle made between an incident wave and a normal drawn to the surface at the point of incidence

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

angle of refraction (*r*) the angle that a refracted ray makes with the normal

anthropogenic human-derived; caused by human activity

antineutrino an elementary particle that accompanies β^- decay

antinode a point along a standing wave at which the wave has maximum amplitude; the result of a crest overlapping a crest or a trough overlapping a trough

apparent position the position that an object appears to an observer, which may be different from its actual position due to the refraction of its light waves

artificial transmutation the conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

atmosphere a unit of pressure; 1 atmosphere is the standard pressure at the surface of Earth

atmospheric refraction the refraction of light rays as they pass through Earth's atmosphere

atom a particle; originally thought to be indivisible, but now known to comprise numerous smaller particles

atomic mass number the total number of protons and neutrons in a nucleus (A)

atomic model a series of descriptions relating to the fundamental structure of matter

atomic number the number of protons in a nucleus (Z)

atomic weight (relative atomic mass) the weighted average of all the masses of the different nuclides in a pure, naturally occurring sample of the element

average speed the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in a given time interval

B

body wave a seismic wave that travels through the body of Earth

boiling point the temperature at which a substance undergoes a phase change from liquid to gas (vaporises)

Boltzmann distribution a formula showing the distribution of energy among the particles of a system

bombarding radiation radiation composed of particles, such as alpha particles or neutrons, that are bombarded at the nucleus to force transmutation and radioactive decay

Brownian motion the random motion of small particles suspended in a fluid as a result of being bombarded by the particles of the fluid

C

calorie the amount of heat energy required to raise the temperature of 1 g of water by 1°C; 1 cal = 4.186 J

calorimeter a highly insulated container that prevents heat energy being lost to the environment, used to measure quantities of heat

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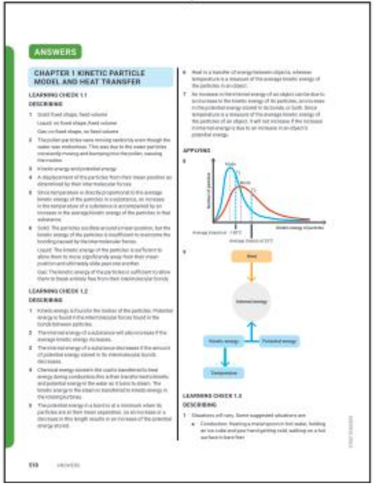

ANSWERS

CHAPTER 1 KINETIC PARTICLE MODEL AND HEAT TRANSFER

LEARNING CHECK 1.1

DESCRIBING

LEARNING CHECK 1.2

DESCRIBING

APPLYING

LEARNING CHECK 1.3

DESCRIBING

Nelson MindTap

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Error bars

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- **Check** your understanding with assumed knowledge reviews.**
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- Access **supporting materials** such as the chapter summary pack and weblinks.
- **Revise** with chapter tests to practice your skills and build confidence.**
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* Complimentary access to these resources is only available to teachers who use this book as part of a class set, book hire or booklist. Not available for single purchases. Alternatively, teacher access can be purchased as a separate subscription for schools. Contact your Cengage learning consultant for information about access and conditions.

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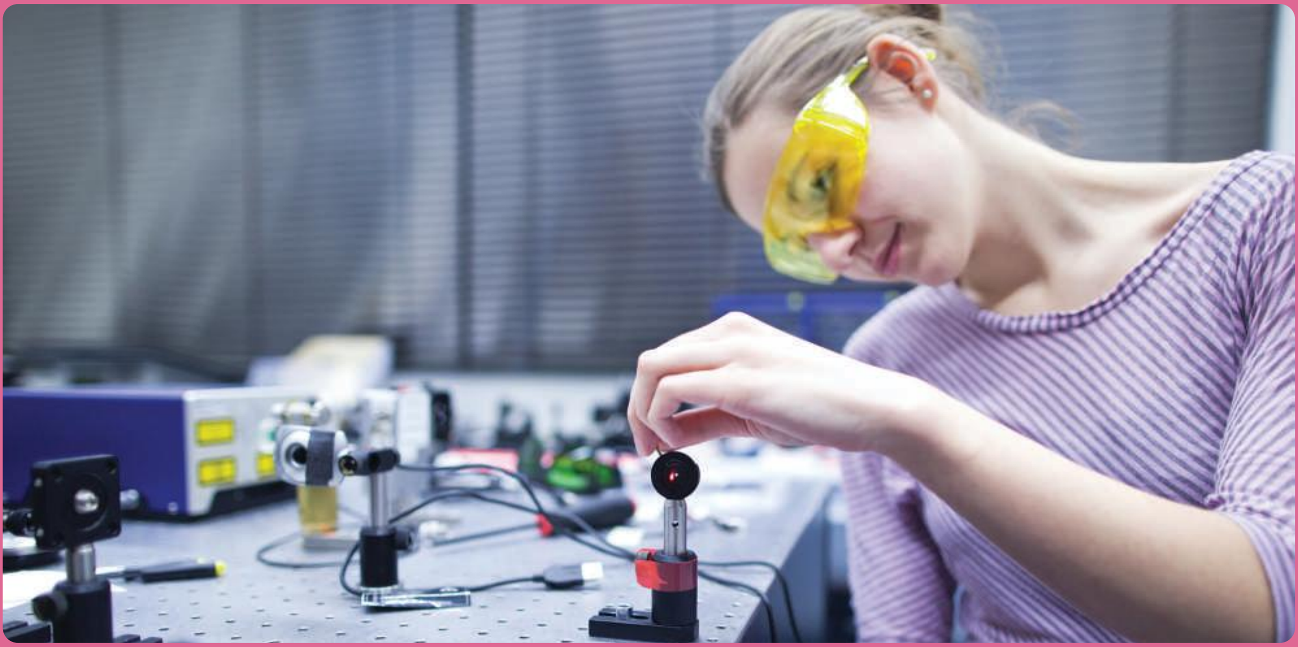
CHAPTER DC

Science research



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SYLLABUS DOT POINTS

SCIENCE INQUIRY SKILLS

Throughout the course of the study, students will:

- identify, research and construct questions for investigation
- propose hypotheses and/or predict possible outcomes
- 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
- 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
  - workplace health and safety guidelines
  - standard operating procedures
  - acknowledgment of sources and referencing

- 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
- use scientific language and representations to systematically record information, observations, data and measurement error, e.g.
  - symbols, units and prefixes
  - indicators of measurement uncertainty 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
  - tables, graphs and diagrams
  - logbooks
- translate information between graphical, numerical and/or algebraic forms
  - units and measurement conversions
  - symbols and notation
- 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
  - scatterplots (with maximum and minimum trendlines and R^2)
  - propagate random error in data processing to show the impact of measurement uncertainties on the final result
  - apply simple treatment of error analysis, e.g. for functions such as addition and subtraction, absolute uncertainties should be added, for multiplication, division and powers, percentage uncertainties should be added
  - calculate the measurement uncertainties in processed data, including the use of absolute uncertainties of the mean (Formula: $\Delta\bar{x} = \pm\frac{(x_{max} - x_{min})}{2}$) and percentage uncertainties (Formula: $\text{percentage uncertainty (\%)} = \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$)
  - calculate the percentage error, when the experimental result can be compared with a theoretical or accepted result (value)

    (Formula: $\text{percentage error (\%)} = \left|\frac{\text{measured value} - \text{true value}}{\text{true value}}\right| \times 100\%$)
- 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
  - apply appropriate graphical representations to analyse data and draw conclusions
- analyse data to identify trends, patterns and relationships; recognising error, uncertainty and limitations of evidence
  - interpret graphs in terms of the relationship between dependent and independent variables; draw and interpret best-fit lines or curves through data points, including evaluating when it can and cannot be considered as a linear function

  - discriminate between precision and accuracy identify that all measurements have limits to their precision and accuracy that must be considered when evaluating experimental results identify that quantitative data obtained from measurements is associated with random error/measurement uncertainties
- select, synthesise and use evidence to construct scientific arguments and draw conclusions
- extrapolate findings to determine unknown values, predict outcomes and evaluate claims
- 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 values
  - discriminate between validity and reliability
  - suggest improvements and extensions to minimise uncertainty, address limitations and improve the overall quality of evidence, e.g.
  - analyse the impact of random error/measurement uncertainties and systematic errors in experimental work and determine how these errors/measurement uncertainties can be reduced
  - discriminate between random and systematic errors
  - identify that experimental design and procedure usually leads to systematic errors in measurement, which causes a deviation in a direction and that repeated trials and measurements will reduce random error but not systematic error
- 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
- appreciate the role of peer review in scientific research.

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Introduction

Conducting structured experiments is an important aspect of the scientific method as it allows for the gathering of information to help develop a greater appreciation and understanding of the world.

Performing research on scientific topics and the process of developing and implementing experimental methods form a large part of the scientific studies and formal internal assessment throughout this course. In fact, the Student Experiment (IA2) and Research Investigation (IA3) make up a significant portion of the internal assessments incorporating both primary and secondary data. Furthermore, the scientific thinking acquired through these processes is regularly examined in the External Assessment. As such, it is important to develop these skills not just for this course, but also to improve critical thinking and apply the scientific method more widely.

ASSUMED KNOWLEDGE

- ✓ The purpose of experiments is to collect information about a key idea or to answer a question.
- ✓ Controlled experiments have a general structure.
- ✓ Variables are factors or conditions that can be changed, controlled or measured and which can influence the result of an investigation.
- ✓ Variables include independent, dependent and controlled variables.
- ✓ The data collected from an experiment needs to be related to the question being investigated.
- ✓ Data collected from an experiment can be presented in different ways depending on the nature of the data.
- ✓ Data can be classified as primary or secondary.

LEARNING OUTCOMES

- ✓ Develop research questions for research.
- ✓ Identify the importance of peer review in scientific research and compare different ideas and information from scientific texts.
- ✓ Plan and modify investigations, including the materials and methods needed to collect valid and reliable data (both primary and secondary data).
- ✓ Consider safety, ethics and the environment when conducting scientific investigations.
- ✓ Determine the best method to present data; for example, tables and graphs.
- ✓ Use scientific language and visual representations to organise and present information accurately.
- ✓ Identify and minimise errors in measurements.
- ✓ Calculate uncertainties and other measures of data accuracy and describe their impact on data.
- ✓ Select and construct the most appropriate data presentation technique.
- ✓ Make predictions based on trends observed in the data.
- ✓ Use mathematical techniques to analyse data to find patterns, trends and relationships.
- ✓ Identify limitations or sources of error or uncertainty.
- ✓ Draw conclusions based on evidence, comparing findings to expected results.
- ✓ Communicate scientific information in a clear and appropriate manner for different audiences.
- ✓ Acknowledge sources and use proper referencing.
- ✓ Reflect on investigations and suggest ways to improve the quality and accuracy of data and findings.

DC.1 Student experiment

Forming

The research question

For your Student Experiment (IA2), you will be required to design an experiment to answer a **research question** related to a topic in the syllabus. In science, the design of experiments is guided by the scientific method (**Figure DC.1.1**) – a systematic and structured approach that ensures that the results are objective, valid and reliable.

research question a question that directs the scientific inquiry activity; it focuses the research investigation or student experiment, informing the direction of the research, and guiding all stages of inquiry, analysis, interpretation and evaluation

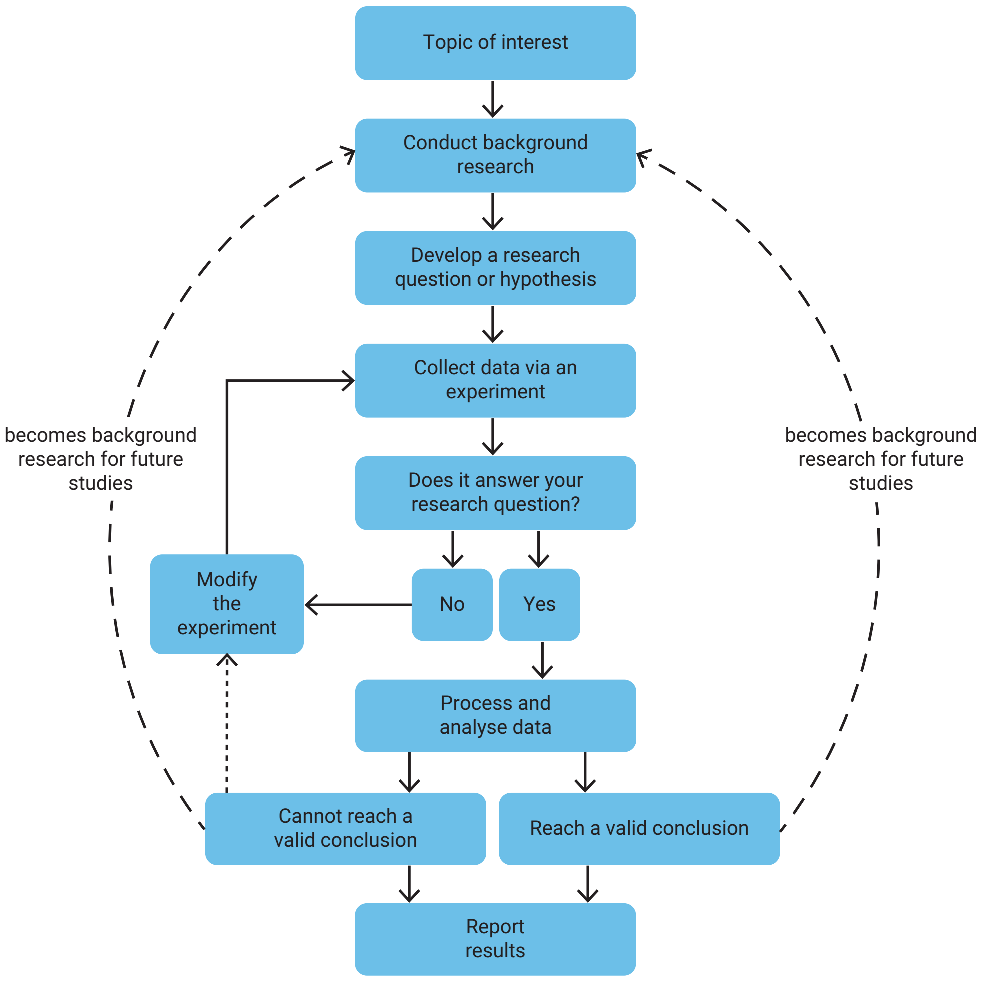


FIGURE DC.1.1 The basic structure of the scientific method

A research question is the question you are trying to answer with your research, and by doing so helps to guide and refine the research and experimental method. For example, a research question could be 'How does the length of a current-carrying conductor affect the current flowing through the conductor if the voltage is kept constant?'

Rationale

When developing a research question, it is important to demonstrate an understanding of the underlying theory related to the topic. This is described in the rationale of your experiment and is also implied through your research question. In the example above, the research question explores the relationship between the length of the wire and the current flowing through the wire. The current flowing through the wire is determined from Ohm's law, the relationship $R = \frac{V}{I}$, where the resistance experienced is proportional to the voltage and inversely proportional to the current. Further, the resistance is related to the length of the wire through the resistivity formula:

$$R = \rho \times l$$

where ρ is the resistivity of the wire ($\Omega\ \text{m}^{-1}$) and l is the length of the wire (m).

With greater research and understanding of the topic, it is likely that you have developed a possible answer to the research question. This becomes the hypothesis. The hypothesis highlights the relationship between the **independent** and **dependent variables**, showing the directional impact that one would have on the other. Building on the example above, a possible hypothesis is 'As the length of the current-carrying conductor increases, the current flowing through the conductor decreases'. In this case, the independent variable is the change in length of the current-carrying conductor and the dependent variable is the current flowing through the conductors.

independent variable a variable on which another variable is dependent; also called the controlled variable

dependent variable the variable that changes because of changes to the independent variable

Finding

Methodology

For your experiment, you will need to modify an existing method from previous studies. During your research, you may have encountered various studies conducted by scientists who were interested in investigating a similar topic. These studies can serve as a valuable foundation for you to build on and refine your own approach. How and what you modify in the experiment will depend on:

- the variables you are testing
- sources of error and bias in the previous method
- the type of data being collected (**quantitative** or **qualitative**)
- how much data you will need to collect to ensure that there is sufficient data for analysis
- access to resources.

Once you have your base experiment (which could be one that you completed in class), a student experiment requires you to make some modifications to design your own student experiment. A modification may be one of three different types (Table DC.1.1).

qualitative non-numerical data; descriptive information

quantitative numerical data; a specific amount

TABLE DC.1.1 Types of modifications that can be made to methodologies for the Student Experiment (IA2)

Type of modification	Explanation	Instruction	Example
Refine	To improve by making subtle changes to the accuracy or precision of the data	• Make improvements without changing the independent or dependent variables.	• Use equipment with a higher level of precision. • Improve the methodology or way of measuring the independent variable. • Change the sample size or number of trials being conducted.
Redirect	To gain further insight by changing the course or direction of the data	• Change the independent variable.	• Measure velocity instead of displacement, or measure current instead of length.
Extend	To change or extend the scope of the current data range	• Change the range of the independent variable. • Extend the range of independent variables.	• Use a wider range of values for the independent variables, such as more measurements that extend beyond the original experiment. • Repeat the revised experiment at a range of voltages.

Although you will not need to rewrite an entire methodology in your experiment, it is important that you justify the modifications you made. For example, if you decided to refine an experiment by using a digital thermometer instead of an analogue thermometer, you could justify this by saying that your refinement will improve the reliability of your data collection because the digital thermometer has a smaller uncertainty and it has greater precision. Similarly, you may refine an experiment by performing a higher number of trials, disregarding outliers and averaging results, and justify this as increasing accuracy and reducing the impact of random error.

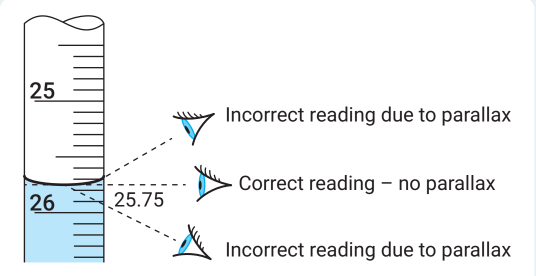


FIGURE DC.1.2 How to read measurements from a measuring cylinder

Having the right equipment is important; however, misreading the measuring instruments leads to inaccurate results. For example, when reading the volume of a liquid in a measuring cylinder, the measurement must be taken at eye level and measured from the bottom of the meniscus to ensure accuracy and to remove parallax error **(Figure DC.1.2)**.

When collecting and recording data, ensure that it is measured in the appropriate units. The units used to collect data will depend on the nature of the experiment. For example, electrical current is often measured in amperes (A), whereas resistance is measured in ohms (Ω). Similarly, devices often measure in grams, requiring conversion into kilograms. Since there are different units to express the same measurement, you will often need to convert between units, especially when graphing, determining gradients and analysing results. **Table DC.1.2** shows common unit conversions.

TABLE DC.1.2 Common unit conversions

Measurement	Common conversions
Distance	1 km = 1000 m = 100 000 cm = 1 000 000 mm
Mass	1 kg = 1000 g = 1 000 000 mg
Current	1 A = 1000 mA
Voltage	1 V = 1000 mV

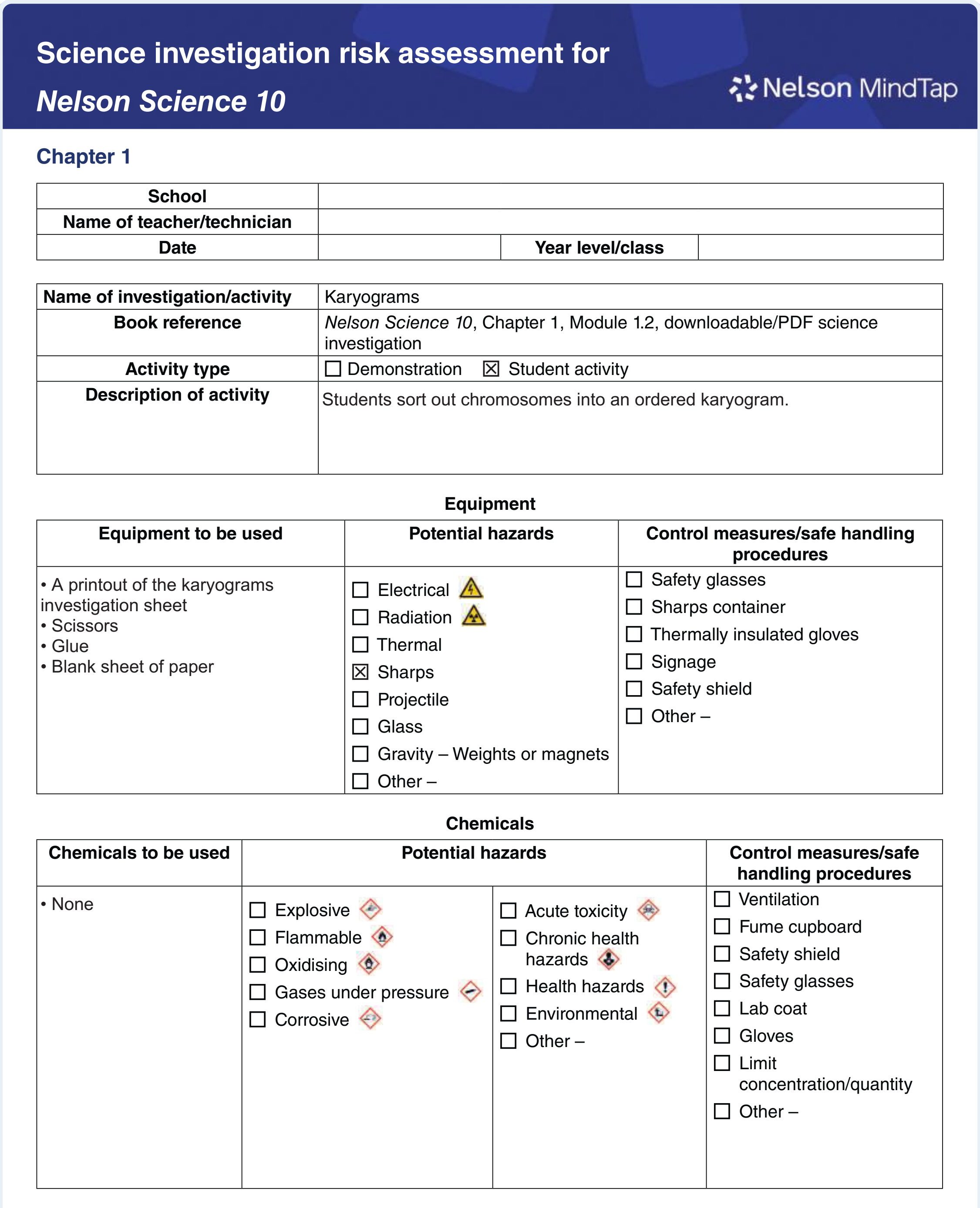
Essentially, any modifications to the methodology are done so to improve the reliability and accuracy of data and therefore the validity and reliability of the experiment. Although you will not need to show your full methodology, you will need to explain and justify any modifications and refinements in the final presentation of your experiment.

If the proposed experiment involves exploring knowledges of First Nations peoples, it is extremely important to understand all the cultural guidelines and protocols involved in conducting such research. As identified by the Queensland Curriculum and Assessment Authority (QCAA), research should 'follow a process of respectful relationship building and reciprocity between the researchers and individuals/communities involved in the research'.

Weblink
Ethical research with Aboriginal and Torres Strait Islander peoples

Health and safety

Health and safety are important considerations for practical exercises in all sciences. When undertaking your own practical research investigations, you must consider any relevant workplace health and safety guidelines. In Queensland, this includes the *Work Health and Safety Act 2011*. As the researcher, you must ensure safe laboratory practices when planning and conducting investigations by using risk assessments, supported by safety data sheets (SDSs), and accounting for risks. SDSs are important when you are using chemicals and specific equipment as part of your investigation. This includes both the use and the disposal of any potentially harmful materials used and produced in your experiment. Even if your research does not use chemicals but requires participants to take some actions that may cause harm, you will still need to complete a risk assessment form **(Figure DC.1.3)**. Your school is likely to have one of these documents for you to complete when you conduct your experiment. If you are unsure of either the ethical, environmental or health and safety aspects of your experiment, check with your teacher.



Science investigation risk assessment for
Nelson Science 10

Nelson MindTap

Chapter 1

School			
Name of teacher/technician			
Date		**Year level/class**	

Name of investigation/activity	Karyograms
Book reference	*Nelson Science 10*, Chapter 1, Module 1.2, downloadable/PDF science investigation
Activity type	☐ Demonstration ☒ Student activity
Description of activity	Students sort out chromosomes into an ordered karyogram.

Equipment

Equipment to be used	Potential hazards	Control measures/safe handling procedures
• A printout of the karyograms investigation sheet • Scissors • Glue • Blank sheet of paper	☐ Electrical ☐ Radiation ☐ Thermal ☒ Sharps ☐ Projectile ☐ Glass ☐ Gravity – Weights or magnets ☐ Other –	☐ Safety glasses ☐ Sharps container ☐ Thermally insulated gloves ☐ Signage ☐ Safety shield ☐ Other –

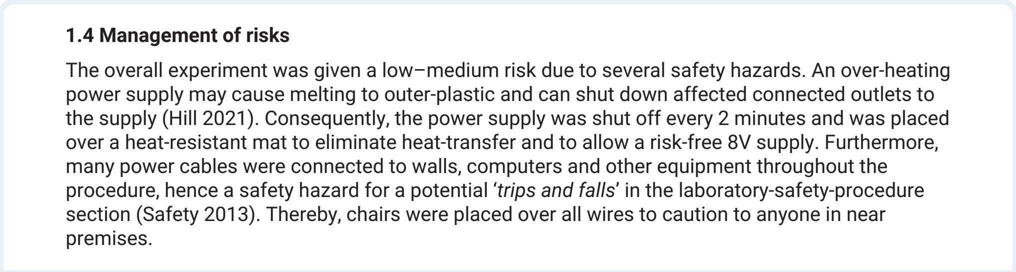
Chemicals

Chemicals to be used	Potential hazards		Control measures/safe handling procedures
• None	☐ Explosive ☐ Flammable ☐ Oxidising ☐ Gases under pressure ☐ Corrosive	☐ Acute toxicity ☐ Chronic health hazards ☐ Health hazards ☐ Environmental ☐ Other –	☐ Ventilation ☐ Fume cupboard ☐ Safety shield ☐ Safety glasses ☐ Lab coat ☐ Gloves ☐ Limit concentration/quantity ☐ Other –

FIGURE DC.1.3 A section of a risk assessment form

Not only do you need to identify the risks inherent in the experiment, you also need to state the steps to reduce or manage the risk. For example, the use of electrical equipment includes the risk of electrical shock and tripping on an electrical lead, which are managed by ensuring devices are turned off when not in use and kept away from sources of water and that movement around the device is limited while in use.

Any risks that you identify need to be highlighted in your experiment, including the steps to mitigate these risks **(Figure DC.1.4)**.



1.4 Management of risks

The overall experiment was given a low–medium risk due to several safety hazards. An over-heating power supply may cause melting to outer-plastic and can shut down affected connected outlets to the supply (Hill 2021). Consequently, the power supply was shut off every 2 minutes and was placed over a heat-resistant mat to eliminate heat-transfer and to allow a risk-free 8V supply. Furthermore, many power cables were connected to walls, computers and other equipment throughout the procedure, hence a safety hazard for a potential '*trips and falls*' in the laboratory-safety-procedure section (Safety 2013). Thereby, chairs were placed over all wires to caution to anyone in near premises.

FIGURE DC.1.4 An example of the inclusion of risks in an experiment

Apart from highlighting any potential dangers, another way to reduce the risk of injury and improve safety is to clearly outline the procedures in the experiment. This also includes the proper use of any materials involved in the experiment. This can be referred to as the standard operating procedures of an experiment.

Ethics

Ethics is a guiding framework that all research investigations must follow. Ethical concepts provide moral guidance for making decisions about the design and implementation of a research investigation. Examples of ethical concepts are shown in **Table DC.1.3**.

TABLE DC.1.3 Descriptions of different ethical concepts

Concept	Description
Beneficence	Having a commitment to do good (and minimise risk and harm)
Integrity	Acting with honesty and transparency
Justice	Ensuring fair distribution of benefits, risks, costs and resources
Non-maleficence	Avoiding harm or ensuring that potential harm is outweighed by benefits
Respect	Respecting individual differences and ensuring the right to autonomy and choice

You must apply your ethical understanding throughout your study of science, particularly for your own research.

Analysing data

primary data data collected directly by a person or group

The **primary data** collected in the experiment should be first organised into a raw data table. When constructing these tables, the independent variable is usually expressed in the first column and the dependent variables from the trials in the experiment are placed in the subsequent columns. For example, when measuring the time taken for a current to pass through a solution of different concentrations, the different concentrations (the independent variable) are presented in the first column, and the time measurements (dependent variable) are presented in subsequent columns **(Table DC.1.4)**. In addition to data, it is important that you record all aspects of your experiment, from initial planning to final evaluation, as this will assist you in constructing your final IA2 Student Experiment report.

TABLE DC.1.4 An example of a table of raw data from an experiment

Radius *r* (m) (±0.0001 m)	Area (m^2) (±4%)	Range s_x (m) (±0.01 m)				
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0.005	0.00008	11.11	13.10	10.12	11.20	10.50
0.010	0.00031	6.32	9.12	6.11	6.52	5.90
0.015	0.000 71	3.98	3.91	3.81	2.83	3.80

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As shown in the table, the units for each measurement are included in the column headings.

Once the data has been collected, the next step is to analyse it. As part of this, we need to make a judgement about the quality of the data in terms of:

- accuracy
- precision
- reliability
- validity
- uncertainties, sources and impacts of error.

It is important to note that each senior subject has different and specific forms of mathematical analysis. What is appropriate for one type of data in one subject may not be appropriate for another. For example, calculated means and uncertainties might be appropriate for a Chemistry or Physics experiment, but mean and standard deviations might be more appropriate for Psychology or Biology experimental data. The following information is a general overview of the types of analysis you could undertake, but it is best to check that the type of analysis you choose is appropriate for your data.

Accuracy and precision

In science, the **accuracy** of a measurement is how close it is to the true value of the quantity being measured. Even when the true value is unknown, scientists can rely on the best available **accepted value** to compare with the experimental measurement result to determine its accuracy. Often the accepted value is the theoretical value calculated for the measurement.

A way to help indicate the accuracy of a measurement is to calculate **percentage error**. Percentage error shows us how close the measured value is to the true or accepted value:

$$\text{Percentage error}\,(\%) = \frac{\text{measured value} - \text{true value}}{\text{true value}} \times \frac{100}{1}$$

accuracy the degree to which the result of a measurement, calculation or specification conforms to the correct value or a standard

accepted value the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

percentage error the difference between a measurement result and an accepted value, expressed as a percentage of the accepted value

WORKED EXAMPLE DC.1.1

A student used a ruler to measure the height of a 100 mL beaker. These beakers are known to have a height of 7.2 cm. The measured value was 6.8 cm.
Calculate the percentage error of the measurement.

ANSWER

1 Determine the measured and true values.

Measured value: 6.8 cm

True value: 7.2 cm

2 Substitute and calculate the percentage error.

$$\text{Percentage error (\%)} = \frac{6.8 - 7.2}{7.2} \times 100$$

$$= -5.6\%$$

This suggests that the measurement is slightly lower than the true value.

A low percentage error indicates a high degree or accuracy, whereas a high percentage error indicates a low degree of accuracy.

precision the closeness of several independent measurements of the same quantity to each other

In contrast, **precision** describes how close a set of measured values are to each other. For single measurements, precision is about the level of detail given by the measurement. For example, 1.3 g (two significant figures) is less precise than 1.312 g (four significant figures). As you can see, some measuring instruments are more precise than others. This can be due to the:

- technology used in the device
- quality of components
- resolution
- scale.

The ability to measure precise results is important because it can affect the reliability and uncertainty of data. Uncertainty will be discussed in further detail later in this chapter. It is important to note that measurements that are precise are not necessarily accurate (Figure DC.1.5).

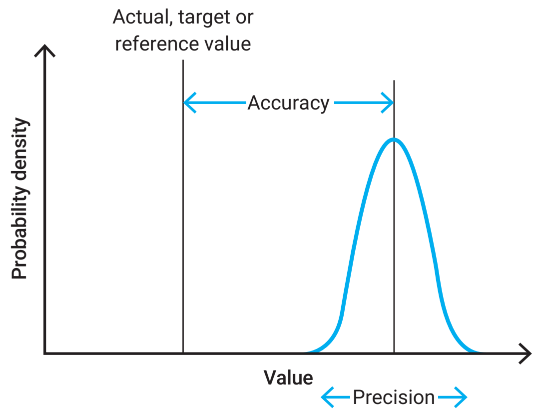

FIGURE DC.1.5 A graph showing the difference between accuracy and precision

Figure DC.1.6 helps further distinguish between accuracy and precision. In parts a and c, the individual indication values cluster closely around the mean, whereas parts b and d show imprecise measurement results because the individual measured values spread significantly around the mean.

For example, for an individual experiencing a fever, having precise measurements of body temperatures of 32.1, 33.2 and 32.0°C does not mean that this is an accurate measure of their body temperature. We know this because humans have a core body temperature of approximately 37.0°C and fever causes body temperature to increase, not decrease.

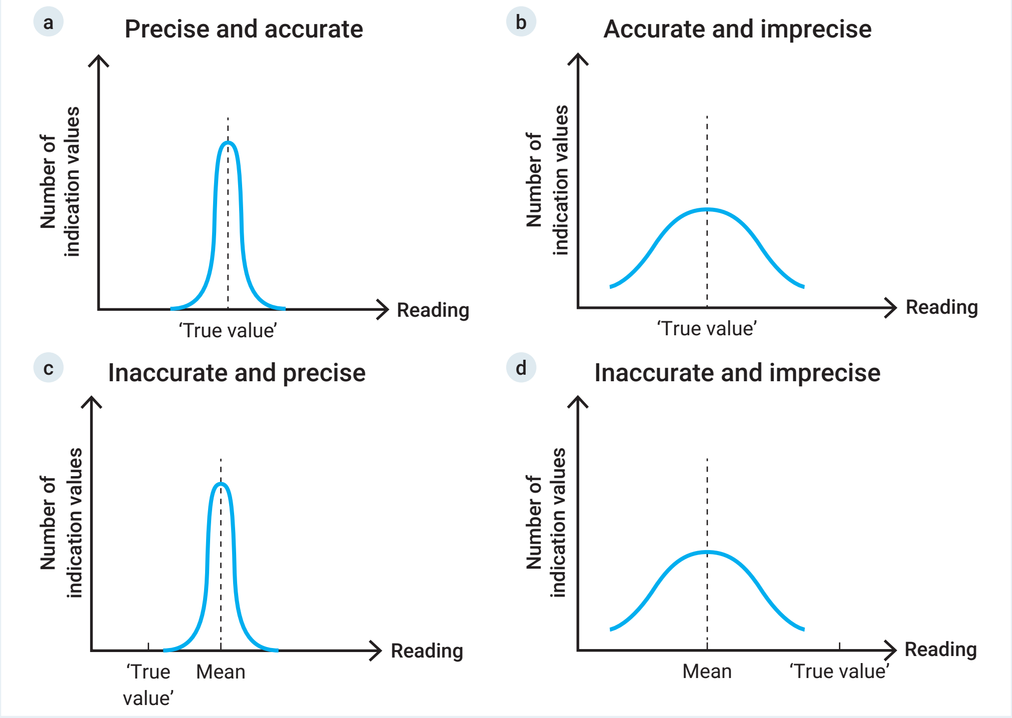

FIGURE DC.1.6 In a plot of measured values versus reading, results can be: (**a**) accurate and precise, (**b**) accurate and imprecise, (**c**) inaccurate and precise or (**d**) inaccurate and imprecise.

To improve the accuracy of measured values, you could:

- conduct multiple trials and average the results
- ensure that all variables except for the independent variable are controlled (also referred to as fair testing)
- ensure that the measuring tools used in the experiment are appropriate for what is being measured.

This helps to minimise the impact of any errors in the experiment that could affect the accuracy of the measured results. Errors will be discussed in more detail in a later section.

Reliability

If an experiment is repeated, you would expect to obtain very similar results each time. When this happens, we say that the experimental results are reliable. However, this is not always the case because errors can affect the data collected. **Reliability** can be measured with uncertainty and standard deviation, concepts that will be described in more detail in a later section. Reliability of results can be improved by carefully controlling all variables apart from the independent variable. We will discuss other factors affecting reliability later in this section.

reliability the extent to which the results of assessments are consistent, replicable and free from error

Validity

The quality of the data affects the **validity** of an experiment. We describe data as being valid if the result is due to the independent variable only and can answer the research question. In our example of measuring the effect of the material on current, if any variabilities in voltage or length are not properly controlled they can also affect the current. As a result, we cannot confidently conclude that the results measured from the experiment are due to the changes in material only. These types of variables are known as an **extraneous variable** and can affect the relationship between the dependent and independent variables. This is why it is important to ensure that all variables other than the independent variable are controlled.

validity the extent to which the experiment measures what it is intended to measure

extraneous variable any variable that is not directly related to the experiment but could affect the results of the experiment

error the difference between a measured value and true value

Apart from extraneous variables, **errors** can also affect the results of an experiment. The two main types of errors are random and systematic errors.

Errors

random error a variation that affects a measurement in a random way so that successive measured values may reflect small changes from each other

mean the average value of a set of values

Random errors are unpredictable variations that can occur during measurement. When taking multiple readings of the same thing, random measurement errors cause small variations so that you end up recording a spread of readings. These errors affect the precision of a measurement and can be caused by limitations of measuring instruments. The effect of random errors can be reduced by making more or repeated measurements and calculating the **mean** (or average). To calculate the mean:

$$\text{Mean} = \frac{\text{sum of measured values}}{\text{total number of measurements taken}}$$

KEY FORMULA

Mean

$$\text{Mean} = \frac{\text{sum of measured values}}{\text{total number of measurements taken}}$$

The mean value is then regarded as the most likely or best estimate of the true value; however, we cannot be certain that it is the true value.

While random errors affect the precision of data, **systematic errors** affect the accuracy of a measurement. These errors cause the readings to differ from the true value by a consistent amount in the same direction. This can occur when measuring instruments are not properly calibrated and will therefore differ from the true value by the same amount. Systematic errors can also be caused by observational error if there is a consistent distortion in the way we view things that causes errors that are the same every time. For example, a tall person may read a thermometer from a higher viewpoint and record a lower measure than the true value every time. To minimise the impact of systematic errors, it is important to know how to use measuring tools properly and to calibrate them before use.

systematic error an error that acts to give a consistent offset in data; for example, consistently above or consistently below

Figure DC.1.7 highlights the differences between random and systematic errors.

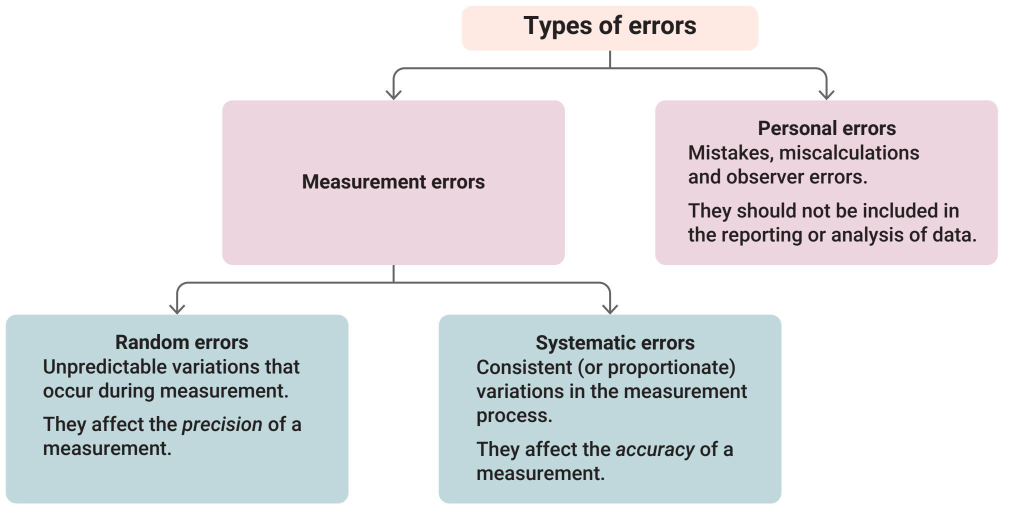

FIGURE DC.1.7 The key differences between random and systematic errors

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

Uncertainty

While systematic errors can be accounted for by subtracting or adding the value of the error, random errors contribute to the **uncertainty** of a measurement. This reflects the lack of exact knowledge of the true value of the measurement. All measurements are subject to uncertainty because there are many sources of variation. For example, **instrumental uncertainty** in measuring tools can result in variability and imprecision of results due to factors such as sensitivity, calibration and resolution. To minimise the impact of instrumental uncertainty, it is important to calibrate tools, ensure that the appropriate tools and techniques are used and consider any limitations when designing the experiment. Uncertainty can also occur because of the way the person taking the reading interacts with the tool.

instrumental uncertainty the inherent limitations and potential errors associated with the measuring instruments or tools used in scientific experiments or observations

Errors and uncertainties can sometimes be quantified. We can estimate the uncertainty of a measurement (usually expressed as ± a certain value). This is known as **absolute uncertainty**.

absolute uncertainty the magnitude of the difference between the observed/measured value and the true value

Absolute uncertainty of repeated measurements

Most experiments require you to take multiple measurements. As mentioned above, doing so and averaging the results can help to reduce the effect of random errors. Imagine you take multiple measurements of your body temperature. The values are 35.6, 36.1, 35.9 and 36.4°C. The difference between the maximum and minimum values is called the **range**. The absolute uncertainty is half of the range:

range the difference between the maximum and minimum values of a measured confidence interval

$$\begin{aligned}\text{Absolute uncertainty} &= \pm\frac{\text{maximum} - \text{minimum}}{2}\\ &= \pm\frac{36.4 - 35.6}{2}\\ &= \pm 0.4^\circ\text{C}\end{aligned}$$

The measurement result would be the mean of the values:

$$\begin{aligned}\text{Mean} &= \frac{35.6 + 36.1 + 35.9 + 36.4}{4}\\ &= 36.0^\circ\text{C}\end{aligned}$$

KEY FORMULA

Absolute uncertainty

$$\text{Absolute uncertainty} = \pm\frac{\text{maximum} - \text{minimum}}{2}$$

The reported value includes both the mean and the absolute uncertainty. In this example, the reported value would be 36.0±0.4°C. In other words, the actual value could lie anywhere between 35.6°C and 36.4°C.

Absolute uncertainty of single measurements

For analogue devices, the uncertainty is normally determined as half of the smallest division on the scale. For example, a glass thermometer with graduations of 1°C has an uncertainty of ±0.5°C.

With digital devices, the limit of reading is normally defined as the smallest division. For example, a digital thermometer that measures in 1°C has an uncertainty of ±1°C. One limitation of this calculation is that it does not indicate the direction of the error. The absolute uncertainty of this digital reading is defined as $\pm\frac{1}{2}$ limit of reading, in this case $\pm\frac{1}{2}$ of 1°C of ±0.5°C.

Percentage uncertainty

Absolute uncertainty can be used to calculate **percentage uncertainty**. Percentage uncertainty is calculated relative to the measured quantity, and is calculated by:

percentage uncertainty a measure of the uncertainty of a measurement compared with the size of the measurement, given as a percentage

$$\text{Percentage uncertainty}(\%) = \frac{\text{absolute uncertainty}}{\text{measured value}} \times \frac{100}{1}$$

A lower percentage uncertainty indicates a more precise measurement, whereas a high percentage uncertainty indicates that the measurement is less precise as due to greater variability.

KEY FORMULA

Percentage uncertainty

$$\text{Percentage uncertainty}(\%) = \frac{\text{absolute uncertainty}}{\text{measured value}} \times \frac{100}{1}$$

Once data has been processed in this way, a table can be presented that also includes these measurements of uncertainty **(Table DC.1.5)**.

TABLE DC.1.5 An example of a summary table showing measurements of uncertainty

Radius r (m) (±0.0001 m)	Area (m^2) (±4%)	Range s_x (m) (±0.01 m)							
		Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Absolute uncertainty of the mean (m) (± x)	Percentage uncertainty of the mean (%)
0.005	0.00008	11.11	13.10	10.12	11.20	10.50	10.73	0.54	5
0.010	0.00031	6.32	9.12	6.11	6.52	5.90	6.21	0.31	5
0.015	0.000 71	3.98	3.91	3.81	2.83	3.80	3.88	0.09	2.3

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Significant figures

Once uncertainty has been calculated, results need to be quoted with the appropriate significant figures.

The following steps can be used to determine the significant figures of a single value.

1. Reading a value from left to right, start counting significant figures at the first non-zero number. For example, for a measurement of 0.024 307 g, the first significant figure is 2. In this case, the first two zeros are not considered significant.
2. Every number after the first significant figure is deemed as significant, including any zeros. In 0.024 307 g, there are five significant figures.

These rules apply even when numbers are expressed in scientific notation. If the above example was expressed as 2.4307×10^{-2} g, then the first significant figure is still 2 and every number thereafter is considered significant.

WORKED EXAMPLE DC.1.2

A student measured the mass of a sample to be 0.0103 g. Determine the number of significant figures in this value.

ANSWER

1 **Determine the first significant figure.**
Reading from left to right, the first significant number is the first non-zero number. According to this rule, the first significant figure in this value is 1.

2 **Count the number of figures in the value that are considered significant.**
After the first significant figure (1), there are two significant figures 0 and 3. As such, there are 3 significant figures in this value.
Written in scientific notation, this value is 1.03×10^{-2} g.

When measurements are used to calculate a final value, the numbers and operations to arrive at the final answer contribute to the significant figures of the final answer.

1. For addition and subtraction, the final answer needs to be expressed to the least number of decimal places. For example, when adding the length of two pencils of 10.5 and 9.42 cm, the final answer should be expressed to one decimal place, 19.9 cm.

2. For multiplication and division, the final answer needs to be expressed to the least number of significant figures. For example, if we needed to calculate the percentage of sugar in a 50.0 g sample, given that there is 2.4 g of sugar present:

$$\text{Percentage} = \frac{2.4}{50.0}$$
$$= 4.8\% \text{ sugar}$$

Because 2.4 has the least number of significant figures (two), the answer is expressed to two significant figures. For multistep questions, retain the appropriate number of significant figures at each step, where the final answer should be expressed based on the final step. In other words, the final answer can be no more precise than the least precise measurement.

WORKED EXAMPLE DC.1.3

A student performed the following calculation using experimental data:

$$\frac{527.11 - 232.3}{5.4}$$

Determine the number of significant figures that the answer should be expressed in.

ANSWER

1 **Identify the order of the steps involved in this calculation.**
The calculation would be performed in the following order:
  - **i** 527.11 – 232.3
  - **ii** Answer from step **i** ÷ 5.4

2 **Identify the number of significant figures in each step.**
  - **i** 4. Since it is a subtraction calculation, we need to express the answer to the least number of decimal places.
  - **ii** 2. Since it is a division calculation, we need to express the answer based on the number with the least significant figures (5.4).

3 **Determine the number of significant figures for the final answer.**
Two

Graphs

Although tables can be an effective way to collect and record data, it is difficult to visualise any trends or relationships between the independent and dependent variables. Presenting data in graphical form makes it easier to identify if any trends exist between the variables.

Many different types of graphs can be used to represent data; for example, column graphs, pie charts, scatterplots and line graphs. Choosing the right graph depends on the nature of the data collected and what you are trying to show. For graphs that involve an *x*-axis and a *y*-axis, the independent variable is represented by the *x*-axis and the dependent variable is represented by the *y*-axis **(Figure DC.1.8)**.

It is also important to choose an appropriate scale when drawing graphs because it helps to ensure that the data is represented fairly and in a way that can be easily interpreted. It also avoids misleading representations that

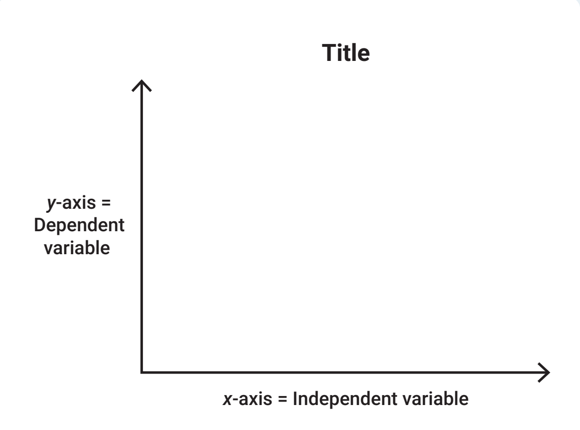


FIGURE DC.1.8 The positive quadrant of Cartesian plane showing the variables represented on the *x*-axis and *y*-axis imply inaccurate relationships between data. All graphs need to have a title that outlines the information being presented and labelling of axes, including units.

Pie charts

Pie charts are best used to show parts of a whole and the percentage composition of each different category. For example, pie charts can be used to show the composition of a mixture of air – nitrogen, oxygen and other gases – and the percentage of each (Figure DC.1.9).

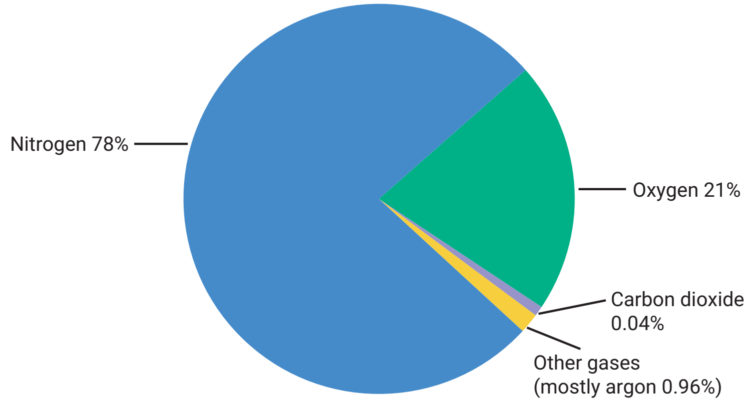


FIGURE DC.1.9 A pie graph representing the composition of air

A limitation with pie charts is that they become visually cluttered when there are many different categories.

Column graphs

Column graphs are useful when comparing quantities or different categories of groups (Figure DC.1.10).

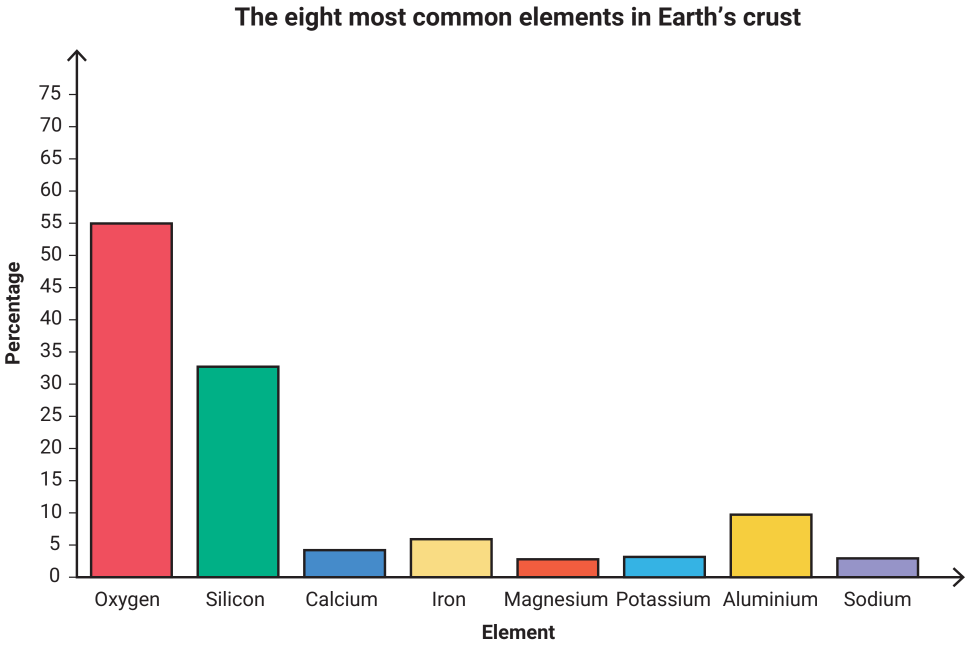


FIGURE DC.1.10 A column graph showing the differences in mineral composition of Earth's crust

These types of graphs are preferred for comparing categories when order or time is important to show changes over time, or when comparing the differences between groups.

Line graphs

Line graphs are ideal when showing trends over time for continuous data, particularly when comparing multiple series over the same period. In line graphs, each data point is connected to the next and the relationship between the two variables can be represented as the equation:

$$y = mx + c$$

where: m = the gradient

c = the y intercept.

For example, the calibration curve measuring the absorbance of light based on concentration of a solution can be represented by a linear graph as shown in **Figure DC.1.11**.

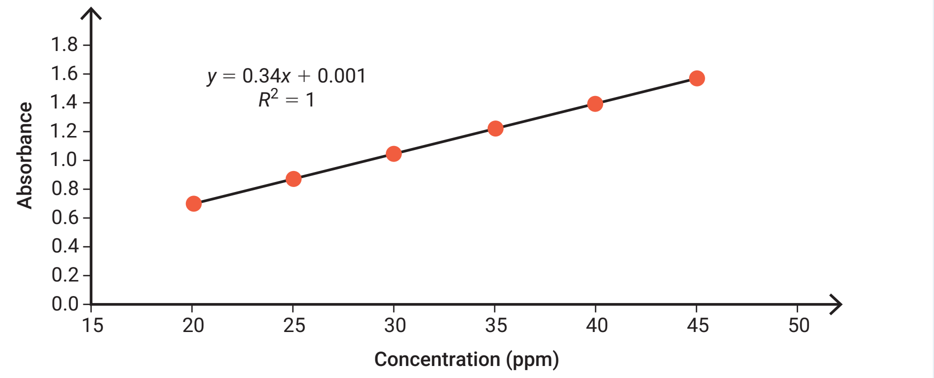


FIGURE DC.1.11 A line graph showing absorbance at different concentrations

The gradient is a useful piece of information that helps to describe the relationship between the independent and dependent variables. For linear relationships, the gradient of the slope helps to identify the nature of the relationship between the independent and dependent variables. To calculate the gradient of a linear graph, m, where the equation is $y = mx + c$:

$$\text{Gradient } (m) = \frac{\Delta y}{\Delta x}$$

Determining the gradient in this way only requires two data points, where the difference in the y values is divided by the x values of the same two points. Depending on the value of the gradient, a:

- positive gradient **(Figure DC.1.12a)** indicates that as the x value (independent variable) increases, so does the y value (dependent variable)
- negative gradient **(Figure DC.1.12b)** indicates that as the x value (independent variable) increases, the y value (dependent variable) decreases
- gradient of zero **(Figure DC.1.12c)** indicates that as the x value (independent variable) increases, there is no change in the y value (dependent variable). As such, there is a constant relationship between the two variables.

Analysing the gradient for non-linear relationships is a bit more complicated and requires us to calculate the gradient of different tangents at specific points along the graph and compare the changes.

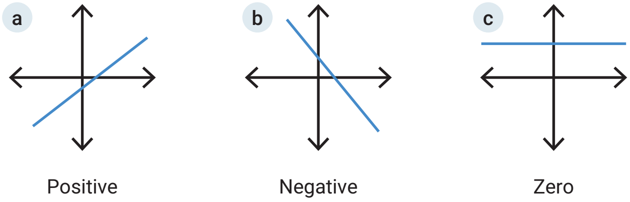


FIGURE DC.1.12 Linear graphs with (**a**) a positive gradient, (**b**) a negative gradient and (**c**) zero gradient

Scatterplots

Scatterplots are similar to linear graphs in that they show individual data points, highlighting the relationship between the independent and dependent variables. However, unlike line graphs, the data points in scatterplots are not connected **(Figure DC.1.13)**.

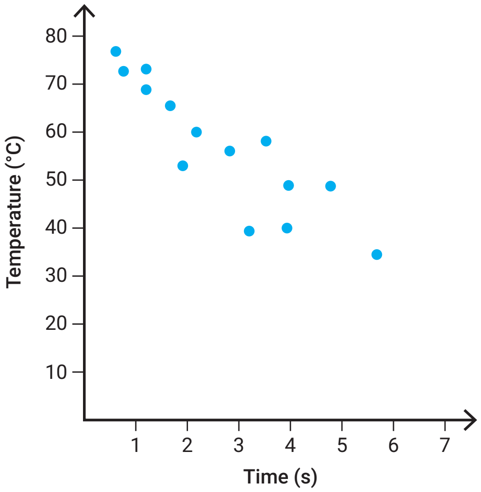


FIGURE DC.1.13 A scatterplot of changes in temperature over time

trendline a line that represents the general direction or pattern of data points

maximum trendline a trendline with the greatest gradient that fits within the data within the uncertainty values

minimum trendline a trendline with the smallest gradient that fits within the data within the uncertainty values

Although the points are not connected, organisation of the data points relative to each other in these graphs can identify a relationship between the variables. **Trendlines** can be drawn through or near the datapoints to help make the relationship between the independent and dependent variable more visible **(Figure DC.1.14)** while also showing the strength of this relationship.

Although it is possible to draw trendlines manually, it is more accurate to use software to draw trendlines. When manually adding trendlines, the line should be drawn so that it minimises the distance between the line and the data points.

If a trend does exist, we can often easily identify whether it is positive (positive correlation) or negative (negative correlation). In a positive trend, the dependent variable increases as the independent variable increases, whereas in a negative trend, the dependent variable decreases as the independent variable increases **(Figure DC.1.15)**.

Maximum and **minimum trendlines** are visual representations of the strength of the relationship between the variables **(Figure DC.1.16)**. A wider range between the two suggests a greater variability of uncertainty in the data, whereas a narrow range suggests a lower variability in the measured values. Analysing maximum and minimum trendlines together can help us predict the potential range of outcomes. For example, using trendlines to forecast temperature changes as a result of emissions can help us predict and prepare for worst-case scenarios. Maximum and minimum trendlines can also help identify potential errors in the experiment. Values that fall

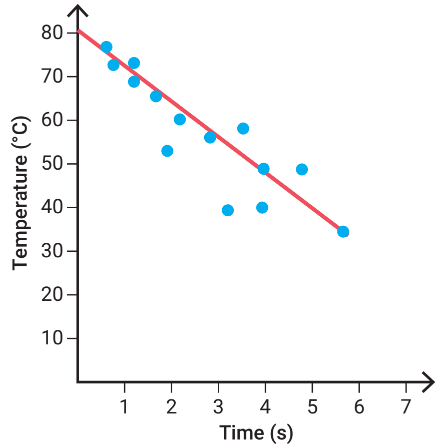
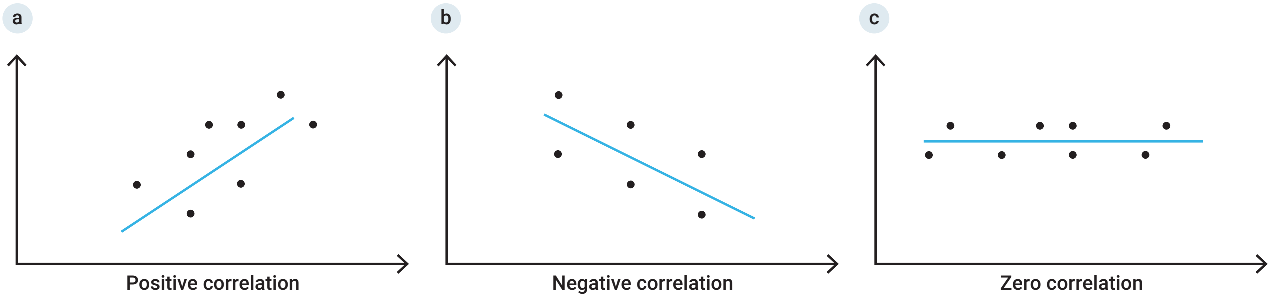


FIGURE DC.1.14 A scatterplot of changes in temperature over time, including a trendline (red)



Positive correlation

Negative correlation

Zero correlation

FIGURE DC.1.15 Scatterplots with trendlines showing (a) a positive trend, (b) a negative trend and (c) zero trend

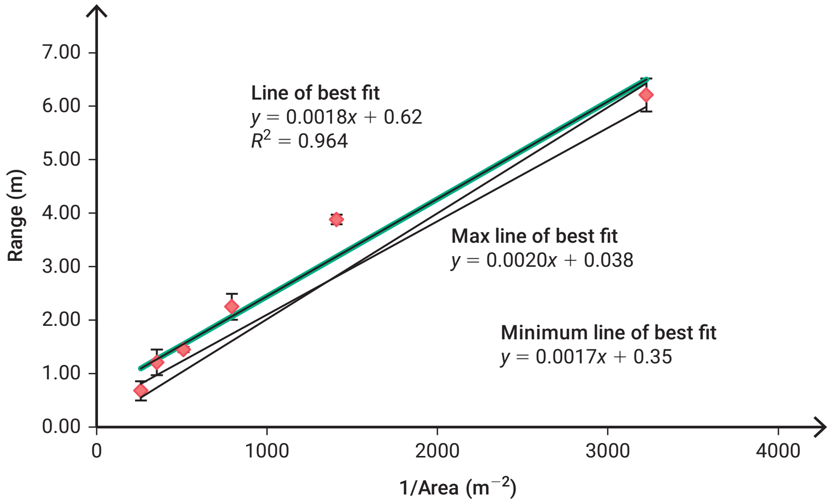


FIGURE DC.1.16 An example of a scatterplot that includes a maximum and minimum trendline

significantly outside the area between the maximum and minimum trendlines suggest an outlier that may have been due to a random error.

Greater variability in certain areas of the graph may also suggest error. For example, when measuring the rate of a reaction at different temperatures, it may be evident that there is a large variability in the rate of the reaction at higher temperatures. This could imply an error in temperature control at higher temperatures.

A common strategy used is to draw a:

- maximum trendline involves drawing a line from the bottom of the error bar of the starting data point to the top of the error bar of the last data point
- minimum trendline involves drawing a line from the top of the error bar of the starting data point to the bottom of the error bar of the last data point.

Error bars are explained in more detail later in this chapter.

line of best fit a straight line through data points in a graph that best expresses the relationship shown in a scatterplot

Although trendlines are more general and can be used for different types of graphs with linear and non-linear data, the **line of best fit** is better suited for linear relationships. Since the line of best fit is used for linear relationships, the data points can be used to establish the relationship expressed as $y = mx + c$.

Although this can be done manually, the calculations can become complex and therefore it is often easier (and more accurate) to use software such as Excel, which can both draw the graph and establish the corresponding equation for the line of best fit. Lines of best fit can be used to predict values not measured in the experiment (extrapolation) or estimate values within the range of data collected (interpolation) that was not directly measured **(Figure DC.1.17)**.

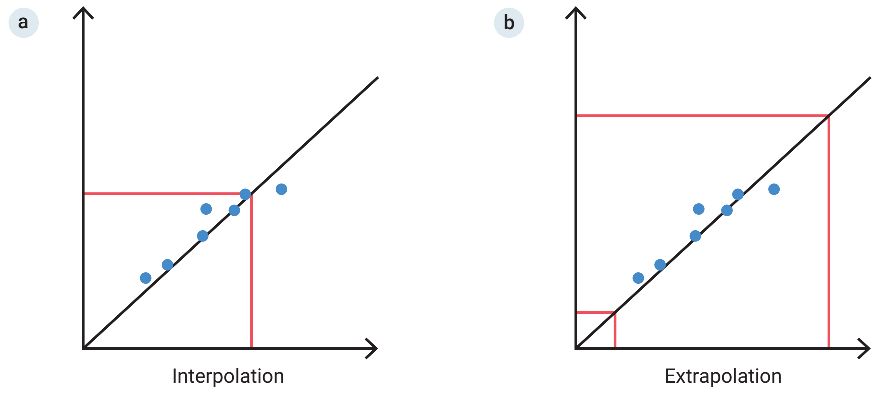


FIGURE DC.1.17 Using a line of best fit to (a) interpolate a data point within the measured values and (b) extrapolate a data point outside of the measured values

Drawing the line of best fit involves specific statistical models such as linear regression and is often accompanied by a quantifiable level of certainty, known as the R-squared value (R^2) (also referred to as the coefficient of determination). Regression analysis provides an equation for a graph so that predictions can be made about the data.

Linear regression is a basic and commonly used type of predictive analysis. The overall idea of regression is to examine two things:

1. Does a set of predictor variables do a good job at predicting an outcome (dependent) variable?
2. Which variables in particular are significant predictors of the outcome variable?

Weblink
Linear regression and Excel

These regression estimates are used to explain the relationship between one dependent variable and one or more independent variables.

This can be calculated in Excel.

Before discussing R^2 values, we must first understand the significance of R values.

Pearson correlation coefficient (R) a statistical measure that quantifies the direction and strength of a relationship between two variables

A method that can be used to quantitatively describe the direction and strength of a linear relationship between the independent and dependent variables is the **Pearson correlation coefficient (R)**, which measures the correlation between two sets of data. R values can be between –1 and 1, where:

- $R = 0$ suggests no correlation
- $R = 1$ suggests a strong positive correlation
- $R = -1$ suggests a strong negative correlation.

The formula to calculate the R value is complicated and therefore it is much easier to use software to help with this calculation. Programs such as Excel have options to calculating R when plotting the graph.

Squaring the R gives us the R^2 value. This shows the linear relationship between two sets of data. In simple terms, it answers the question, 'Can I draw a line graph to represent the data?' Calculating this coefficient does not allow you to fit a line to your data (use a regression analysis for this). However, the value is not able to tell the difference between the independent and dependent variables; for example, investigating a high-kilojoule diet causing diabetes might give a correlation of 0.8. However, you could also get the same result with the variables switched around – diabetes causes a high-kilojoule diet. Therefore, as a researcher you must be aware of the data you are putting in and note the difference between correlation and causation:

- $R^2 > 0.8 =$ *strong* correlation
- $R^2 < 0.5 =$ *weak* correlation.

In physics specifically, we often refer to the R^2 coefficient of determination when graphing linear relationships and use a threshold of 0.95 to denote a very strong correlation that indicates a high level of precision in the graph modelling the relationship.

Non-linear graphs

Not all trends show a linear pattern. For example, graphs showing the acceleration of an object by plotting displacement over time are curved. In such cases where the relationship is not linear, manipulation of the variables is required. This may be squaring a variable, where $s \propto t^2$, or deriving an inverse square, where $F \propto \frac{1}{d^2}$ to produce a linear relationship.

The simplest way to identify whether a relationship between two variables is linear or non-linear is to plot the data points on a graph to identify the overall trend. Gradient analysis can be conducted on non-linear graphs by calculating the instantaneous gradient of the tangent line at each data point and comparing the extent of the changes between each point. The tangent line is a straight line that 'touches' the data point and shares the same gradient as the curve at the given data point **(Figure DC.1.18)**.

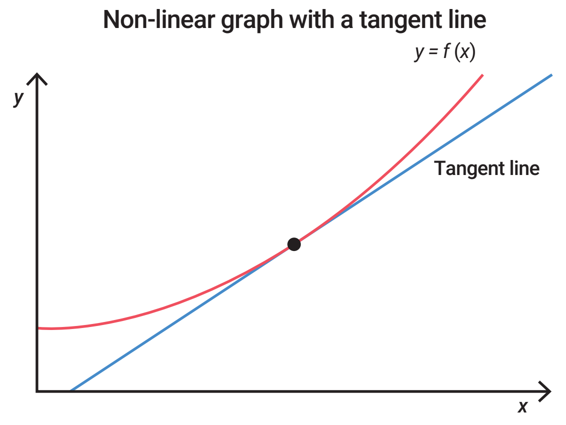
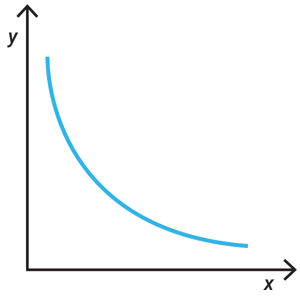
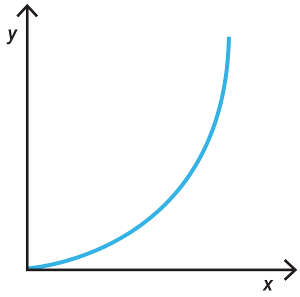
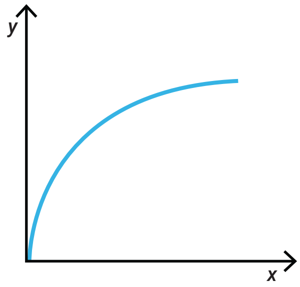
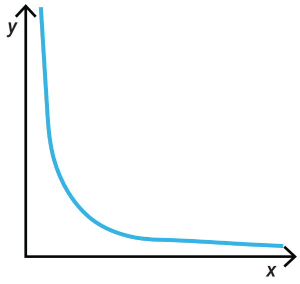


FIGURE DC.1.18 An example of a tangent touching a data point on a non-linear graph

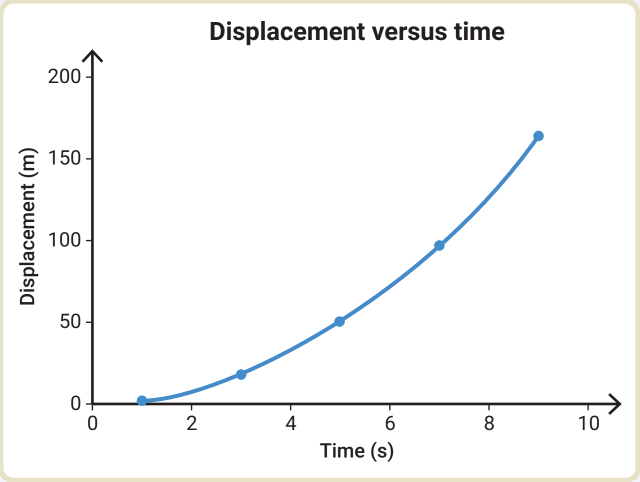
However, there are methods to linearise non-linear relationships. The technique to do this depends on the shape (or the relationship) of the initial graph **(Table DC.1.6)**.

TABLE DC.1.6 Different methods used to linearise data

Graph shape	Relationship	How to linearise the data
	There is an inverse relationship between the variables where y is inversely proportional to x.	Graph y as a function of $\frac{1}{x}$.
	There is a proportional relationship between the variables where y is the square of x (or x^2).	Graph y as a function of x^2 (rather than just x).
	There is a proportional relationship between the variables where the square of $y(y^2)$ is proportional to x.	Graph y^2 (rather than just y) as a function of x.
	There is a proportional relationship between the variables where y is proportional to the inverse of x^2.	Graph y as a function of $\frac{1}{x^2}$.

WORKED EXAMPLE DC.1.4

A student conducted an experiment measuring the displacement (m) of an object over time. The data and graph are shown below.



Time (s)	Displacement (m)
1.05	2
2.95	18
5.10	50
6.95	97
9.05	164

Linearise the data by drawing a new graph with manipulated variables to determine the relationship.

ANSWER

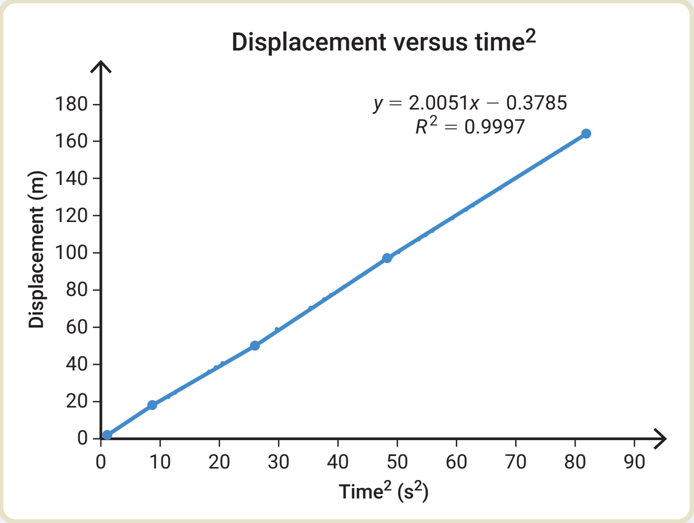
1 Use Table DC.1.6 to identify the type of graph presented.
The shape of the graph shows a relationship where *y* is proportional to the square of *x*.

2 Identify the method that can be used to linearise this data.
Graph *y* as a function of x^2.

3 Calculate the new *x* values.

Time^2 (s^2)
1.1025
8.7025
26.010
48.3025
81.9025

4 Draw the new graph.



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Error bars

Error bars

To illustrate uncertainty, your graphs should incorporate error bars. These extend from data points to demonstrate the uncertainty of the measurement **(Figure DC.1.19)**.

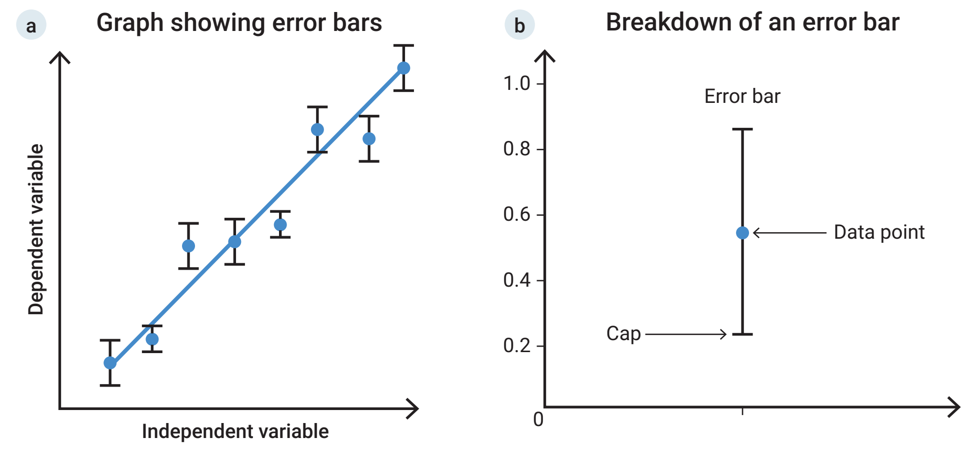


FIGURE DC.1.19 (**a**) A scatterplot that has incorporated error bars. (**b**) The structure of an error bar.

The upper and lower limits of the error bars can be determined by using descriptive statistics such as standard deviation or absolute uncertainty. (Note: There are different types error bars; e.g. standard deviation, confidence intervals, uncertainty.) To draw error bars on graphs:

1. Identify the data point.
2. Calculate the uncertainty of the mean for the data point. This will determine the upper and lower limits of the error bar.
3. Use the values from step 2 to identify the maximum and minimum value for the data point. Use this to draw the error bar.

Graphing applications such as Excel have an option to include error bars in graphs. This is a faster and often more accurate method to generating graphs with error bars.

Weblink
Drawing graphs with error bars

A larger error bar indicates that the values are spread out and suggests greater uncertainty than a smaller error bar which signals that the measurements are clustered around the data point. Error bars can be drawn for different types of graphs **(Figure DC.1.20)**, although, in Physics, data is typically described using scatterplots.

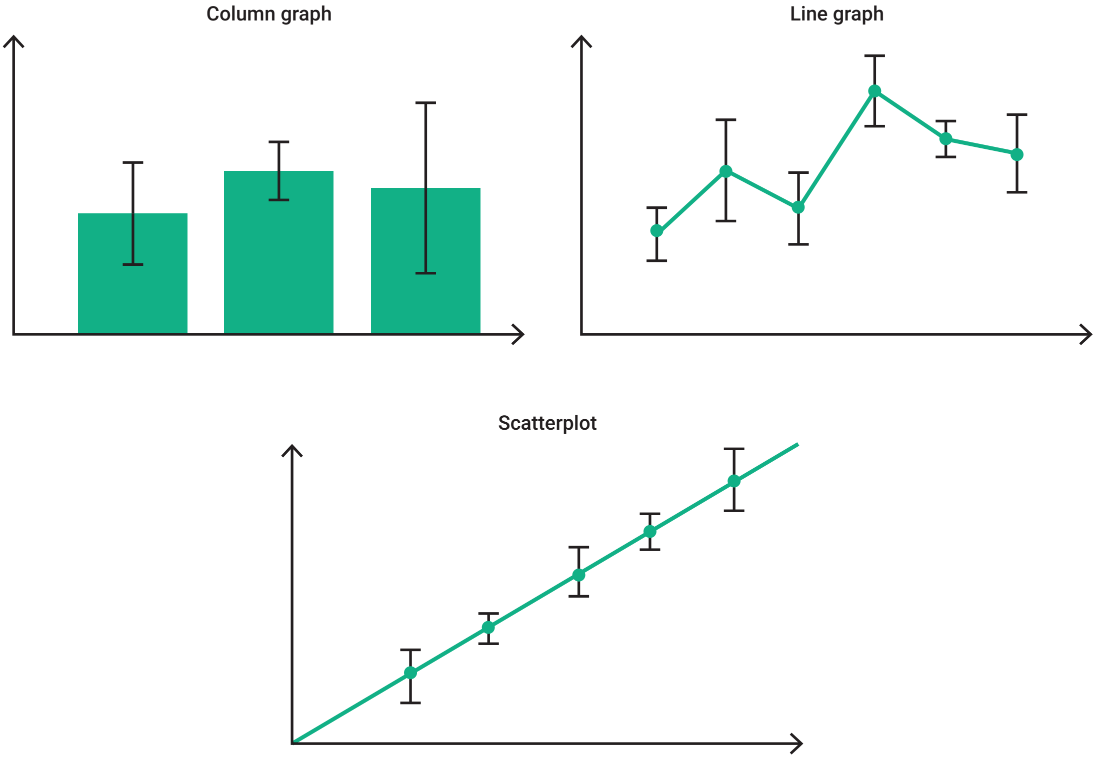


FIGURE DC.1.20 Column graphs, line graphs and scatterplots that include error bars

Other representations of data

Scientific drawings

Textbooks are full of scientific drawings that represent structures, organisms and processes. These drawings are highly detailed, accurate and clear. For example, consider the representation of the lattice structure of metals showing the presence of delocalised electrons **(Figure DC.1.21)**.

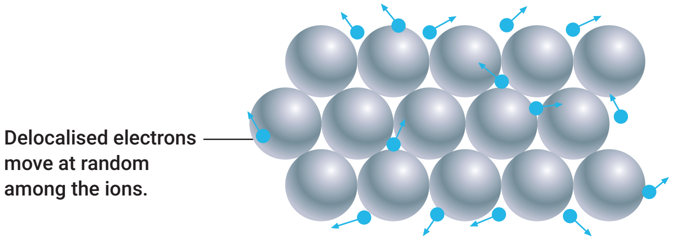


FIGURE DC.1.21 The lattice structure of metals allows delocalised electrons the ability to flow freely throughout the metal.

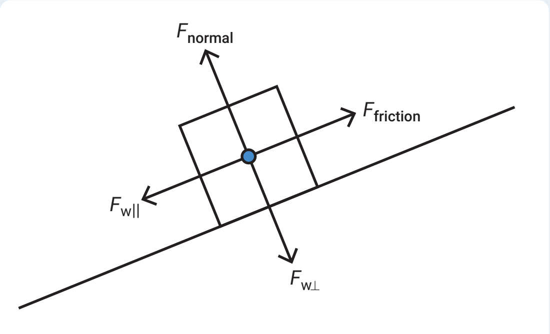


FIGURE DC.1.22 A free-body force diagram for an object at rest on an inclined plane

Scientific drawings contain labels and annotations and are also drawn to scale to show the relative proportions of the forces applied, as seen by the free-body force diagram in **Figure DC.1.22**.

Identifying trends and relationships

The purpose of an experiment is to collect relevant data that can be analysed and used to understand the relationship between the independent and dependent variables.

Analysing graphs

When analysing graphs, it is important to consider all aspects presented in the graph. Consider the graph shown in **Figure DC.1.23**. What we tend to notice first is the overall trend in the data. The graph shows a positive trend where the voltage increases as the current increases. We determine this visually based on the shape of the line; however, it is possible to use the positive gradient for the line. The large R^2 value of 0.996 (very close to 1) suggests high correlation between both variables.

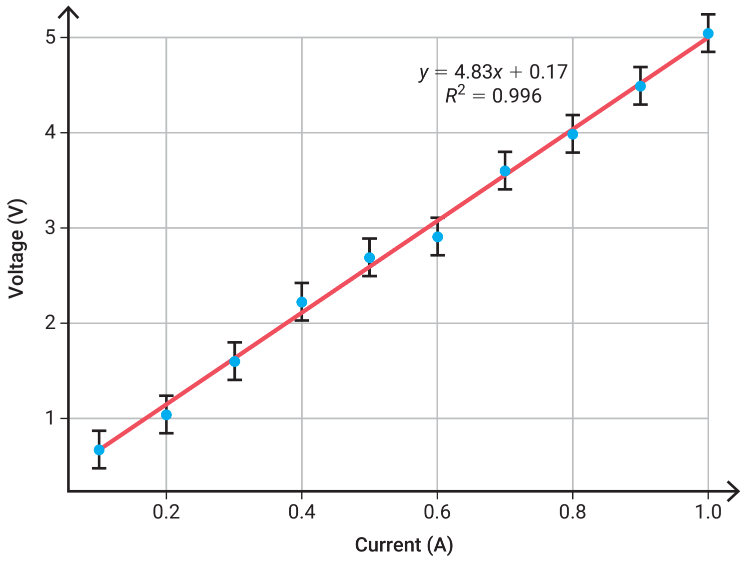


FIGURE DC.1.23 A graph showing the relationship between voltage across and current through a resistor

The graph in Figure DC.1.23 also contains error bars showing the uncertainty in each measurement. This provides an indication of the precision and effect of random error in each measured value.

Although not as easy to visually identify as graphs, raw data tables can also be interpreted to identify the relationship between two variables; for example, the raw data table for the graph in Figure DC.1.23 **(Table DC.1.7)**.

TABLE DC.1.7 A data table for the experiment testing the relationship between different materials and the impact on the voltage across and current through the resistor

Current (A)	Trial 1 (V)	Trial 2 (V)	Trial 3 (V)	Mean voltage (V)	Absolute uncertainty (V)	Percentage error (%)
0.1	0.48	0.52	0.49	0.50	±0.2	40.0
0.2	1.08	1.05	1.12	1.08	±0.2	18.5
0.3	1.50	1.47	1.53	1.50	±0.2	13.3
0.4	2.01	1.97	2.04	2.01	±0.2	10.0
0.5	2.48	2.54	2.49	2.50	±0.2	8.0
0.6	3.05	3.00	3.04	3.03	±0.2	6.6
0.7	3.52	3.47	3.55	3.51	±0.2	5.7
0.8	3.99	4.04	4.01	4.01	±0.2	5.0
0.9	4.56	4.52	4.49	4.52	±0.2	4.4
1.0	5.01	5.04	4.99	5.01	±0.2	4.0

The percentage error in the lower current values is relatively high. This suggests significant uncertainty of the measured value, making them less reliable. However, the percentage error decreases as the current increases, indicating that the results are more reliable.

Interpreting and evaluating evidence

To demonstrate that you have a robust understanding of the results of the experiment, it is important to identify the relationship between the variables and comment on the reliability and validity of the relationships, using your calculations of errors and uncertainty. Although it sounds counterintuitive, highlighting sources of error in your experiment and describing its effect on your results strengthens your argument. It also allows you to identify any limitations and offer suggestions for improvements and/or extensions to your experiment. By doing so, you are demonstrating an ability to critically analyse data, which helps to develop well-informed arguments.

Apart from reiterating the trends shown in the data, you need to scientifically justify the argument. This is done by referencing theory and previous studies to explain the phenomena being shown through the data. For example, in an experiment measuring the effect of current on force in a conductor, we would want to refer to the theory relating to moving charges inside a magnetic field and use that to justify the arguments made from the trends identified from the data.

The culmination of this allows us to draw well-informed conclusions that help to answer the research question.

An annotated student experiment

LEARNING CHECK DC.1

DESCRIBING

1 **Describe** the difference between:
   - **a** accuracy and precision
   - **b** reliability and validity.

2 **Identify** two strategies to improve the accuracy of data.

3 **Identify** the type of data most suited to:
   - **a** pie charts
   - **b** line graphs
   - **c** column graphs.

4 **Describe** the importance of:
   - **a** keeping a detailed record of what occurs an experiment
   - **b** SDSs
   - **c** ethics in experiments.

5 Sequence these in the most logical order they should appear within a scientific report:

   results, methodology or modifications, research question, data analysis

APPLYING

6 **Consider** the following research question.

   'How does the degree of refraction vary when light passes through different mediums?'

   Identify the:
   - **a** dependent variable
   - **b** independent variable.

7 A student wanted to conduct an experiment to see whether eating food before running had any effect on how far she could run. Write a research question for this experiment.

8 A student is conducting an experiment involving the use of a glass measuring cylinder to measure and pour a sample of acid into a 100 mL glass beaker. **Identify** one safety concern associated with the experiment and how the risk can be minimised.

9 In a medical experiment, a participant was asked to undergo a series of additional tests that could reveal sensitive information about their health situation. The participant refused to give consent to the tests. However, the experimenter ignored this and requested for the tests to be conducted anyway. Which ethical concept has the experimenter breached? **Explain** your answer.

10 **Identify** the number of significant figures in the following.
   - **a** 0.0023
   - **b** 2.430 07
   - **c** 8.1005
   - **d** 0.7

11 A student measured a value of 20 cm in their experiment with an absolute uncertainty of 1 cm.
   - **a** **Calculate** the percentage uncertainty.
   - **b** What does this value suggest about the precision of the measurement?

12 A group of students designed an experiment to measure the melting points of different substances. The students obtained five different substances: A–E. They set up a melting point apparatus and heated each substance until it melted, recording the temperature at which melting occurred.

a **Identify** an extraneous variable for this experiment.

b Each student took turns measuring the melting point of each sample each day. Students brought in their own thermometers, and it was noticed that some used digital thermometers while others used analogue thermometers. **Identify** the type of error that occurred as a result of this.

13 In a particular set of measurements, a student recorded the following: 14.2, 14.1 and 14.3 cm. **Calculate** the absolute uncertainty.

14 The results from a student experiment involving the measurement of the velocity of a sphere dropped from various heights are shown below.

Height (m)	Velocity (m s^{-1})			Mean velocity (m s^{-1})
	Trial 1	Trial 2	Trial 3	
0.5	3.11	3.13	3.15	
1.0	4.41	4.43	4.45	
1.5	5.40	5.42	4.44	
2.0	6.24	6.28	6.30	
2.5	6.98	7.02	7.04	

a **Identify** the dependent and independent variables for this experiment.

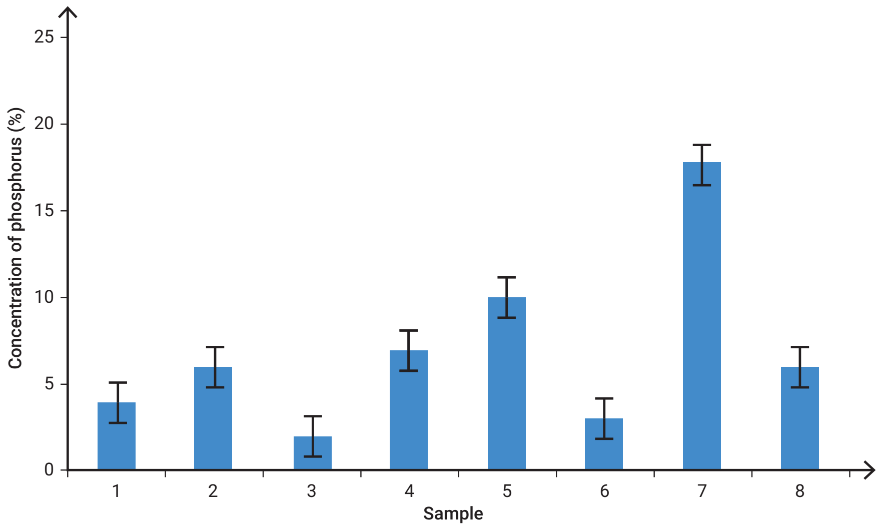
b **Calculate** the mean value for each height.

c Use the values to draw a graph to represent this data.

d **Determine** the correlation (if any) between the independent and dependent variables.

ANALYSING

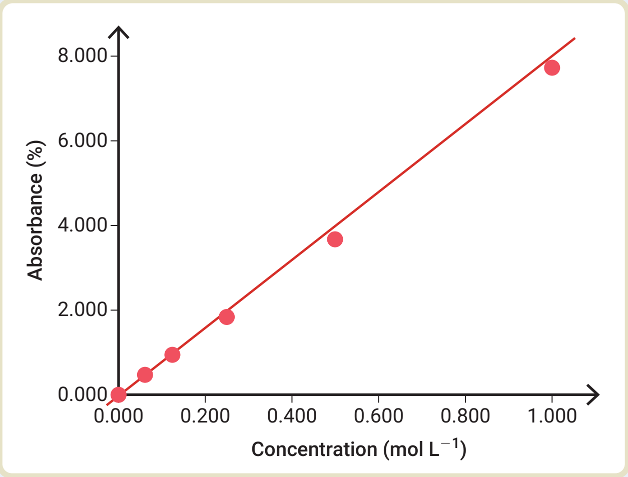
15 Consider the following graph.



a **Determine** the dependent variable.

b Which sample shows the greatest variability?

16 The following graph was drawn for an experiment measuring the change of absorbance as a result of a change of concentration.



a What is the name of the type of graph drawn?
b What is the name given to the line drawn in the graph?
c **Calculate** the gradient (m) of the line.
d **Determine** the approximate absorbance at a concentration of 0.2000.
e Based on the graph, would you expect the R value to be greater or less than 0? **Explain** your response.

DC.2 Research investigation

To help prompt your Research Investigation (IA3) assessment, your teacher will provide a list of claims that you can investigate. These claims will be related to particular topics outlined in the syllabus. After selecting a claim, you will be required to research a question to investigate. Unlike the student experiment, the research investigation requires you to collect and analyse **secondary data** about your topic and particular research question.

secondary data data that is collected by someone else

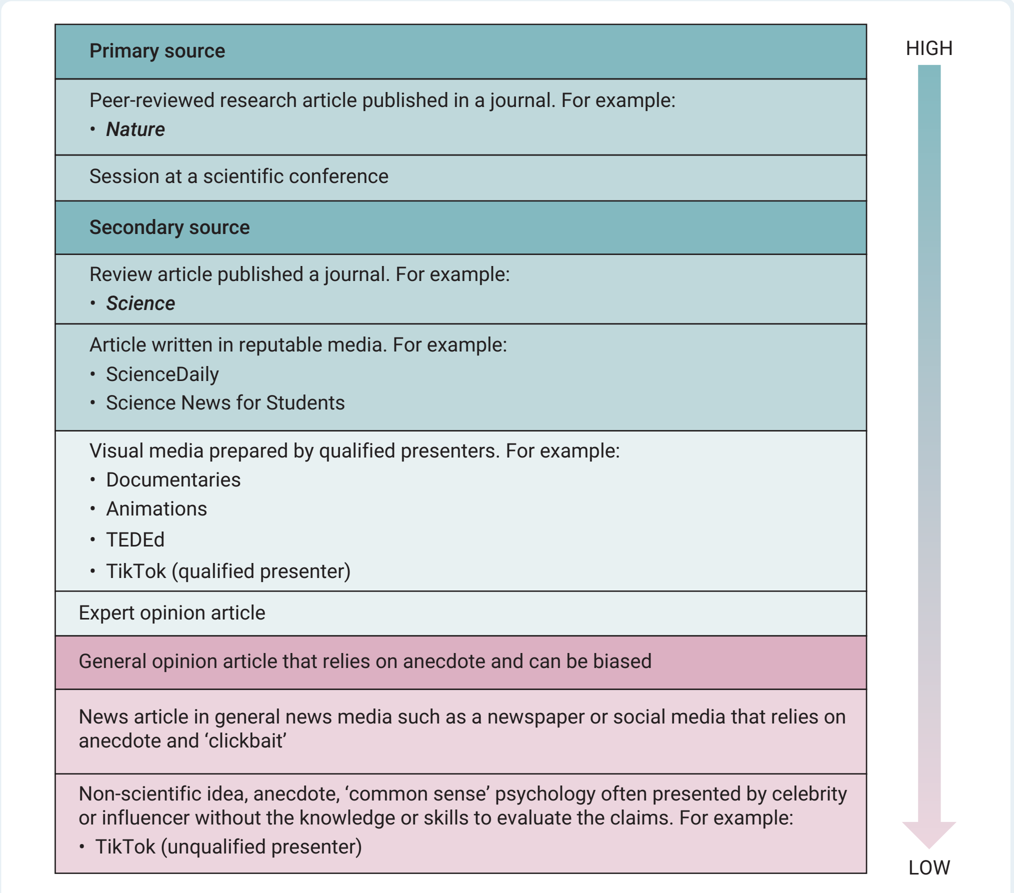
Forming and finding

Researching

As with the student experiment, you will need to conduct research before developing a research question. This involves reading scientific articles and books and investigating other resources to develop a solid understanding of the topic. From blogs to scientific journals, there are many resources available to help develop your understanding. These sources may be available through open access (e.g. Google Scholar) or through organisations such as government websites and local or national libraries. Open Science, an initiative by Creative Commons, has a list of open-source scientific articles that are freely available. For scientific research, it is important to use a variety of credible resources. Therefore, you will need to be able to assess the reliability of the sources you are using. For example, blogs that can be written by anyone are not as reliable as scientific articles from a peer-reviewed journal **(Figure DC.2.1)**.

Weblinks
Open Science

Evaluating the information you find



Primary source

Peer-reviewed research article published in a journal. For example:
- *Nature*

Session at a scientific conference

Secondary source

Review article published a journal. For example:
- *Science*

Article written in reputable media. For example:
- ScienceDaily
- Science News for Students

Visual media prepared by qualified presenters. For example:
- Documentaries
- Animations
- TEDEd
- TikTok (qualified presenter)

Expert opinion article

General opinion article that relies on anecdote and can be biased

News article in general news media such as a newspaper or social media that relies on anecdote and ‘clickbait’

Non-scientific idea, anecdote, ‘common sense’ psychology often presented by celebrity or influencer without the knowledge or skills to evaluate the claims. For example:
- TikTok (unqualified presenter)

FIGURE DC.2.1 Sources of information based on their reliability

This is why the peer review process in scientific research is so important **(Figure DC.2.2)**. For an article to be published in a journal, it must be reviewed by multiple experts, who evaluate and make suggestions for further improvement. Before it can be resubmitted, the author must review and respond to the suggestions. This process can take months. Only once this process has been completed can the article be accepted by the journal.

When using sources that are not from peer-reviewed journals, it is important to assess the reliability and validity of the information. It is helpful to ask yourself question such as:

- Is the author(s) an expert in this domain?
- Does the resource use evidence to support the claim?
- Is the methodology valid?
- If evidence is used, where does the data come from?
- Is this publication trustworthy?
- Is there any bias; for example, is there a conflict of interest among the researchers?

It is also a good idea to cross-reference the information presented by these resources with other sources such as primary sources and textbooks. This initial research helps you to develop a rationale for your investigation, and as a result helps to craft a research question that is relevant to the claim. As with the student experiment, the research question needs to be able to be tested.

To help the reader have the necessary context for the research investigation, you need to provide a level of background. The background needs to provide enough of a foundation

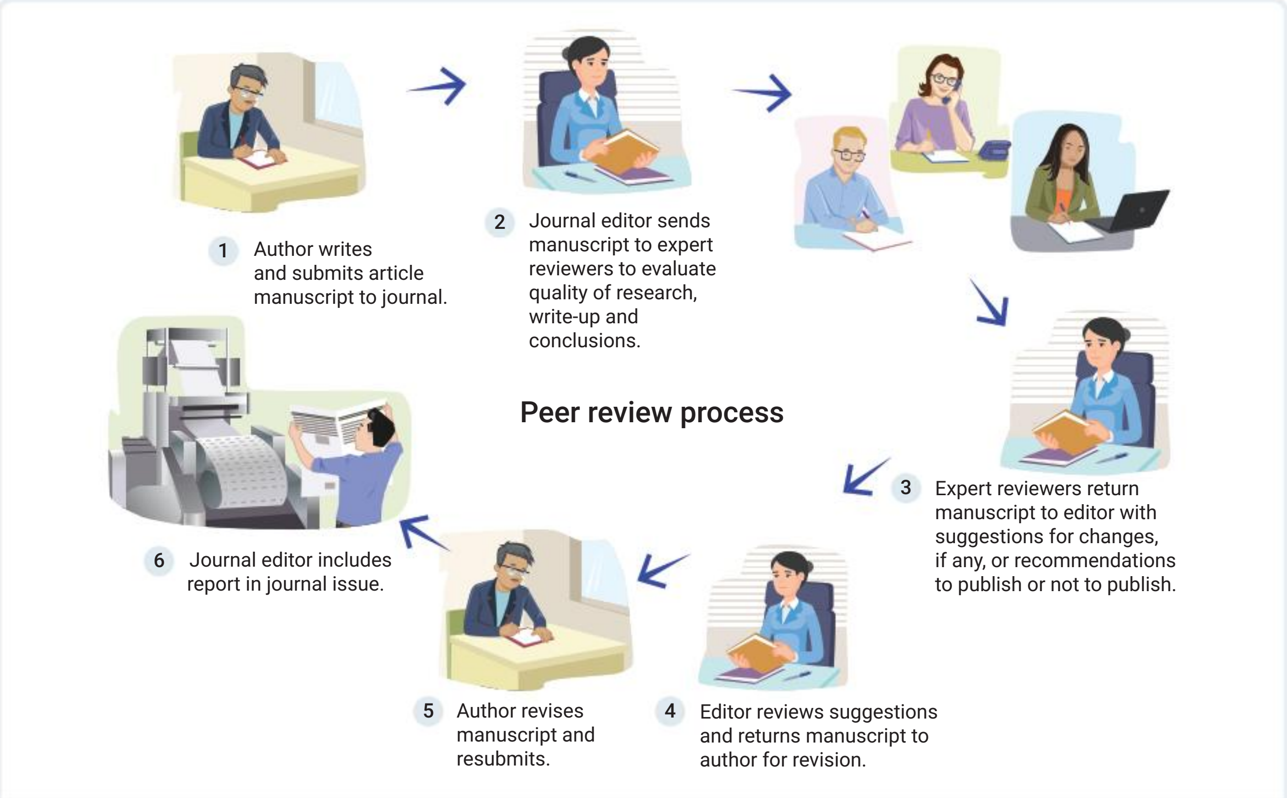


FIGURE DC.2.2 The peer review process

that the reader can understand the theoretical underpinnings of the research while also showing that you have used scientific evidence to develop a research question that aligns with the claim.

The ability to communicate scientific understanding to an audience is often an overlooked skill. How we present the information depends on what we are sharing and the audience we are sharing the details with. For example, when communicating to a younger audience who are unfamiliar with many scientific concepts, it is important to use language that is accessible and visuals to help foster a foundational understanding of the topic. When communicating findings to those in the scientific community, we need to use scientific language, including correct nomenclature, units and symbols specific to the scientific theory.

Weblinks
Referencing style guides
Referencing sources

Since experiments and scientific research draws on the knowledge, thoughts and ideas developed by others, we need to appropriately acknowledge the source of the information. The referencing format that is required depends on the discipline; however, in most cases, science uses the APA (American Psychological Association) referencing style.

Analysing evidence

As part of your assessment, you will need to find scientific evidence from previous research related to your research question. The data derived from these studies is used in the same way as the data collected from your student experiment; to identify trends and relationships between variables to answer the research question.

Since there are multiple data points, you will need to individually analyse the data presented by each study. For instance, consider **Figure DC.2.3**, which shows a section of a Research

Study 1

Research uncovered that as CO_2 emissions were increased, the rate of other gases, such as methane and water vapour also increased, creating a positive feedback. Scheffer et al concluded that feedback could account for an increase in the rate of global warming by 15–78% on a century scale. This high level of inaccuracy does impact the validity of the model, as it is difficult to generalise. Figures 3 and 4 displayed below are predicted models displaying the effect on equilibrium with feedback.

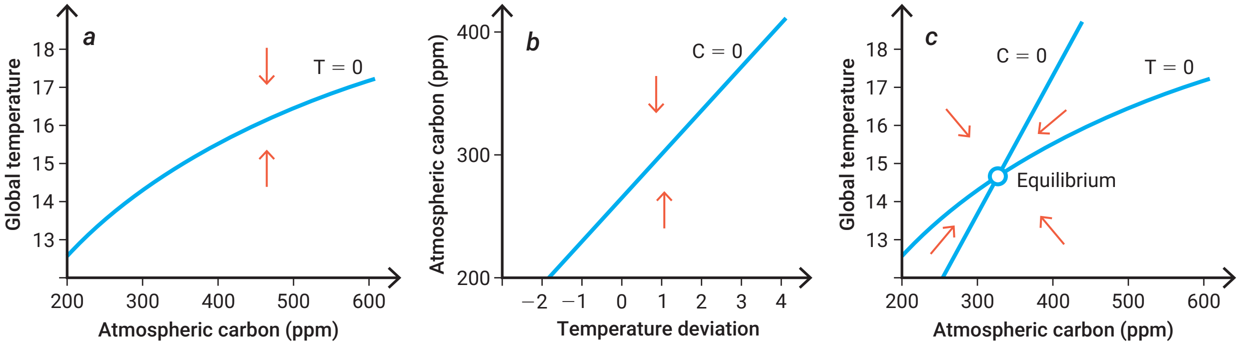


Figure 3: Graph displaying the relationship between carbon in ppm and temperature

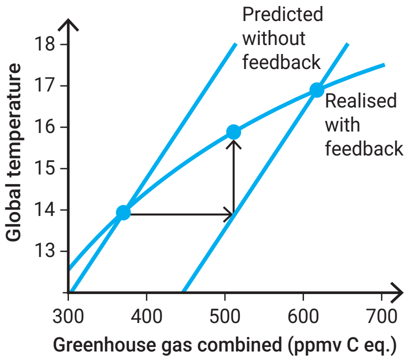
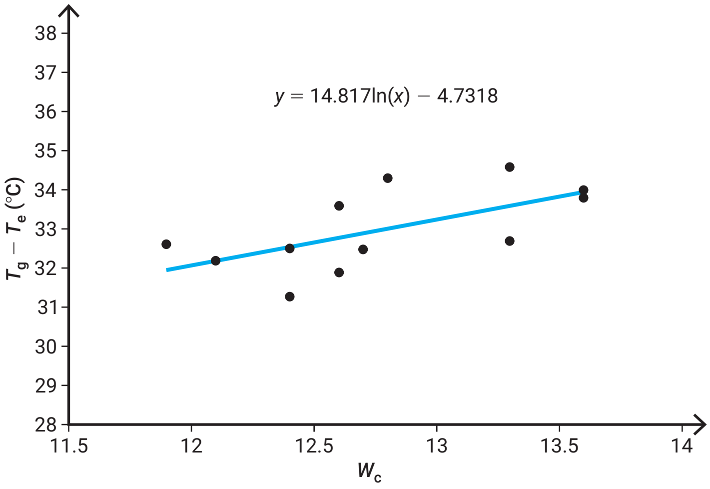


Figure 4: The proposed impact of a positive feedback on equilibrium

Study 2



The graph above shows a clear positive linear relationship between an increasing humidity level and the greenhouse effect. The outliers for (W_c) 12.4, 12.75 and 13.5 still follow the general trend and therefore do not significantly impact the reliability of the data.

Figure 5: Relationship between humidity and temperature

Study 3

Stephens et al (1993) utilised data from numerous observations from varying climates around the world to understand the water vapor feedback system and its relationship to the greenhouse effect. The data was then processed using multiple formulae to create the figures seen below.

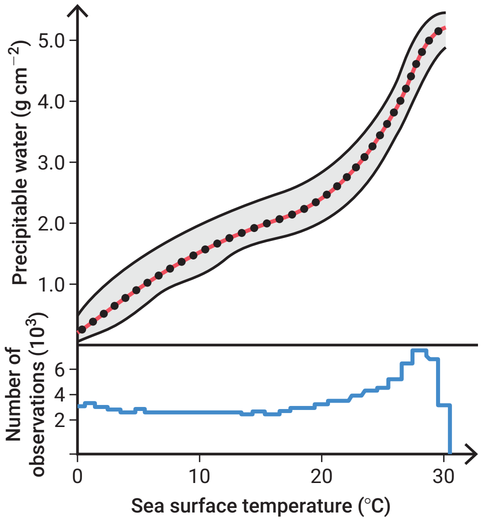


Figure 6: Relationship between surface temperature and water vapour after a 10% increase in CO_2

Figure 6 displays these results after processing data. It was found that the amount of precipitable water dramatically increased following a doubling of CO_2 which heated the environment (expressed as a surface temperature on x-axis). Specifically, as the CO_2 created more heat due to the greenhouse effect, the amount of precipitable water increased substantially.

QCAA

FIGURE DC.2.3 Analysis of results from three different studies

Investigation (IA3) where the student analyses three different studies investigating the relationship between the release of greenhouse gases and blackbody radiation.

Understanding the trends presented in each study allows you to develop a well-rounded conclusion for the research question.

Interpreting evidence

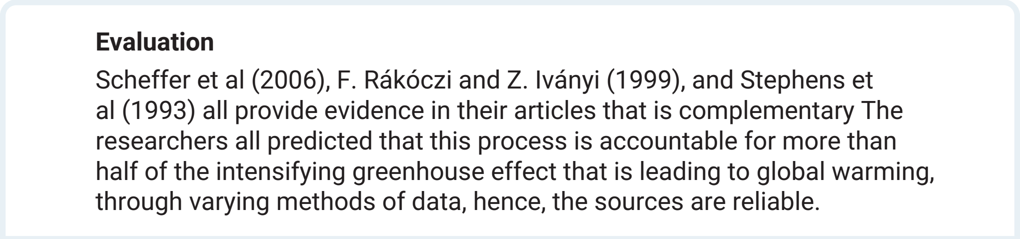
As you now know, presenting data and describing trends and relationships on their own is not sufficient. We need to be able critique the evidence itself and use the evidence to justify the argument being made and to draw a conclusion.

Assessing both the raw data and the quality of the evidence allows us to draw a conclusion from the investigation. When developing your conclusion, ensure that it directly answers the research question. Sometimes when assessing studies at an individual level, the data may point towards a particular conclusion. However, when studies in the same area are evaluated together, an overall analysis may suggest a different conclusion. If your investigation shows a different conclusion from the studies used, that in itself is an important conclusion. It highlights that further investigation is required to develop a deeper understanding of the area.

Evaluating evidence

The quality of the evidence can impact the reproducibility of the research and strength of the conclusions drawn **(DC2.4)**. We can assess the quality of the evidence by identifying any limitations caused by errors and/or uncertainty. This may include assessing the:

- appropriateness of the method
- sample size
- sources of error
- degree of uncertainty of the data.



Evaluation

Scheffer et al (2006), F. Rákóczi and Z. Iványi (1999), and Stephens et al (1993) all provide evidence in their articles that is complementary The researchers all predicted that this process is accountable for more than half of the intensifying greenhouse effect that is leading to global warming, through varying methods of data, hence, the sources are reliable.

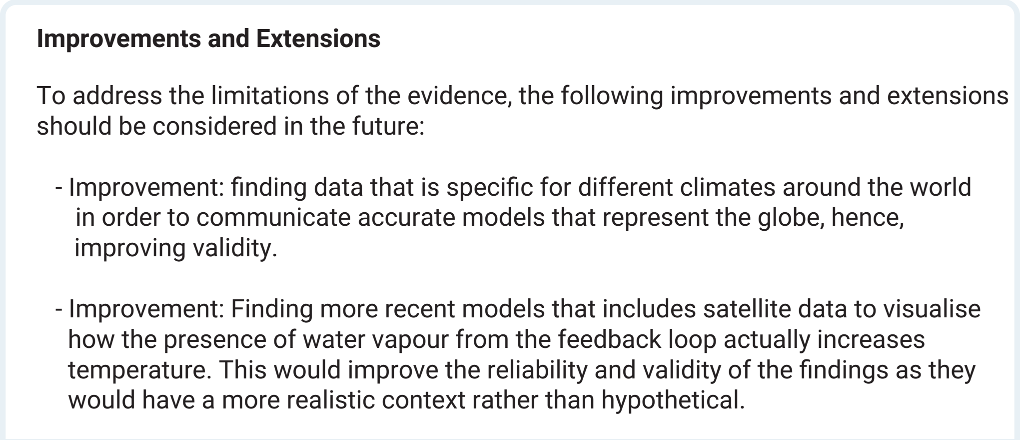
QCAA

FIGURE DC.2.4 An excerpt evaluating the evidence provided by previous scientific studies where the green highlighted text shows discussion about the quality of the evidence.

This would also help to make any interpolation or extrapolations of the findings to further analyse the research claim.

It is also important to suggest any further improvements for future studies related to this area **(Figure DC.2.5)**. For example, you could identify any changes that you would make to the methodology to improve the validity or reliability of the data from the experiment. Suggestions for improvement should also address any limitations present in the experiment, including any:

- experimental limitations; for example, time available to conduct the experiment, errors
- methodological limitations; for example, accuracy and reliability of measurement techniques, ethical constraints
- external limitations; for example, environmental factors that can introduce variability, access to proper equipment.



Improvements and Extensions

To address the limitations of the evidence, the following improvements and extensions should be considered in the future:

- Improvement: finding data that is specific for different climates around the world in order to communicate accurate models that represent the globe, hence, improving validity.

- Improvement: Finding more recent models that includes satellite data to visualise how the presence of water vapour from the feedback loop actually increases temperature. This would improve the reliability and validity of the findings as they would have a more realistic context rather than hypothetical.

QCAA

FIGURE DC.2.5 Suggestions for further investigation for an experiment

As you can appreciate, being able to interpret and evaluate data is crucial for reaching informed conclusions about your research. Not only do you need to speak about the data, you need to be able to use the evidence to justify any arguments made from the research.

LEARNING CHECK DC.2

DESCRIBING

1 **Identify** the difference between primary and secondary data.

2 **Describe** the role of the peer review process in scientific research.

APPLYING

3 A student conducted an experiment to investigate the effect of different lengths of a wire on the resistance of the wire. The student tested four different lengths: 10, 20, 30 and 40 cm. The resistance was measured using a digital multimeter. **Identify** one experimental and one methodological limitation for this experiment.

4 **Consider** the following passage:

Velocity, a fundamental concept in the field of physics, plays a crucial role in understanding the motion of objects. Velocity describes the rate at which an object changes position. In studying velocity, scientists can analyse the factors that influence the speed and direction of an object.

Rewrite the passage so that it can be read and understood by a primary school student who is studying science.

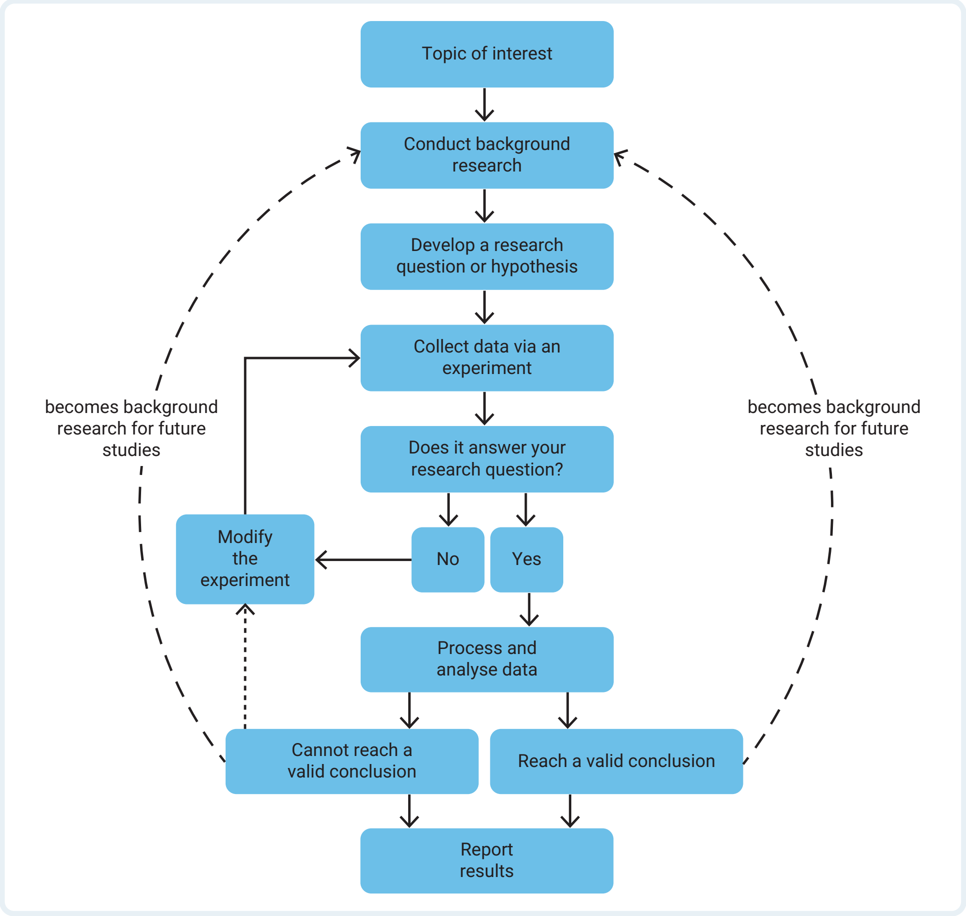
5 A student used the following source for their research investigation.

Cruzan, J. (2012). 'The most important solvent'. Retrieved from http://www.drcruzan.com/Water.html.

Use information from the 'Referencing sources' weblink to show how this resource would be referenced in in text.

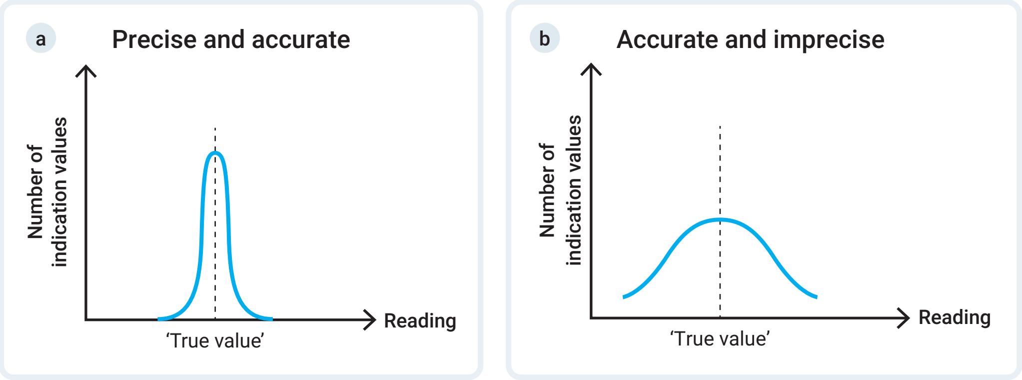
Conducting research

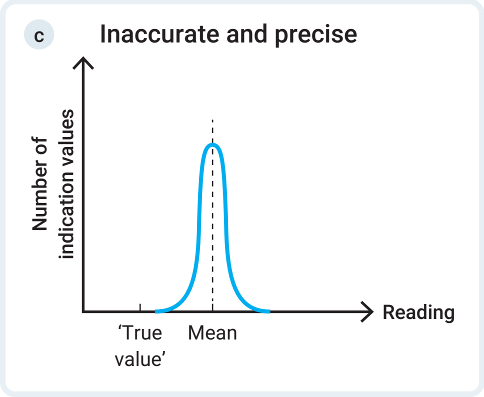
- The scientific method follows a particular process aimed to maximise accuracy, reliability and objectivity while minimising uncertainty and error.

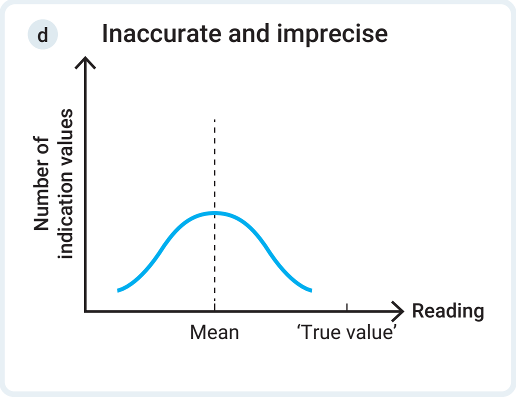


Analysing data

- Precision describes the closeness of data, whereas accuracy describes how close the measured value is to the true value.
- The quality of data affects the validity of the experiment.







- Errors affect the accuracy and precision of data. These can be categorised into:
  - random errors
  - systematic errors.
- Uncertainty describes the variability in the measured results:

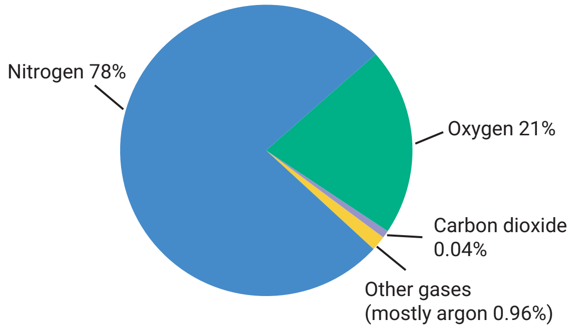
$$\text{Absolute uncertainty} = \pm\frac{\text{maximum} - \text{minimum}}{2}$$

$$\text{Percentage uncertainty}(\%) = \frac{\text{absolute uncertainty}}{\text{measurement}} \times \frac{100}{1}$$

Graphs

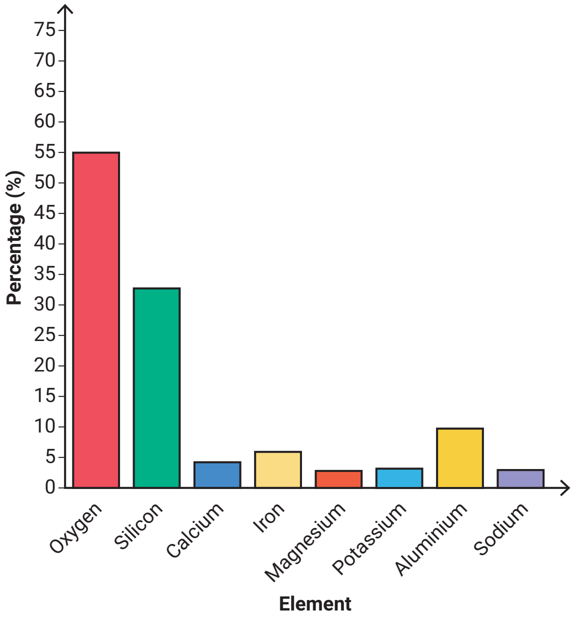
- There are many different graphical representations of data, including:
  - linear graphs
  - column graphs
  - pie charts
  - scatterplots.

Pie charts

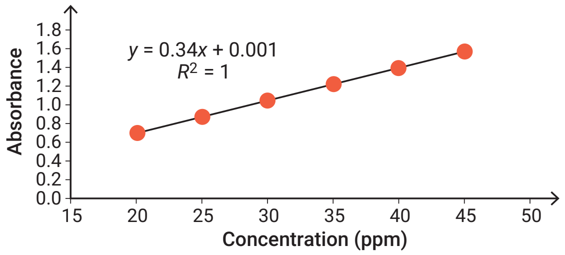


Column graphs

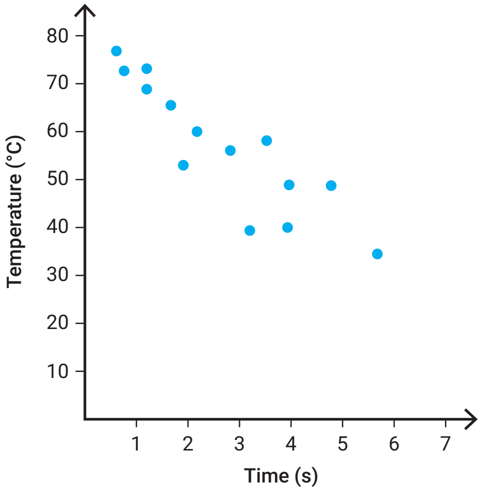
The eight most common elements in the Earth's crust



Line graphs

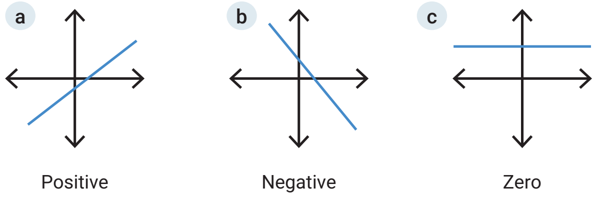


Scatterplots

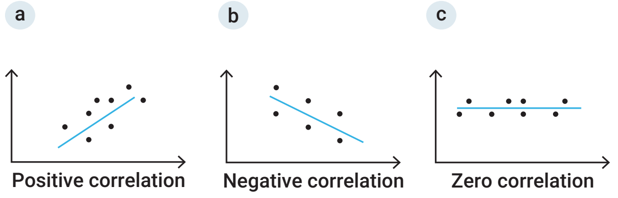


- Graphs help to show the relationship between variables. Although they can show correlation, this does not mean causation.

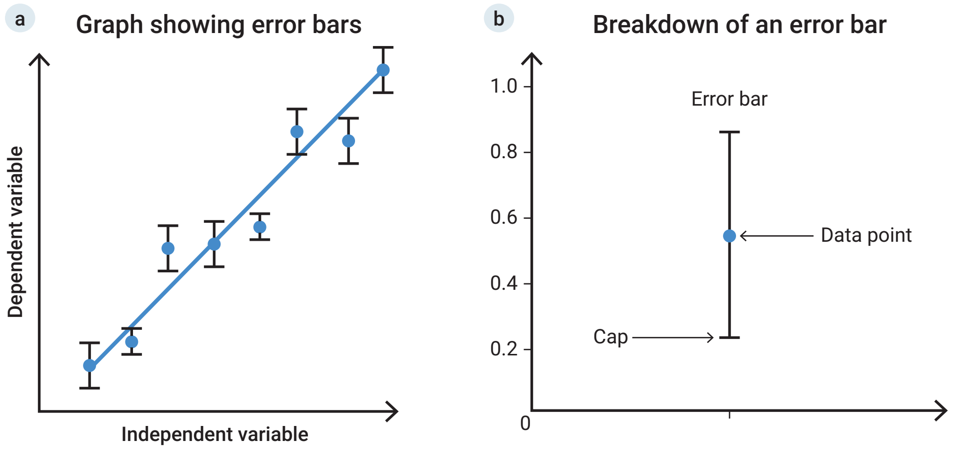
Correlation trends of line graphs



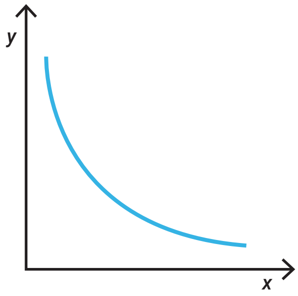
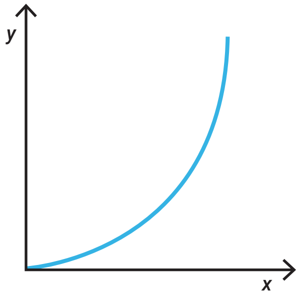
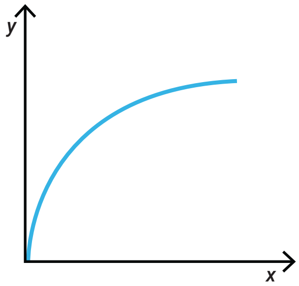
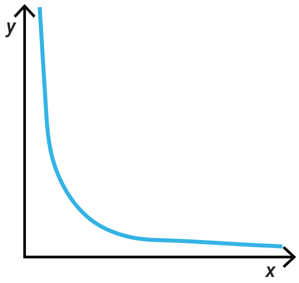
Correlation trends of scatterplots



- Error bars on graphs help to visualise variability of measurements around the mean.
  - The central point shows the data point.
  - The upper and lower limits show the variability of the measured values.



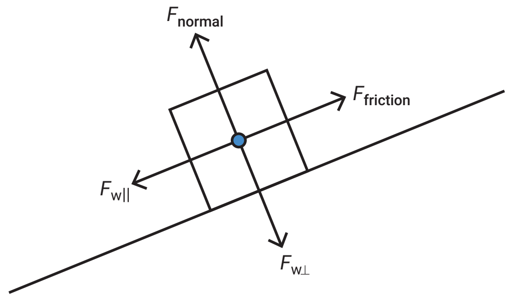
- Non-linear data can be linearised using various methods. This depends on the type of relationship between the variables.

Graph shape	Relationship	How to linearise the data
	There is an inverse relationship between the variables where y is inversely proportional to x.	Graph y as a function of $\frac{1}{x}$.
	There is a proportional relationship between the variables where y is the square of x (or x^2).	Graph y as a function of x^2 (rather than just x).
	There is a proportional relationship between the variables where the square of y (y^2) is proportional to x.	Graph y^2 (rather than just y) as a function of x.
	There is a proportional relationship between the variables where y is proportional to the inverse of x^2.	Graph y as a function of $\frac{1}{x^2}$.

Other representations of data

- Data can also be represented using profile diagrams, maps and a combination of maps and charts.

Scientific drawings



Interpreting and evaluating evidence

- Apart from speaking to the trends shown in the data, when analysing data it is also important to assess the:
  - appropriateness of the method
  - sample size
  - sources of error
  - degree of uncertainty of the data.
- When evaluating evidence, make sure to also address any limitations present in the experiment, including:
  - experimental limitations; for example, time available to conduct the experiment, errors
  - methodological limitations; for example, accuracy and reliability of measurement techniques, ethical constraints
  - external limitations; for example, environmental factors that can introduce variability, access to proper equipment.

Communicating findings

- When communicating findings, make sure to:
  - use appropriate conventions and nomenclature
  - use language appropriate to the audience
  - reference appropriately using the relevant referencing system.

CHAPTER EXAM

MULTIPLE CHOICE

1. Which measure provides information about the spread or variability of data points in a data set?

A Mean
B Mode
C Outlier
D Standard error

2. Which of the following data sets would be considered as precise but not accurate in a physics experiment?

A Time taken for a pendulum to complete 10 oscillations measured using a stopwatch with a consistent error of 0.2 s (Readings: 9.8, 9.6, 9.7 s)
B Distance travelled by a rolling ball measured using a metre stick with a worn-out scale (Readings: 25.5, 25.3, 25.4 cm)
C Force applied to stretch a spring measured using a spring scale with a loose hook (Readings: 12.1, 12.3, 12.2 N)
D Velocity of a moving object measured using a speedometer that consistently overestimates the actual speed by 5 km h^{-1} (Readings: 55, 55, 60 km h^{-1})

Questions 3 and 4 relate to the following information.
A Physics student measures the displacement of an object using a ruler. The student reads the volume as 25.0 cm. However, a more precise instrument, shows the actual volume to be 25.6 cm.

3. What is the percentage error in the student's measurement?

A 2.3%
B 2.5%
C 2.8%
D 3.1%

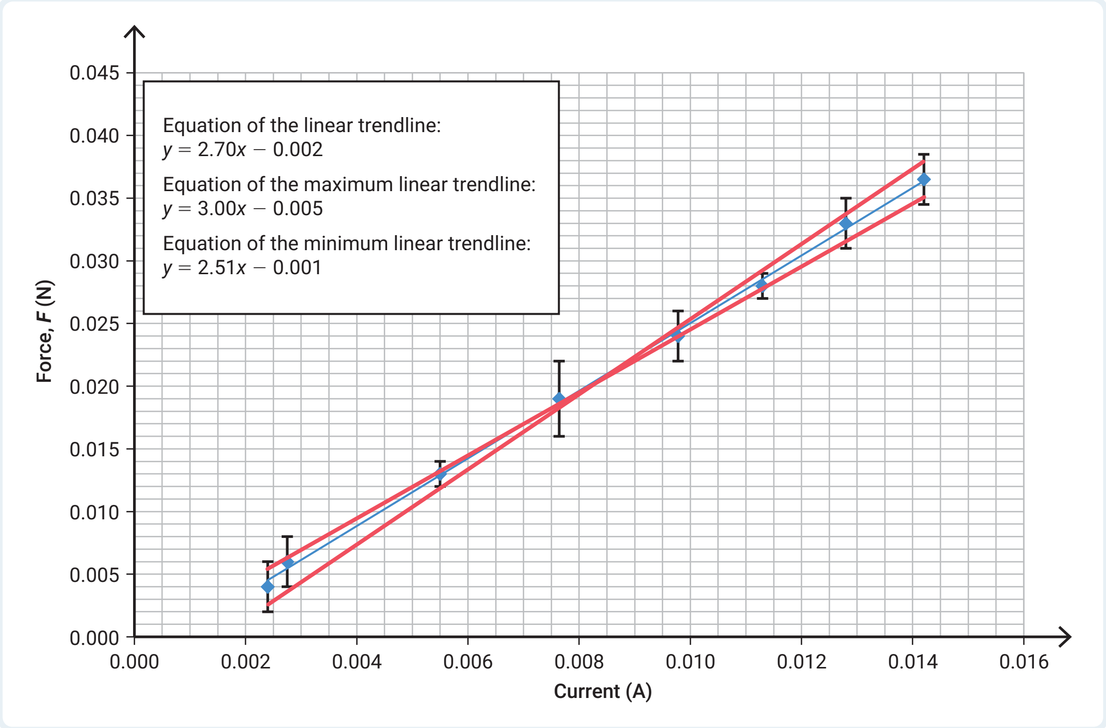
4. Which of the following actions would not improve the reliability of the student's results in subsequent measurements?

A Estimating the displacement between the markings on the ruler
B Repeating the measurement with the same ruler and averaging the results
C Using a ruler with smaller markings (e.g. millimetre scale instead of centimetre scale
D Calibrating the ruler by measuring a known distance using a different instrument

5. In a Physics experiment, students investigated the effect of the angle of incidence on the angle of reflection. Which of the following can be considered an extraneous variable?

A Angle of incidence
B Wavelength of the light
C Roughness of the reflecting material
D Temperature of the room during the experiment

Questions 6–8 relate to the following information.
A student conducted an experiment to measure changes in current.



6. The independent variable is:

A current (A).
B force (N).
C time (s).
D voltage (V).

7. Which of the following correctly describes the trend shown by the graph?

A The current does not affect the force exerted.
B As the current increases, the force exerted decreases.
C As the current increases, the force exerted increases.
D As the current increases, the force exerted remains constant.

8. The R^2 was calculated to be >0.99. This implies that there is:

A no correlation between the variables.
B weak correlation between the variables.
C strong correlation between the variables.
D negative correlation between the variables.

9. Which of the following options can be considered a random error in a physics experiment?

A Diverging from the specified experimental procedure
B A poorly calibrated measuring instrument
C Inconsistent air resistance affecting the motion of an object
D Misalignment of the measuring instrument during data collection

10. Which of the following cannot improve the reliability of results in an experiment measuring electrical conductivity of different materials?

- **A** Increasing the replicates in each measurement
- **B** Using various electrode configurations to measure conductivity
- **C** Calibrating the conductivity meters before taking measurements
- **D** Reducing the number of data points collected in each measurement

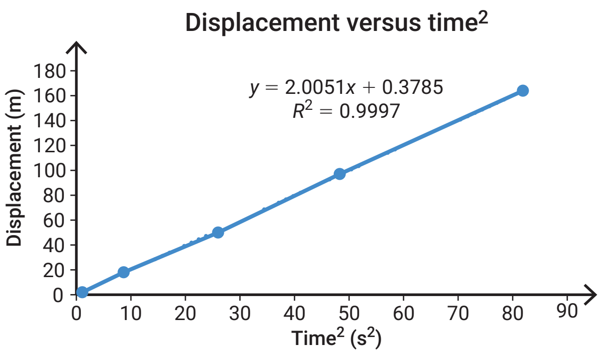
SHORT RESPONSE

11. The following is a description of an experiment.

Students are investigating the effect of varying forces on the acceleration of an object. In the experiment, the object is subjected to three different forces: 10, 20 and 30 N. All experiments are conducted under the same conditions of mass and friction, and the acceleration of the object is measured at regular time intervals.

Write an appropriate research question for this experiment.

12. A student wanted to measure the changes in vertical displacement over time of an object. The following graph was drawn from the data collected.



- **a** **Identify** the dependent and independent variables.
- **b** **Describe** the trend shown by the graph.
- **c** Using the R^2 value, **identify** the strength of the relationship between the variables.
- **d** Write the mathematical relationship between the variables.

13. As the volume of a gas is changed at a set temperature, so too does its pressure change. The following table shows pressure measurements taken of a gas in a chamber as its volume is changed at a set temperature.

Volume V of container (L)	Pressure P of gas (kPa)
1.0	100.0
2.0	50.0
3.0	33.3
4.0	25.0
5.0	20.0
6.0	16.7
7.0	14.3
8.0	12.5
9.0	11.1
10.0	10.0

a **Sketch** an appropriate graph to represent this data.

b Use an appropriate method to linearise the data. Draw a graph, preferably using Excel, to represent the manipulated data.

c Write a mathematical equation to describe this relationship.

14. Hooke's law predicts that force exerted on a spring is proportional to how much it stretches or compresses, $F = -kx$. The variable k quantifies the stiffness of the spring. A student conducted an experiment to test this and obtained the following results.

Displacement (m)	Force (N)
0.1	5 ± 0.2
0.2	10 ± 0.3
0.3	15 ± 0.4
0.4	20 ± 0.5
0.5	25 ± 0.6
0.6	30 ± 0.7
0.7	35 ± 0.8
0.8	40 ± 0.9
0.9	45 ± 1.0
1.0	5.0 ± 1.1

a Use the data to **sketch** a graph of the relationship.

b **Determine** the average uncertainty of the force measurements.

c **Describe** the trend seen in the graph.

d **Determine** the gradient of the linear relationship and state what it represents.

ANSWERS

CHAPTER DC SCIENCE RESEARCH

LEARNING CHECK DC.1

DESCRIBING

1 **a** Accuracy describes the comparison between a measured value and the true value, whereas precision describes the comparison between measured values.

b Reliability refers to how consistent and replicable the results of an experiment are. Validity refers to the degree to which the results of an experiment are similar to the true values or real values.

2 Conduct more trials, ensure all variables except for the independent variable are well controlled, ensure the measurement devices are appropriate and calibrated.

3 **a** Percentages or proportions of a whole

b Trends over time of continuous data

c Comparing quantities of different categories, types or groups

4 **a** Assists in the construction of experimental reports that are a true reflection of what occurred in an experiment and what its findings were in terms of a justified answer to the research question

b Ensures that all materials and equipment are used safely and appropriately

c To ensure that all experiments are conducted with integrity, with the consideration of the wellbeing and respect of others and the environment

5 Research question, methodology or modifications, results, data analysis

APPLYING

6 **a** Degree of refraction

b Medium type

7 How does eating before exercise affect performance?

8 Example 1: Skin or eyes being exposed to acid. Wearing safety glasses would minimise the risk. Example 2: The student could drop the measuring cylinder, causing it to break and shatter. The pieces of glass could damage the skin.

Risk minimisation: Wear gloves and closed-toe shoes to protect against broken glass.

9 The experimenter has neglected to consider the wellbeing of the test subject by breaching informed consent. The experiment ignored the participant's refusal to be tested and performed the procedure anyway. Participants need to give formal consent to participate in experiments and the experimenter must respect their wishes, not go against them.

10 **a** 2 **b** 6 **c** 5 **d** 1

11 **a** Percentage uncertainty $= \frac{1}{20} \times 100 = 5\%$

b It is of moderate precision.

12 **a** Examples: type of heating apparatus, quantity of substance, type of thermometer used

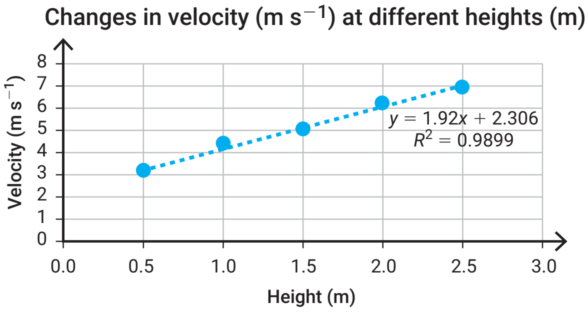
b Random error

13 Absolute uncertainty $= \frac{14.3 - 14.1}{2} = \pm 0.1$ cm

14 **a** Dependent variable: velocity (m s^{-1}), independent variable: drop height (m)

b 0.5 m: 3.13 m s^{-1}, 1.0 m: 4.43 m s^{-1}, 1.5 m: 5.09 m s^{-1}, 2.0 m: 6.27 m s^{-1}, 2.5 m: 7.01 m s^{-1}

c



d There is a positive, linear correlation between drop height and velocity.

ANALYSING

15 **a** Concentration of phosphorus

b Sample 3

16 **a** Scatter plot

b Line of best fit

c 8.000

d 1.700

e Greater than zero because it is a positive correlation

LEARNING CHECK DC.2

DESCRIBING

1 Primary data is first-hand data collected by you, the researcher or experimenter, whereas secondary data is collected by someone else.

2 Peer review is important to assess the reliability and validity of experimental evidence. It is a form of quality assurance.

APPLYING

3 Experimental limitation: the limited number of lengths tested Methodological limitation: the accuracy and precision of the device used to measure the length of the wires

4 Velocity is a way of measuring how fast or slow an object is moving. It is important to measure so that we can study the motion of objects.

5 See weblink (Cruzan, 2012)

CHAPTER EXAM

MULTIPLE CHOICE

1	D	**2**	A	**3**	A	**4**	A	**5**	C
6	A	**7**	C	**8**	C	**9**	C	**10**	D

SHORT RESPONSE

11 How does changing the magnitude of an applied force on an object with fixed mass affect its acceleration?

12 a Independent: time squared (s^2)

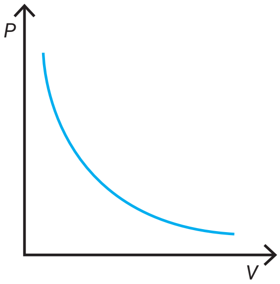
Dependent: displacement (m)

b There is a linear positive correlation between time squared and displacement.

c The R^2 value is very close to 1, indicating a strong correlation.

d If displacement = s, and time = t, $s = 2.0051t^2 - 0.3785$

13 a



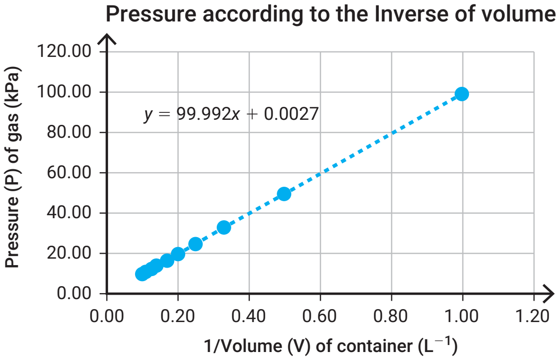
The graph has the characteristic shape of an inversely proportional relationship.

b As the relationship appears to be inversely proportional ($P \propto \frac{1}{V}$), the best way to linearise the data is to plot the inverse of volume vs pressure.

c Data used for linearisation:

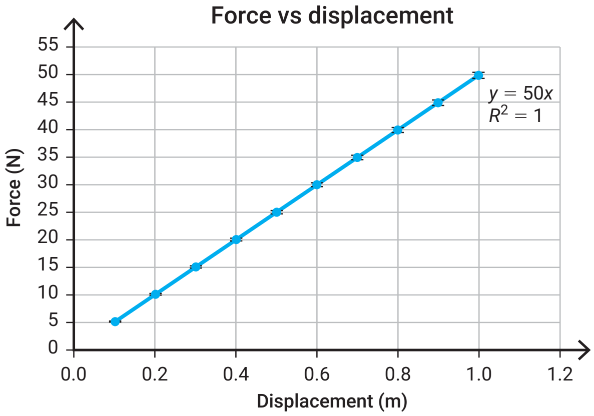
$\frac{1}{\text{Volume}}$ V^{-1} of container (L^{-1})	Pressure P of the gas (kPa)
1.00	100.00
0.50	50.00
0.33	33.30
0.25	25.00
0.20	20.00
0.17	16.70
0.14	14.30
0.13	12.50
0.11	11.10
0.10	10.00

Linearised plot:



c Mathematical relationship using the line equation:
$P = 99.992V^{-1} + 0.0027$

14 a



b 0.65 N

c There is a positive linear correlation between force and displacement.

d The gradient is 50 N m^{-1}. This represents k, or the spring's stiffness.

UNIT 1

Thermal, nuclear and electrical physics

ABCDstock/Shutterstock.com

Topic 1: Heating processes
CHAPTERS RELATED TO THIS TOPIC AREA: 1–5

Topic 2: Ionising radiation and nuclear reactions
CHAPTERS RELATED TO THIS TOPIC AREA: 6–8

Topic 3: Electrical circuits
CHAPTERS RELATED TO THIS TOPIC AREA: 9–11

Unit 1: Thermal, nuclear and electrical physics provides a basis for student exploration of how physics is used to describe, explain and predict energy transfers and transformations pivotal to modern society. Understanding heating processes, nuclear models, nuclear reactions and radioactivity, as well as electrical energy and circuit design, will allow you to appreciate global energy needs and how they may be addressed in a socially, economically and ethically responsible way. Student inquiry and analytical skills are developed through experimentation, investigation, worked examples, questions and activities that offer opportunities for interpretation, construction of algebraic, graphical and symbolic representation and analysis of quantitative data and qualitative information.

UNIT OBJECTIVES

By the end of this unit, students should be able to:

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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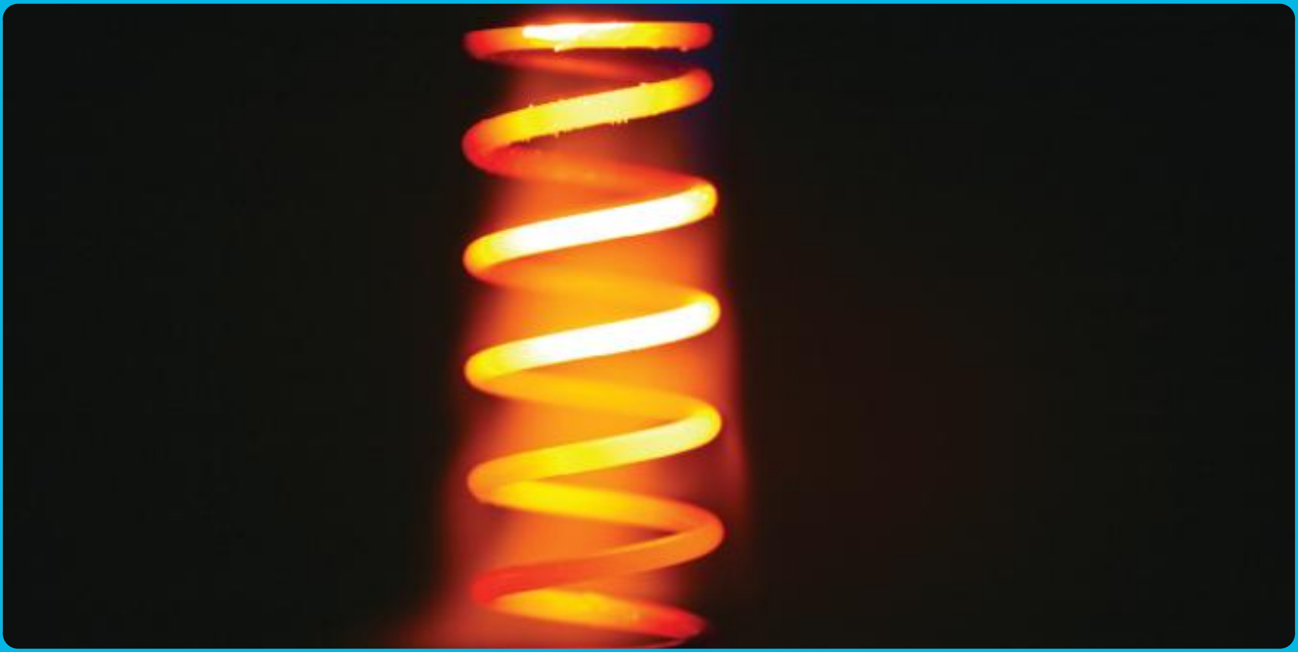
CHAPTER

1

Kinetic particle model and heat transfer



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SYLLABUS DOT POINTS

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.

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Introduction

Thermodynamics is a fundamental branch of physics that deals primarily with the study of energy, how it is transferred and how it affects matter. Even though it was first developed more than 200 years ago, thermodynamics remains one of the most successful strands of physics. In particular, the study of thermal energy and how it is shared among particles is finely interwoven into many scientific disciplines and has led to many significant scientific advancements and technological breakthroughs. Although its theoretical roots lie with the Ancient Greek idea of atoms, thermodynamics continues to drive much of today's cutting-edge research, including the origins of the universe, strange new states of matter and the direction of time.

In this chapter, the kinetic particle model will be explained in detail. It will be used to describe the concepts of heat, temperature, internal energy and how energy can be transferred between substances.

Worksheet

- Energy and particles

ASSUMED KNOWLEDGE

- ✓ Simple unit conversions.
- ✓ Energy is usually expressed in joules (J) or kilojoules (kJ).
- ✓ Thermal energy is energy related to the motion of particles.
- ✓ Temperature is the average kinetic energy of particles in a system.
- ✓ Thermometers contain scales that can be read to measure temperature.
- ✓ Particle theory states that matter is made up of particles that are constantly moving, have spaces in between them, and have different energy levels depending on their state of matter.
- ✓ Conduction, convection and radiation are three mechanisms of heat transfer.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain the kinetic particle theory of matter
- ✓ describe and explain the concepts of thermal energy, temperature, kinetic energy, heat and internal energy
- ✓ calculate unknown values pertaining to thermal energy, temperature, kinetic energy, heat and internal energy
- ✓ describe and explain heat transfers in terms of conduction, convection and radiation
- ✓ analyse data to describe the relationship between the frequency and wavelength of electromagnetic radiation
- ✓ use a Boltzmann distribution to predict the distribution of energies of particles at specific temperatures
- ✓ consider information to appraise the usefulness and application of different temperature scales
- ✓ consider information to explore the development of scientific models to explain thermodynamic phenomena.

1.1 Kinetic particle model of matter

matter a physical substance

plasma a collection of free-moving electrons and ions that can be accelerated by magnetic and electric fields

kinetic particle model the model that explains the properties of the different states of matter; the particles in solids, liquids and gases have different amounts of energy, are arranged differently and move in different ways

atomic model a series of descriptions relating to the fundamental structure of matter

Matter can exist in four different states: solid, liquid, gas and **plasma**. Solids have fixed shapes and volumes and are mostly incompressible. Liquids have fixed volumes, take on the shape of their container and are more or less incompressible. Gases have no fixed shape or volume and are compressible. Plasmas are similar to gases but are made up of charged particles.

The **kinetic particle model** of matter is used to explain a number of observations including the properties of the different states of matter, how the properties of matter change with the addition of thermal energy and how matter can change between states.

The kinetic particle model is centred on the Ancient Greek idea that if a small piece of matter were cut up into increasingly smaller pieces, there would come a point at which it could no longer be divided any further. This final piece was called an atom, which is Greek for 'indivisible'.

Even though today the **atomic model** is widely accepted, evidence to support it did not come until much later when, in the 18th and 19th centuries, the development of the microscope and the study of chemical interactions led to a deeper understanding of the movement of small particles.

One of the most significant discoveries that supported the atomic theory came in 1827 from the work of Robert Brown who, while observing the motion of tiny pollen grains suspended in water, noticed that even though the water was completely motionless, the grains still moved about in a completely random motion like that depicted in Figure 1.1.1.

This observation is only reasonable if we assume that the particles of water are in continuous motion and constantly bump into each other. If this is accepted, then the movement of the pollen grains can be explained if their motion was continuously undergoing change under the influence of collisions with water particles.

The continuous motion of these particles, **Brownian motion**, forms the basis of the kinetic particle model. The model is successful in describing matter in the gaseous state. If the model is expanded to include two more assumptions, an important relationship between the average kinetic energy of the particles (atoms or **molecules**) and the overall temperature of the gas as a whole can be **derived**.

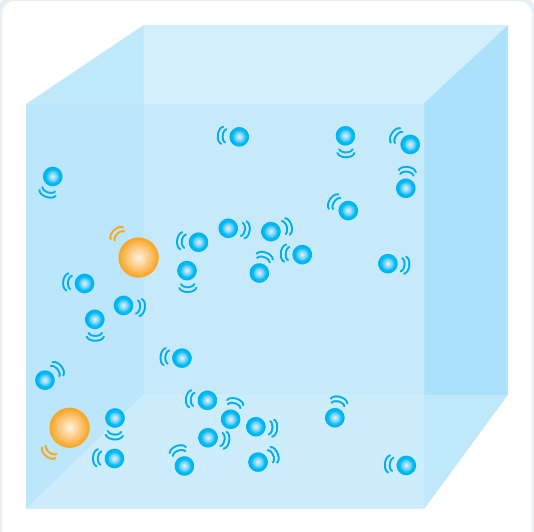

FIGURE 1.1.1 Robert Brown observed that tiny pollen grains suspended in water underwent continuous random motion despite the water being completely still. This is referred to as Brownian motion.

The three assumptions of the kinetic particle model are as follows.

- All matter is made up of small particles in constant motion; they have **kinetic energy**.
- Collisions between particles are perfectly elastic; the total kinetic energy before the collision is the same as after the collision.
- The particles obey classical mechanics and only interact with each other when they collide.

In an **elastic collision**, kinetic energy is conserved. Kinetic energy is transferred from one particle to another, but not converted into **potential energy**. This model of a gas is the kinetic particle or **ideal gas** model. When we make these assumptions about a gas, we refer to the gas as an ideal gas. In this instance, it can be shown that the average kinetic energy of the particles in an ideal gas is directly proportional to the **temperature** of the gas.

The ideal gas equation states that the faster the particles of a gas are moving, the higher the temperature of the gas. The development of this relationship underpins our understanding of temperature.

Although this equation holds well for ideal gases, in reality, the last assumption of the kinetic model is not entirely correct in that the particles in substances interact even when they are not in the process of colliding. In all known substances, there is some degree of attraction between the particles within them.

The particles (atoms or molecules) are attracted to each other by **intermolecular forces** that bind them together and cause them to behave a bit like springs. There is an ideal length for any bond, but it is possible for the bond to be stretched and compressed. When this bond is stretched away from its ideal length by the movement of particles, the energy can be stored as **elastic potential energy**.

Ultimately, it is the balance achieved between the kinetic energy given to the particles because of the temperature of the substance and the strength of the intermolecular bonds that give rise to the particular state of matter that a substance is found in (Figure 1.1.2).

KEY FORMULA

The average kinetic energy of an ideal gas is directly proportional to its temperature.

$$E_{\text{k average}} \propto T$$

where:

$E_{\text{k average}}$ = average kinetic energy of the particles in a substance (J)

T = temperature (K)

Brownian motion the random motion of small particles suspended in a fluid as a result of being bombarded by the particles of the fluid

molecule a collection of atoms bound together by chemical bonds

derive to obtain or create from base principles

kinetic energy the energy of an object resulting from its motion

elastic collision a collision between two or more objects in which there is no loss of kinetic energy

potential energy energy that is stored in a system because of the configuration and interaction of the bodies within the system

ideal gas a theoretical gas whose particles have no attraction to or repulsion from each other

temperature a measurement of the average kinetic energy of the particles in a substance

Weblink
Kinetic theory of gases

Syllabus link
Chapter 6 of this book and Units 3 & 4 discuss modern understandings of the atom.

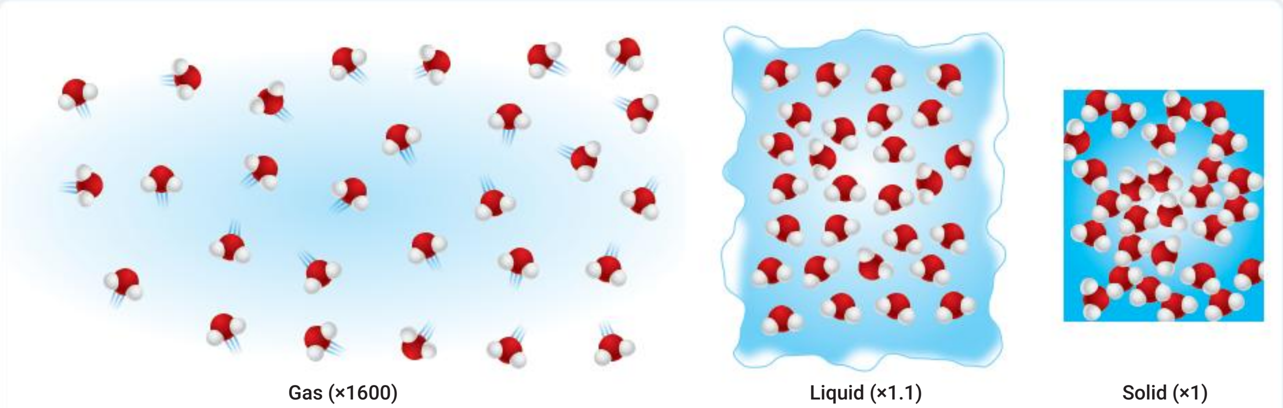

FIGURE 1.1.2 The states of matter showing approximate volume changes. (Note the change in scale: a mass of gas has a volume approximately 1600 times greater than the same mass of solid.)

intermolecular force an electrostatic force of attraction or repulsion between neighbouring particles of a substance

elastic potential energy energy that is stored by the deformation of an elastic object

Gases

In a gas, which for a given substance occurs at higher temperatures than its liquid and solid state, the average kinetic energy of the molecules or atoms is large enough that they can break free from the bonds holding them together. The particles are free to move in any direction and only interact through elastic collisions. Generally, when they do collide, the force of attraction is too small to keep them close together.

Liquids

In a liquid, the particles have less kinetic energy, so the bonds begin to have an effect, but they still only very loosely bind the particles together. There is potential energy associated with the interactions between the particles, causing them to stay together, but they have enough kinetic energy so that they can slide over each other.

Solids

In a solid, the kinetic energy of the particles is low enough that the intermolecular forces keep the particles bound together as a cohesive whole. Even though the material may not be going anywhere, every atom or molecule is still moving about constantly, vibrating or oscillating about its relatively fixed position. It is a bit like a large assembly of students all sitting in their own chairs, but each one fidgeting and leaning to the side to talk to their neighbours.

LEARNING CHECK 1.1

DESCRIBING

1 **Identify** the shape and volume traits of solids, liquids and gases.
2 Use 'Brownian motion' to **explain** how the pollen particles in Robert Brown's observations were continuously moving.
3 **Identify** the two types of energy that affect the motion of the particles in an object.
4 What causes the storage of energy in the form of elastic potential energy in the particles of an object?
5 If the temperature of an object increases, what must be happening to the average kinetic energy of its particles?
6 **Explain** the three states of matter in terms of their motion and intermolecular bonding.

1.2 The energy model

Energy exists in many forms, often named by its origin, including heat, light, mechanical, gravitational, electrical, magnetic, sound, chemical and mass. No matter the form, energy is still energy. All forms of energy can be *transformed* from one form to another and *transferred* from one place to another. For example, when you turn on an electrical bar heater, the electrical energy is transferred from the electrical wires to the heater, and in the process is transformed to radiant heat and light energy.

The SI unit of measurement of energy is the **joule** (J). It is approximately equivalent to the effort required to lift a 100 g apple from the ground to a height of 1 m.

joule the SI unit of energy; 1 J = 1 kg m^2 s^{-2}

The two major forms of energy are kinetic energy (energy associated with movement) and potential energy (energy stored and ready to be used). All energy sources can ultimately be reduced to these two forms.

Weblink
Kinetic energy

Kinetic energy

Kinetic energy is the energy a body has due to its motion. There are several forms of kinetic energy. For example, a moving train **(Figure 1.2.1)** has bulk translational kinetic energy due to the straight-line motion of the whole train. It has bulk rotational kinetic energy in the rotating wheels and engine parts. It has disorganised vibrational kinetic energy due to the vibrations of the atoms and molecules in the solid materials from which it is made.

In the kinetic particle model, each atom or molecule in a substance has kinetic energy due to the random velocity that it has at any one time. It is important to remember that there is a range of kinetic energies that the particles may have, but that an average kinetic energy can be calculated.

When these particles collide elastically with each other, the total kinetic energy of the colliding particles before the collision is equal to the total kinetic energy of the particles after the collision. This can be written in the following two ways:

$$E_{\text{k initial}} = E_{\text{k final}} \qquad \Delta E_{\text{k}} = 0$$

where:

$E_{\text{k initial}}$ = initial kinetic energy of a particle (J)
$E_{\text{k final}}$ = final kinetic energy of a particle (J)
ΔE_{k} = change in kinetic energy of a particle (J)

KEY FORMULA

The conservation of kinetic energy in an elastic collision is:

$$E_{\text{k initial}} = E_{\text{k final}} \qquad \Delta E_{\text{k}} = 0$$

where:
$E_{\text{k initial}}$ = initial kinetic energy of a particle (J)
$E_{\text{k final}}$ = final kinetic energy of a particle (J)
ΔE_{k} = change in kinetic energy of a particle (J)

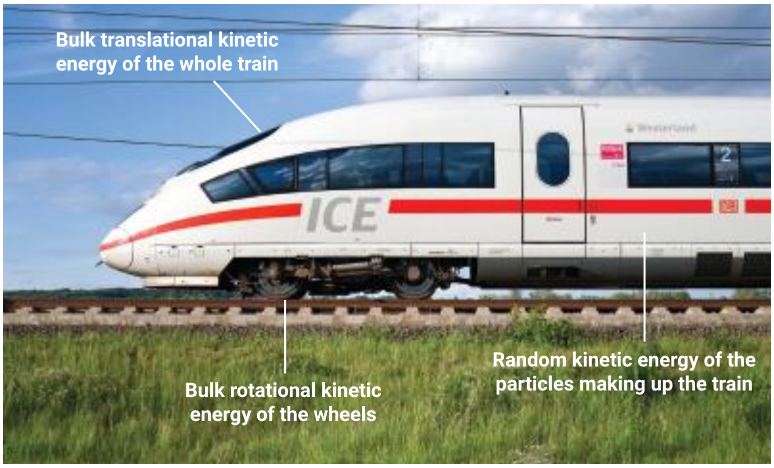

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FIGURE 1.2.1 A moving train has different forms of kinetic energy.

Potential energy

Weblink
Potential energy

Stretching an elastic band requires work to create stored energy, the potential to do work. When the elastic band is released, this stored energy is transformed to kinetic energy.

Potential energy is stored in the way the particles are connected to each other through the existence of intermolecular forces that form bonds between the particles. There is an ideal length for these bonds, but when the bonds are stretched or compressed by the kinetic energy of the particles, energy is stored as potential energy. This is like the energy that is stored in a bungee cord: when the cord is stretched, energy is stored as elastic potential energy; when the potential energy stored in the cord gets great enough, it can cause the jumper to spring back upwards against the force of gravity.

Internal energy

internal energy the sum of the kinetic energy of the particles in a system and the potential energy stored in a system

The **internal energy** (U, sometimes called the thermal energy) of a substance is the sum of the kinetic energy of its particles and the potential energy stored in their bonds and can be written as:

$$U = E_\mathrm{k} + E_\mathrm{p}$$

where:
U = internal energy of a substance (J)
E_k = total kinetic energy of the particles of a substance (J)
E_p = total potential energy stored in the bonds of a substance (J)

It does not include any kinetic energy due to the bulk movement of the material, or potential energy due to external forces such as gravity. However, thermal energy is a form of energy, and as such is important to consider when applying the **first law of thermodynamics** (the conservation of energy).

first law of thermodynamics in the universe, energy can neither be created nor destroyed; however, energy can change form and energy can flow from one place to another. The total energy of an isolated system remains constant

If a solid body is heated, its temperature increases. The particles gain kinetic energy and, on average, vibrate faster. Therefore, as temperature increases, the amount of internal energy increases as well.

At melting point, there is a **phase change**. The kinetic energy of the particles does not change any more until the phase change is complete. The ‘bungee cords’ are affected and the particles become further separated. During the phase change, the energy input results in an increase in the distance between particles, not their kinetic energy. In this case, when energy is added to a substance undergoing a phase change, even though there is no increase in temperature (no increase in kinetic energy), the internal energy is still increasing because more potential energy is being stored in the bonds.

phase change a change in physical state (e.g. solid to liquid)

A system with internal energy can transfer heat to its environment, and may also be able to do work by applying a force to some part of its environment. The volume of an amount of

KEY FORMULA

The internal energy of a substance is equal to the sum of the potential and kinetic energy of all of its particles.

$$U = E_\mathrm{k} + E_\mathrm{p}$$

where:
U = internal energy of a substance (J)
E_k = total kinetic energy of the particles of a substance (J)
E_p = total potential energy stored in the bonds of a substance (J)

gas is typically about 1500 times greater than the same amount of the liquid material. This difference in volume is used in engines to do work. For example, in a steam engine, water is boiled by burning coal in a firebox inside or against a boiler. The heat from the burning coal acts to change the state of the water from liquid to gas. The pressure of the steam pushing on a piston does work on rods that connect to the wheels, and thus drives the locomotive. Hence, the internal energy of the fuel, the coal, is converted into work done on a train being pulled behind the engine. This is possible because of the change of state of the water, and the different properties of the two states.

Syllabus link
Chapter 5 discusses energy transfers by heat and work in more detail.

Temperature

A cup of water takes much less time to come to a boil (100°C) than a saucepan of water. The final temperature is the same for both, but the larger mass of water in the saucepan requires more heat to bring it to the same temperature, even though all the particles in the cup have, on average, the same kinetic energy as the particles in the saucepan. Thus, temperature is, to a good first approximation, a measure of the average random kinetic energy of the particles making up a body.

When a material is heated, the average kinetic energy of the particles increases. **Figure 1.2.2**, which is called a **Boltzmann distribution**, shows the wide range of kinetic energies of particles in the same mass of iron at two different temperatures. The peak of the curve is the most common (mode) kinetic energy of the particles.

Boltzmann distribution a formula showing the distribution of energy among the particles of a system

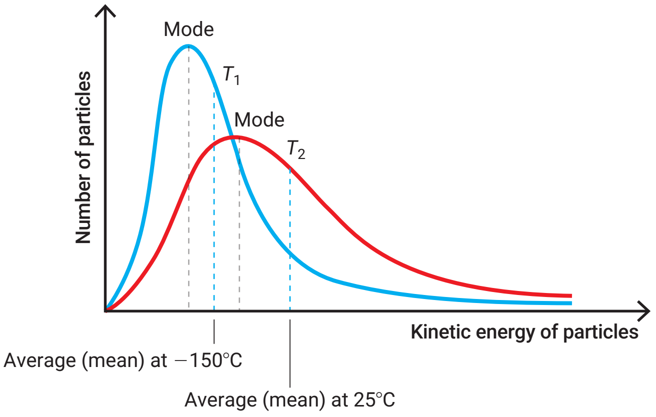


FIGURE 1.2.2 A Boltzmann distribution of the kinetic energies of the particles in a sample at two different temperatures, T_1 (−150°C) and T_2 (25°C)

When energy is added to a substance, the proportion of atoms vibrating faster increases. The average kinetic energy of particles, and therefore the temperature, increases.

Heat

In physics, **heat** has a definite meaning that may be different from your common understanding of the term. Heat refers to energy that spontaneously moves between two substances because there is a difference in temperature between them.

When heat is added to a substance, it generally results in an increase in kinetic energy of the particles, which results in an increase in the temperature of the substance. It is important to note that heat refers to the energy that is actually being transferred, not the kinetic energy itself. Another term that can be used interchangeably with 'heat' is **thermal energy**.

heat the transfer of thermal energy through a substance or between substances

thermal energy heat; the form of energy that gives rise to an increase in the kinetic energy of particles

LEARNING CHECK 1.2

DESCRIBING

1 **Describe** where kinetic energy and potential energy are found in a substance at a molecular level.

2 What happens to the internal energy of a substance if the average kinetic energy of its particles increases?

3 **Identify** what happens to the internal energy of a substance if the amount of potential energy stored in its intermolecular bonds decreases.

4 **Determine** the energy transformations that occur when the steam produced in a coal-fired power plant cause the turbines to spin.

5 **Explain** what happens to the potential energy of a bond if the bond is stretched or compressed away from its ideal length.

6 **Compare** heat and temperature.

7 **Explain** why an increase in the internal energy of a substance does not always result in an increase in temperature.

APPLYING

8 **Construct** an approximate Boltzmann distribution for the number of particles at a range of kinetic energies in a sample of water at the following temperatures.

  a −150°C
  b 25°C

9 **Construct** a flow diagram that shows the relationships between the concepts of kinetic energy, potential energy, internal energy, heat and temperature.

anthropogenic human-derived; caused by human activity

1.3 Heat transfers

Understanding heat and controlling the transfers and transformations of heat energy is vital for the survival, health and wellbeing of all living things. Humans have a unique responsibility to use that knowledge wisely.

As a society, we continue to produce and consume large amounts of energy. Much of this energy is wasted as heat that is released into the environment. This ‘wasted’ heat results in an increase in the overall amount of thermal energy in the global system and is a key component of **anthropogenic** climate change. In reducing the global climate footprint, there is an increasing focus on the use of insulation, increasing efficiency and transitioning to renewable energy sources such as solar, wind, wave, hydro and fusion.

Heat energy always moves from a region of high temperature to a region of low temperature. It can be transferred by conduction, convection or radiation (Figure 1.3.1) – processes that are vital to the continued existence of life on Earth.

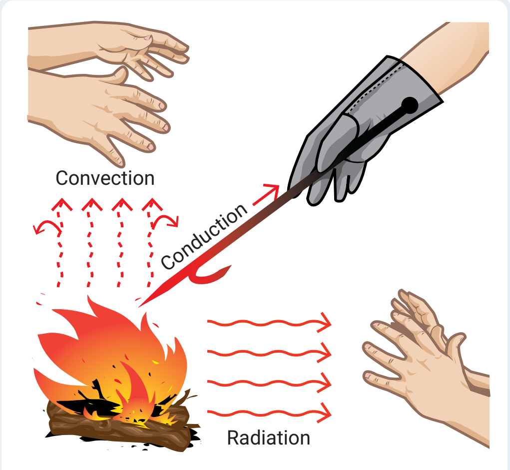


FIGURE 1.3.1 Heat can be transferred by conduction, convection and radiation.

Conduction

Conduction is the transfer of heat energy through a substance by the action of particle collisions. When two substances at different temperatures are in contact with each other, the particles of the hotter substance collide with those in the colder substance and transfer kinetic energy. This transfer of heat results in a decrease in the total kinetic energy of the hotter substance and an increase in the overall kinetic energy of the colder substance.

Different materials have different conducting properties. **Thermal conductivity** is a measure of how efficiently heat flows through a substance. Solids are better **heat conductors** than liquids or gases. **Heat insulators** are poor heat conductors.

Metals

Metals are particularly good heat conductors. They have large thermal conductivities. The large numbers of unattached electrons in metals are relatively free to move, and so transfer kinetic energy quickly. These **delocalised valence electrons** transfer energy to other electrons and atoms faster than electrons that are tightly bonded (Figure 1.3.2).

conduction the process by which energy is transferred through the collision of particles

thermal conductivity a measure of how efficiently heat can be conducted through a material

heat conductor a material that readily allows the transfer of heat

heat insulator a material that is a poor conductor of heat

delocalised valence electrons the outer electrons of metal atoms that are free to move

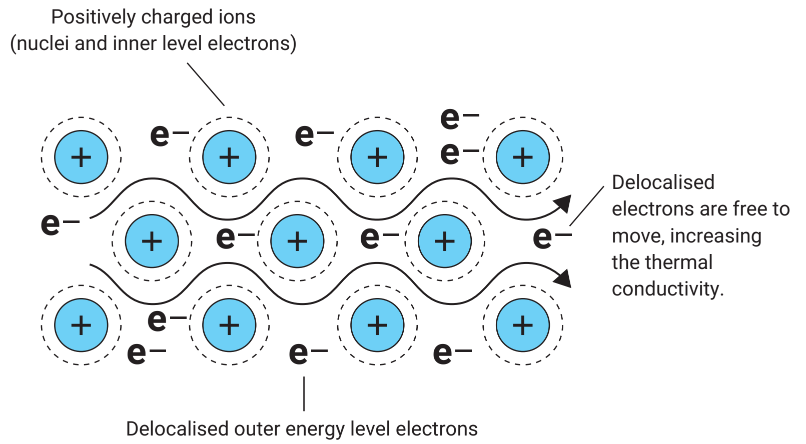


FIGURE 1.3.2 The delocalised electrons in metals are free to move and can conduct thermal energy quickly.

Weblink
Simulation of thermal conduction

Good heat conductors, such as liquid sodium, are used in some nuclear reactors to transfer heat to water. Other good conductors are used in refrigerators, disc brakes, computer heat sinks and car engine radiators.

Almost all non-metal materials, including gases, are insulators. Unlike metals, non-metals do not have free delocalised electrons. Energy transfer occurs between relatively fixed neighbouring particles. When they are cold, birds and cats fluff their feathers and fur to trap air, which acts as an insulator. Consequently, less heat is transferred from their bodies.

Good insulators are used in house insulation, thermos (Dewar) flasks, padded jackets and doonas.

The Dewar flask

Sir James Dewar (1842–1923) designed a flask to minimise energy transfers by conduction, convection and radiation. Dewar flasks are used to store hot or cold liquids such as liquid nitrogen (boiling point 77 K) and liquid oxygen (boiling point 90 K). They have a double-walled Pyrex glass vessel with silvered walls to reflect heat (Figure 1.3.3). The space between the walls of the flask is evacuated. The small neck also helps reduce heat transfer.

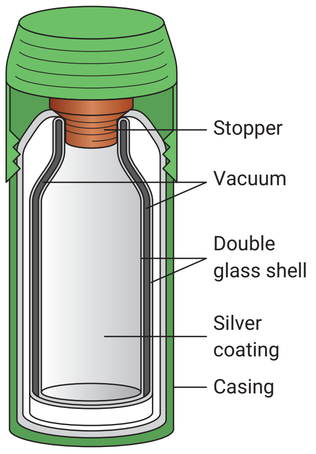


FIGURE 1.3.3 A Dewar flask is used to store hot or cold substances.

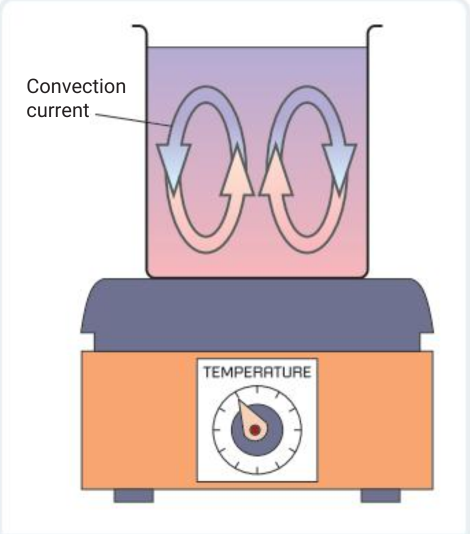


FIGURE 1.3.4 Convection currents and convection cells occur where warm and cold fluid masses intersect; for example, in the atmosphere and oceans and in hydronic home heating systems.

Convection

Convection is the transfer of heat energy by the bulk movement of particles. The flow of particles away from a warmer to a cooler region produces a convection current. These currents result in a net flow of heat away from the warmer region to the colder region.

Convection currents only occur in fluids (substances that flow when an external force is applied to them, e.g. liquids and gases), which have relatively weakly connected particles, and more so in gases than liquids because the particles in a gas are less tightly connected. In Figure 1.3.4, warm, less dense water at the bottom flows upwards, while the denser water at the top sinks. A **convection cell** is produced.

Thermal currents

Thermal currents (thermals) were first used for glider flight in 1921 by William Leusch in Germany, 20 years after the first powered flight. The pilot uses a thermal to increase altitude by flying in a spiral pattern before flying off to the next thermal. Thermals appear over towns, freshly ploughed fields, sealed roads and, occasionally, over power stations and fires.

Weblink
Heat transfer

Radiation

Radiation is energy transfer that does not need a medium. Unlike conduction and convection, radiation does not involve particles of matter. Except at 0 K, all objects emit electromagnetic radiation (Figure 1.3.5).

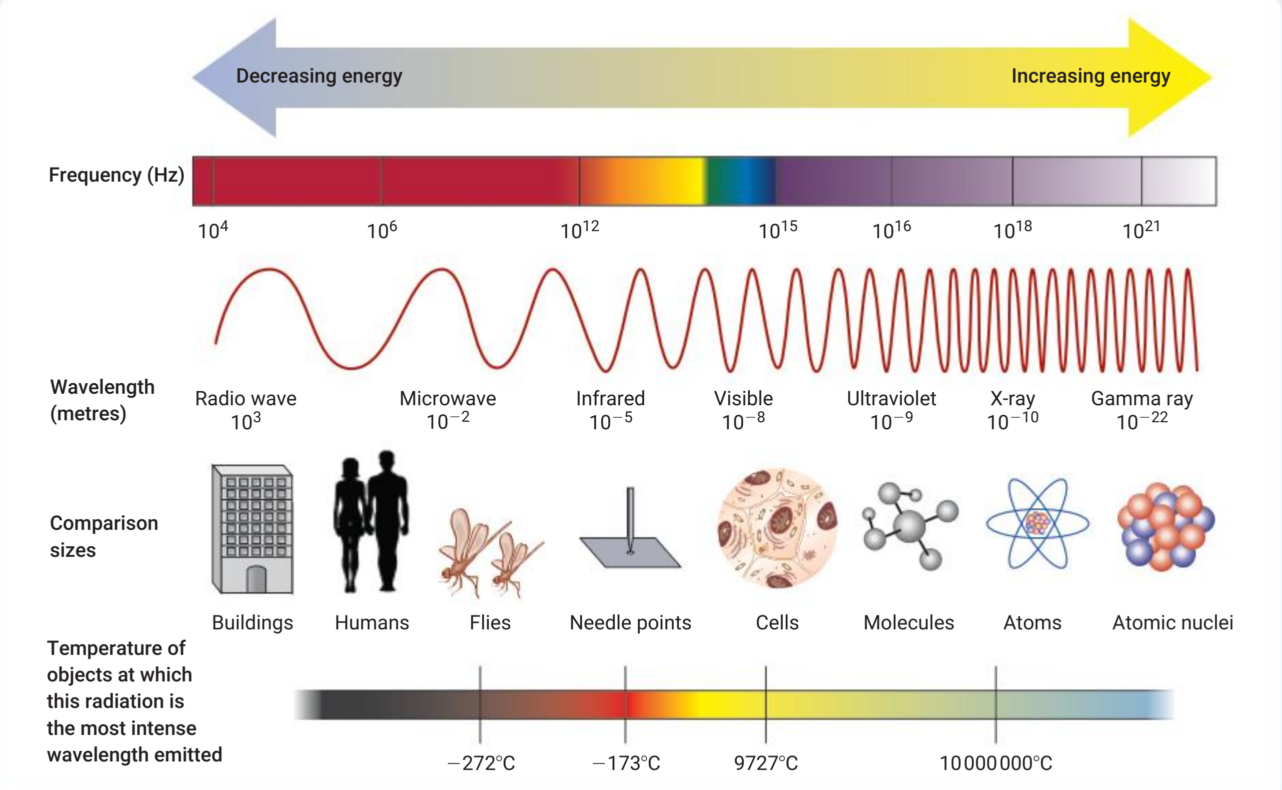


FIGURE 1.3.5 The electromagnetic spectrum

The intensity of radiation from an object clusters around a peak temperature on a Planck radiation curve such as the one shown in **Figure 1.3.6**. Any object with a temperature greater than absolute zero emits electromagnetic radiation. In space, gas clouds (about 0 K) emit radio waves, stars (3000–30 000 K) emit ultraviolet and visible light. Warm bodies mostly emit infrared radiation. At about 500 K, objects glow dull red. Stars such as Spica, which mostly emit ultraviolet light, have temperatures of about 22 000 K. The radiation emitted by objects can be compared to Planck curves in order to calculate their temperature.

When radiated energy (radiant heat) interacts with an object, some of that energy is absorbed and the rest is reflected. The fraction that is absorbed depends on the type of surface material, its texture and its colour. Black and dark-coloured surfaces absorb more radiant heat than white or light-coloured surfaces. Hence, a black car gets hotter inside than a white car on a sunny day.

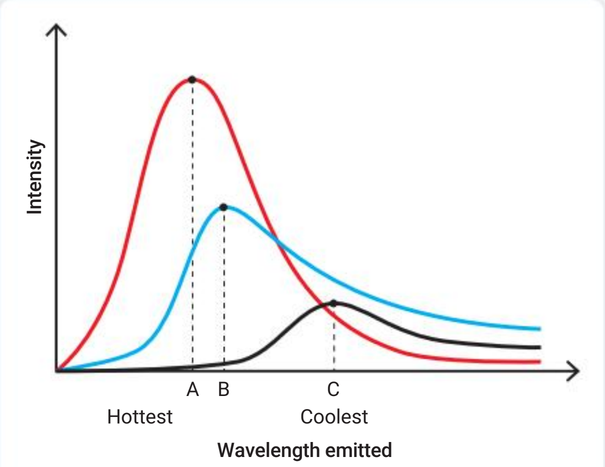


FIGURE 1.3.6 Planck curves showing peak intensities for three objects at different temperatures. Note that the temperature of the objects ranges from coolest on the right to hottest on the left.

LEARNING CHECK 1.3

DESCRIBING

1 **Identify** situations where heat transfer by the following would be commonly observed.
  - **a** Conduction
  - **b** Convection
  - **c** Radiation

2 List the following regions of the electromagnetic spectrum in order of increasing temperature of their sources.
  - Infrared
  - X-ray
  - Visible

APPLYING

3 **Explain** why copper is a better thermal conductor than wood.

4 **Explain** why the temperature at the surface of a large body of water is generally warmer than the water lower down.

5 **Describe** the heat exchanges that occur in the process of energy being transmitted from the Sun onto the surface of Earth and eventually into the movement of air in the form of wind.

6 **Apply** your understanding of heat exchange to draw the motion of water directly above an erupting underwater volcano.

Worksheet
Energy and particles

convection the process by which energy is transferred through the bulk motion of a fluid

convection current fluid circulating as a result of heating at a point or localised region; movement of a fluid because of convection

convection cell the condition that occurs when there are density differences within a fluid; the density differences result in rising and falling currents

thermal current a rising air column of hotter air caused by the process of convection

radiation the process by which heat is transferred without the need for a medium; energy transfer across space; energy from radioactive atoms

CHAPTER SUMMARY

Key formulas

- The kinetic particle model assumes that:
    - all matter is made up of small particles that are constantly moving
    - when particles collide, the total kinetic energy before and after the collision is the same
    - the particles only interact with each other when they collide.
- When particles collide elastically, the total kinetic energy before and after the collision is the same.
- The average kinetic energy of an ideal gas is directly proportional to its temperature:

$$E_{\text{k average}} \propto T$$

where: $E_{\text{k average}}$ = average kinetic energy of the particles in a substance (J)
T = temperature (K)

Energy

- Energy is transformed from one form to another and transferred from one place to another.
- Kinetic energy is energy due to motion.
- Energy is conserved in an elastic collision:

$$E_{\text{k initial}} = E_{\text{k final}} \qquad \Delta E_{\text{k}} = 0$$

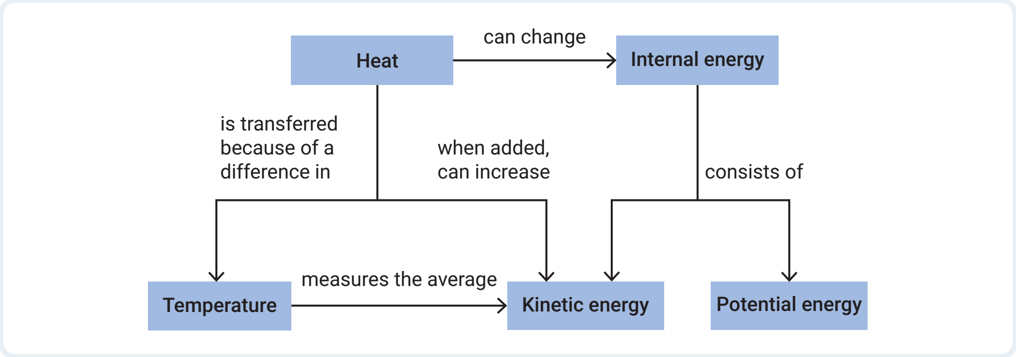
where: $E_{\text{k initial}}$ = initial kinetic energy of a particle (J)
$E_{\text{k final}}$ = final kinetic energy of a particle (J)
ΔE_{k} = change in kinetic energy of a particle (J)

- The internal energy of a substance is equal to the sum of the potential and kinetic energy of all of its particles:

$$U = E_{\text{k}} + E_{\text{p}}$$

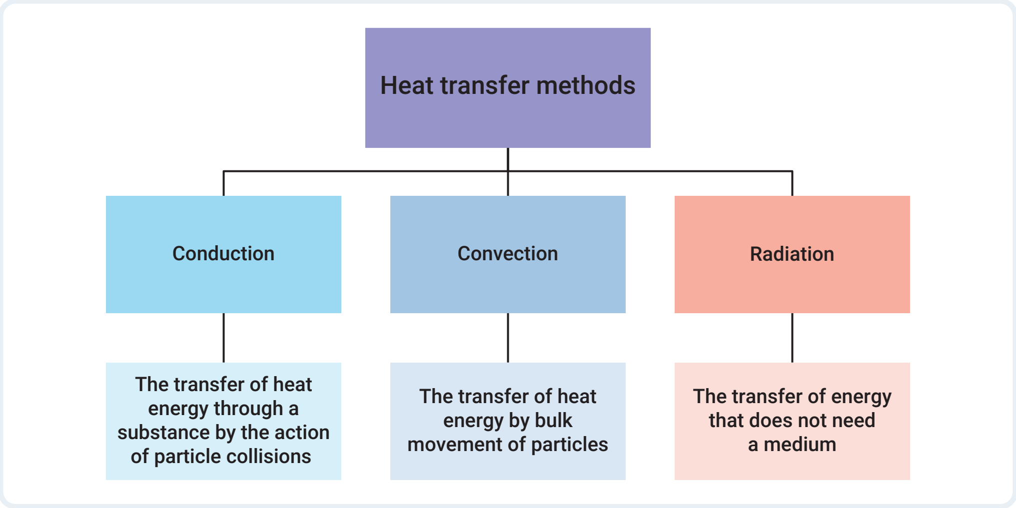
where: U = internal energy of a substance (J)
E_{k} = total kinetic energy of the particles of a substance (J)
E_{p} = total potential energy stored in the bonds of a substance (J)

- Energy, heat and temperature are interrelated.



Heat transfer methods

- The three main methods of heat transfer are conduction, convection and radiation.



CHAPTER EXAM

MULTIPLE CHOICE

1. If a substance is described as having a fixed shape and volume, which of the following states of matter is the substance in?

A Gas
B Liquid
C Plasma
D Solid

2. Which of the following is not an assumption of the kinetic particle model?

A Temperature is transferred through conduction.
B Collisions between particles are perfectly elastic.
C The motion of particles obeys classical mechanics.
D All matter is made up of small particles in constant motion.

3. Which of the following is an example of potential energy?

A Energy that is transferred as heat
B Energy that emits infrared radiation
C Energy due to the motion of an object
D Energy stored by the displacement of particles

4. Which of the following properties of a metal gives rise to it being described as a good heat conductor?

A Its shiny lustre
B Its malleability
C Its reactivity with acids
D Its large number of free electrons

5. Which of the following heat transfer methods would be most likely to occur in a volume of gas?

A Conduction
B Condensation
C Convection
D Radiation

6. An object with a temperature of –150°C would most likely emit radiation in what part of the electromagnetic spectrum?

A Gamma rays
B Infrared
C Radio waves
D Visible light

7. Steam at 100°C is more dangerous than the same mass of water at 100°C because the steam:

A is less dense.
B moves faster.
C contains more internal energy.
D has a higher specific heat capacity.

8. When a liquid evaporates:

A it absorbs heat.
B it gives off heat.
C its temperature drops.
D its temperature rises.

9. At a football match, a flamethrower shoots flames up into the air when a goal is scored. You instantly feel the heat where you are sitting high up in the stands. The heat was most likely transferred to you by:

A conduction.
B convection.
C insulation.
D radiation.

10. A minute after the event in Question 9, you feel a wave of warm air rise up to you high in the stands. This heat was most likely transferred from the flamethrower to you by:

A conduction.
B convection.
C insulation.
D radiation.

SHORT RESPONSE

11. **Explain** what happens to the particles of a substance when heat is added to it.

12. If a container of liquid contains 10 000 J of internal energy and 6000 J of potential energy, calculate the amount of kinetic energy of the particles.

13. Contrast the average kinetic energy per particle as well as the total kinetic energy between a large bathtub full of water at 60°C and a 100 mL beaker full of water at 70°C.

DATA ANALYSIS

14. **Analyse data**

Look at Figure 1.3.5. **Describe** the relationship between frequency of electromagnetic radiation, wavelength of electromagnetic radiation and energy.

15. **Analyse data**

Consider the Boltzmann distribution in Figure 1.2.2. Include a third temperature showing the distribution of kinetic energies of particles at 200°C.

CHAPTER

2

Temperature and specific heat capacity

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SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- 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 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.
- Investigate the proportional relationship between heat and temperature change.
- Investigate specific heat capacity of a substance.

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Introduction

One of the most important and interesting processes undertaken by scientists is that of experimental investigation. Science is about discovering knowledge and processes through observation and experiment, by verifiable and reproducible means, which is what investigation is all about. This is why investigations are central to science, and why they are so much fun.

In this chapter, we will investigate how to measure the temperature of an object and the relationship between temperature and applied heat. We will also examine why the temperature of an object changes when heat is added.

Practicals

- Accuracy and precision of thermometers
- Specific heat capacity of water
- Specific heat capacity of metals

Worksheets

- Understanding specific heat capacity
- Hot water systems and heat energy loss

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ The Celsius scale is used to measure temperature.
- ✓ Heat is a type of energy that can flow from an area of high temperature to an area of low temperature.
- ✓ Heat can be absorbed by or reflected from materials.
- ✓ A thermometer is used to measure temperature.
- ✓ Temperature measures the average kinetic energy of particles in a system, whereas heat describes the transfer of energy between systems or objects.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain quantitative and qualitative measurements
- ✓ categorise quantitative and qualitative measurements
- ✓ describe and explain the Celsius and Kelvin temperature scales
- ✓ use $T_K = T_C + 273$ to convert between °C and K
- ✓ recall that 0 K is approximately –273°C
- ✓ describe and explain the second law of thermodynamics
- ✓ compare the temperatures in common contexts of modern life
- ✓ explain that a change in temperature is due to the addition or removal of energy from a system
- ✓ describe and explain the concept of specific heat capacity
- ✓ solve problems involving specific heat capacity
- ✓ interpret data from specific heat capacity experiments using mathematical, tabular and graphical analysis
- ✓ use power to determine the rate of heat being delivered to a system such as a calorimeter
- ✓ perform extrapolations and interpolations using experimental data
- ✓ linearise data to investigate proportionality
- ✓ consider information to:
  - appraise the development, usefulness and application of different temperature scales
  - explore the development of scientific models to explain thermodynamic phenomena.

2.1 Converting temperature

In common experience, the temperature of an object is a measure of how hot or cold something is. A freshly brewed cup of coffee is said to be hot and a swimming pool on a winter's day is said to be cold. These are examples of **qualitative** measurements.

qualitative non-numerical data; descriptive information

quantitative numerical data; a specific amount

The temperature of an object is directly related to the average kinetic energy of the particles making up the substance. As it is very difficult to measure the kinetic energy of these individual particles, it is important to be able to gain a **quantitative** measurement of the temperature of a substance.

A numerical temperature scale

One way to define a numerical temperature scale is by assigning arbitrary values to two common temperatures and then creating a scale of values between them.

The scale that is most commonly used today is the Celsius or centigrade scale (in a few countries the Fahrenheit scale is used). The most important scale for scientists is the absolute or Kelvin scale.

Celsius

The Celsius scale uses the boiling and freezing points of water at a standard atmospheric pressure as the fixed points that represent temperatures that are universally familiar. The Celsius scale assigns the value of 0°C ('zero degrees Celsius') to the freezing point of water and 100°C to its boiling point. The distance between these points is then divided into 100 equal intervals, each marking a degree (hence, the term the 'centigrade' scale).

The Kelvin scale

The Kelvin scale was developed in the 1800s by William Thompson (also known as Lord Kelvin), who critically examined the recently discovered relationship between the volume and temperature of a gas. As a result of his investigations, he theorised that the volume of an ideal gas should become zero at a temperature of approximately −273°C. The only way that this could happen, he hypothesised, was if the kinetic energy of the particles was also zero. It is for this reason that he coined the term **absolute zero** to indicate infinitely cold.

Kelvin used absolute zero as the basis for an absolute temperature scale. Each increment on this scale is called a kelvin rather than a degree and is equal in value to 1° on the Celsius scale. When reporting the temperature in kelvin, the symbol K is used in place of the degree Celsius (°C) symbol.

Just like the Celsius scale, the boiling and freezing points of water are used to determine the range of the Kelvin scale. Water is said to freeze at 273 K (stated as '273 kelvin') and therefore the boiling point is 100 K higher at 373 K (Figure 2.1.1).

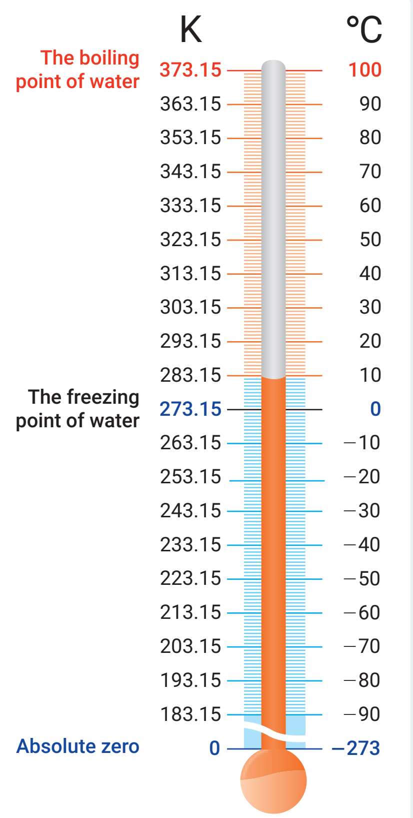

FIGURE 2.1.1 The Kelvin scale compared with the Celsius scale

absolute zero the theoretical lowest possible temperature; −273°C on the Celsius scale or 0 K on the absolute or Kelvin scale

KEY FORMULA

Conversion between the Kelvin (absolute) and Celsius scales:

$$T_K = T_C + 273$$

where:

T_K = temperature in kelvin (K)
T_C = temperature in degrees Celsius (°C)

WORKED EXAMPLE 2.1.1

a The highest ever recorded temperature in Queensland was measured on 12 February 2017 in Thargomindah, when the Bureau of Meteorology recorded a sweltering 47.2°C. Calculate what this temperature is on the Kelvin scale.

b Under standard atmospheric conditions, gaseous oxygen becomes liquid at 90 K. Calculate what this temperature is on the Celsius scale.

ANSWERS

a 1 Use the equation.

$T_K = T_C + 273$

2 Substitute the known values.

$T_K = 47.2 + 273$

3 Calculate the answer and use the correct units.

$T_K = 320.2\ \text{K}$

b 1 Use the equation.

$T_K = T_C + 273$

2 Rearrange for the value of interest.

$T_C = T_K - 273$

3 Substitute the known values.

$T_C = 90 - 273$

4 Calculate the answer and use the correct units.

$T_C = -183°\text{C}$

The Kelvin scale is popular in scientific circles because it does not contain negative numbers and is therefore convenient for recording very low temperatures such as the point at which gases become liquid (e.g. nitrogen gas becomes liquid at −195°C or 78 K). The lack of negative numbers makes it simpler to compare different temperatures. Some interesting temperatures are listed in Table 2.1.1.

Weblink
Interactive temperature converter

TABLE 2.1.1 Interesting temperatures on the Kelvin and Celsius scales

Interesting temperatures	Temperature	
	K	°C
Absolute zero	0	−273
Average temperature of space	2.725	−270.425
Helium liquefies	4	−269
Oxygen liquefies	90	−183
Lowest recorded surface air temperature on Earth (Russia's Vostok Station in Antarctica, on 21 July 1983)	184	−89
Average surface air temperature on Earth	288	15
Normal human body temperature	310	37
Highest recorded surface air temperature on Earth (Furnace Creek Ranch in Death Valley California, USA)	331	58
Titanium melts	1941	1668
Temperature of the surface of the Sun	5778	5505
Temperature in the core of the Sun	15.7×10^6	15.7×10^6

Absolute zero

The Kelvin scale uses absolute zero – the temperature at which the motion of particles should cease – as its reference point, but the **second law of thermodynamics** states that heat always moves from a hotter object to a colder object, so can we actually reach absolute zero?

The answer is no, because for a substance to reach the lowest of temperatures, 0 K, it would need to transfer energy to something that is colder. For this to occur, the second object would need to be below absolute zero, and we are yet to find anything that cold! In addition, the kinetic particle model states that at absolute zero, there is no energy and hence no movement in any of the particles of matter even at a subatomic level. There is no evidence that such a state can exist.

second law of thermodynamics the direction of heat flow is always from a hotter object to a colder object

LEARNING CHECK 2.1

DESCRIBING

1 **Identify** the lowest possible temperature on the Kelvin scale. How is this defined?
2 Why is it important to have a universal temperature scale that is used by all scientists?
3 Outline the advantages of using the Kelvin scale when taking measurements.
4 **Classify** the following measurements as qualitative or quantitative.
  - **a** The water is warm.
  - **b** The water is 318 K.
  - **c** The patient has a temperature of 38.4°C.
  - **d** The patient is running a temperature.
  - **e** Today is hotter than 35°C.

APPLYING

5 The temperature at which most people begin to feel a burning sensation is 54°C. What is this temperature on the Kelvin scale?
6 Write an equation that allows you to convert a temperature on the Kelvin scale to a temperature on the Celsius scale.
7 **Explain** any disadvantages there may be in using the Kelvin scale.

2.2 Measuring temperature

As the temperature of a substance changes, so do many of its properties. Some properties change in predictable ways; for example, the volume of most substances increases when they are heated. The concrete in footpaths changes size depending on its temperature, and it is for this reason that expansion joints are included to prevent cracking. Another property that can change is the electrical resistance of an electrical conductor; generally, resistance increases as temperature increases because the increased vibration of the particles inhibits electrical flow.

Weblink
Simulation of the what thermometers measure

To measure the temperature of an object quantitatively, an instrument called a **thermometer** is used. There are many different types of thermometers, but they all operate by making a measurement of some form of temperature-dependent property of the thermometer (Figure 2.2.1). Table 2.2.1 lists some common types of thermometers and the properties that allow them to measure temperature.

thermometer a device that measures temperature or a temperature gradient


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FIGURE 2.2.1 Many different thermometers are used to measure the temperature of objects. They all measure a property of the thermometer that changes with temperature.

TABLE 2.2.1 Physical properties that allow thermometers to indicate temperature change

Type of thermometer	Property
Mercury in glass	Different coefficients of expansion between mercury and glass
Thermocouple	Different temperature-dependent electrical properties of different metals that are brought into contact
Thermostat	Variation in electrical resistivity of a material with temperature
Thermal paint	Colour change with temperature
Bimetallic strip	Variation in coefficients of expansion between two different metals to detect temperature changes
Infrared	The electromagnetic radiation radiated from a surface to measure temperature on the absolute temperature scale
Digital	The variation in resistivity of a material with temperature; the greater the resistance, the lower the current

PRACTICAL ACTIVITY 2.2.1

ACCURACY AND PRECISION OF THERMOMETERS

Research question

Are there differences in the accuracy and precision among a range of thermometers?

Aim

To measure and compare the precision and accuracy of a variety of thermometers

Materials

- a collection of different thermometers (e.g. alcohol thermometer, probe thermometer, infrared thermometer)
- Styrofoam cup
- glass beaker
- water
- boiling chips
- crushed ice
- Bunsen burner
- tripod
- heating mat
- retort stand
- barometer

RISK ASSESSMENT

What are the risks in doing this activity?	How can you manage these risks to stay safe?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Hot water can scald.	Wear safety glasses. Avoid spilling or splashing boiling water.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

Part A: Thermometer identification

1. If possible, note the manufacturer, serial number and manufacture date of each thermometer. Record this in a table like the data table for Part A.
2. Record the temperature range of the thermometer.
3. Record the type of thermometer.
4. Find the precision of the thermometer by looking at either the intervals marked or the specifications of the thermometer.

Part B: Calibration at the ice point of water

1. Fill a Styrofoam cup with crushed ice.
2. Add enough pre-cooled distilled water to cover the ice, but not enough so that the ice floats.
3. Thoroughly stir the ice-water mixture for a period of approximately 1 minute.
4. Secure the thermometer to the retort stand so that it is properly inserted into the ice-water mixture.
5. Allow the temperature of the thermometer to stabilise and record the result in a table like the data table for Part B.
6. Repeat steps 1–5 for each thermometer.

Part C: Calibration at the boiling point of water

1. Set up the beaker on the tripod with the Bunsen burner beneath it.
2. Half-fill the beaker with water and add a few boiling chips.
3. Secure the thermometer to the retort stand so that it is properly inserted into the water.
4. Light the Bunsen burner and allow the water to come to its boiling point.
5. Allow the temperature on the thermometer to stabilise and record the result in a table like the data table for Part C.
6. Repeat steps 1–5 for each thermometer.
7. Record the atmospheric pressure in the room in which you are experimenting.

Results

Data table for Part A

Thermometer data	Thermometer 1	Thermometer 2	Thermometer 3	Thermometer 4
Manufacturer				
Serial number				
Date of manufacture				
Range				
Type				
Precision				

Data table for Part B

Thermometer data	Thermometer 1	Thermometer 2	Thermometer 3	Thermometer 4
Ice point temperature (°C)				
Uncertainty (°C)				

Data table for Part C

Thermometer data	Thermometer 1	Thermometer 2	Thermometer 3	Thermometer 4
Boiling point temperature (°C)				
Uncertainty				
Atmospheric pressure (mmHg)				

Analysis of results

1. Report the ice point temperature for each thermometer, including the absolute uncertainty and the percentage uncertainty.
2. Calculate the relative error in the ice point measurement of each thermometer, if the ice point occurs at 0.0°C.
3. Report the boiling point temperature for each thermometer, including the absolute uncertainty and the percentage uncertainty.
4. Calculate the relative error in the boiling point measurement of each thermometer, if the boiling point occurs at the temperature associated with the measured atmospheric pressure as given in Table 2.2.2.

TABLE 2.2.2 The relationship between the boiling point of water and atmospheric pressure

Atmospheric pressure (mmHg)	Boiling point of water (°C)
760	99.996
750	99.629
740	99.257
730	98.880
720	98.499
710	98.112
700	97.720
690	97.323
680	96.921
670	96.512
660	96.098
650	95.676
640	95.249
630	94.814
620	94.371
610	93.921
600	93.463

Interpretation

5 For which thermometers did the ice point of water lie within the range of measurements?

6 For which thermometers did the boiling point of water lie within the range of measurements?

7 Rank the thermometers in order of decreasing precision.

Evaluation

8 Which of the thermometers would you choose to use if an experiment asked you to repeat the above measurements? Why?

9 Tap water commonly contains dissolved salts. What effect will this have on the freezing point of water? What type of error will this result in?

10 What effect would wetting the stem of the thermometers have on the measured results? What type of error would this result in?

LEARNING CHECK 2.2

DESCRIBING

1 **Describe** a thermometer.

2 For each of the digital and thermostat thermometers listed in Table 2.2.1, **identify** the property that allows the thermometer to measure temperature.

3 **Explain** the key features of a thermometer that allows it to make a measurement of the temperature of an object.

APPLYING

4 Why do railway lines have gaps between each section of line?

2.3 Changes in temperature

It is common knowledge that an increase in temperature requires an addition of heat. But the exact mechanics of how this takes place requires an understanding of the kinetic particle model.

In the 18th century, heat flow was considered to be a movement of a fluid called the 'caloric'. This fluid has never been detected and we now consider heat to be a transfer of energy. A common unit to measure heat still in use today is the **calorie** (cal), which is the amount of heat energy required to raise the temperature of 1 g of water by 1°C. It is equivalent to 4.186 J.

calorie the amount of heat energy required to raise the temperature of 1 g of water by 1°C; 1 cal = 4.186 J

The modern understanding of temperature change is that as heat is added to a substance, it increases its internal energy. If this change in internal energy is due to an increase in kinetic energy (remembering that internal energy is the sum of kinetic and potential energy), there will be a resulting increase in temperature. This is because the temperature of an object is proportional to the average kinetic energy of the particles in that object.

Adding heat initially increases the kinetic energy of particles in contact with the heat source through the process of conduction. This results in an immediate increase in the average kinetic energy of the entire object.

These particles then go on to elastically collide with their neighbouring particles and transfer some of their kinetic energy in the process. This results in a decrease in the kinetic energy

diffusion the spontaneous movement of substances or energies from areas of high concentration to areas of low concentration

of the original particles, which may subsequently come in contact again with the heat source and once again gain kinetic energy. As a result of the collision, the neighbouring particles that gained kinetic energy may then go on to elastically collide with their neighbouring particles or indeed with the original particles again. In this way, heat flows or undergoes **diffusion** throughout an entire object very quickly.

The speed of this process depends on the thermal conductivity of the substance, and it continues as long as the heat source is present or until a phase change temperature is approached.

When the temperature of an object is reduced, the particles in direct contact with a colder object lose kinetic energy through conduction. As each collision transfers energy from one particle to another, the particles in contact with the colder object are steadily losing energy, and the average kinetic energy and hence the temperature of the overall substance decreases (Figure 2.3.1).

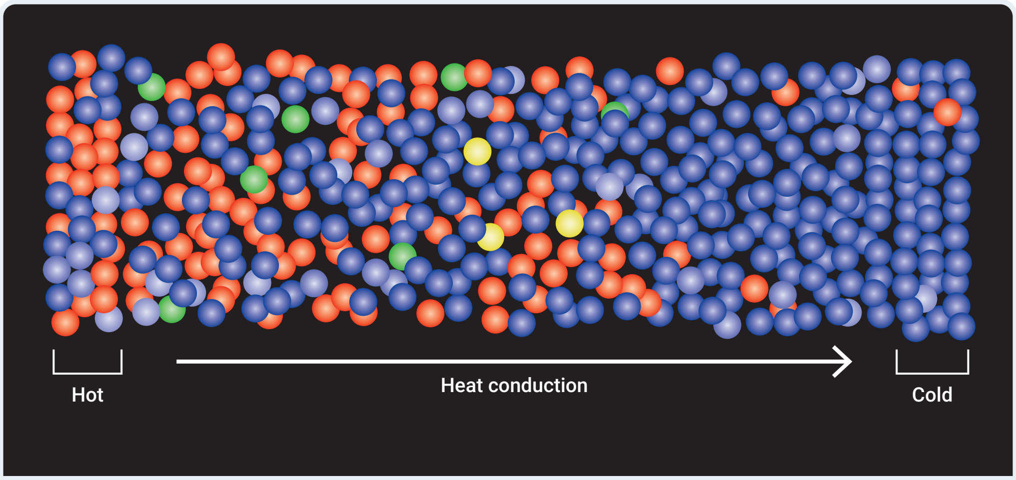

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FIGURE 2.3.1 An image representing the kinetic energy of individual particles in a liquid as heat is conducted through it from a heat source on the left. Particles in red have a higher kinetic energy than particles in blue.

LEARNING CHECK 2.3

DESCRIBING

1 List the two common units of heat. Which one of these is the SI unit?

2 **Describe** how heat is connected to kinetic energy.

3 When a heat source warms an object, does temperature flow between them?

APPLYING

4 **Explain** what is happening on a particle level when a bar heater is used to warm up a room.

5 **Explain** what is happening on a particle level when an air conditioner is used to cool down a room.

6 **Calculate** how many joules of energy are in 150 calories.

7 **Calculate** how many calories are in 1400 J.

8 The watt is a unit that quantifies the rate of energy transfer and is 1 J s^{-1}. If a 200 W heating filament is placed in water for 2.0 minutes, how much heat is transferred to the water?

2.4 Specific heat capacity and proportionality

If heat flows into an object, its temperature will rise (as long as it is not undergoing a phase change).

Early experimenters discovered that the amount of heat Q required to change the temperature of a substance is proportional to the mass m of the substance and the temperature change ΔT that the substance goes through. This can be neatly described by the equation below, where c is a material-specific quantity called its specific heat capacity:

$$Q = mc\Delta T$$

where:

Q = the amount of heat added to or removed from the substance (J)

m = the mass of the substance (kg)

c = the specific heat capacity of the substance (J kg^{-1} °C^{-1} or J kg^{-1} K^{-1})

ΔT = the change in temperature (°C or K)

KEY FORMULA

Specific heat capacity

$$Q = mc\Delta T$$

where:

Q = the amount of heat added to or removed from the substance (J)

m = the mass of the substance (kg)

c = the specific heat capacity of the substance (J kg^{-1} °C^{-1} or J kg K^{-1})

ΔT = the change in temperature (°C or K)

The **specific heat capacity** of a substance is a measure of the amount of energy required to raise the temperature of 1 kg of that substance by 1°C. This is a physical property of the material and is related to its structure. Specific heat capacity has units of J kg^{-1} °C^{-1} or J kg^{-1} K^{-1}.

Water has a high specific heat capacity. Cooking oil has a much lower specific heat capacity. Oil heats up and cools down almost twice as quickly as water. Table 2.4.1 gives the specific heat capacities of some common substances.

specific heat capacity the amount of energy required to increase the temperature of 1 kg by 1°C (or kelvin) of a substance without a change of phase; unit: J kg^{-1} K^{-1} or J kg^{-1} °C^{-1}

Weblink
Specific heat capacity

TABLE 2.4.1 Specific heat capacities of some common substances

Substance	Specific heat capacity (J kg^{-1} K^{-1})
Water	4180
Ethylene glycol (antifreeze)	2400
Cooking oil	2800
Ice	2100
Steam	2000
Air	1000
Aluminium	900
Soil	800
Crown glass	670
Iron	450
Copper	380
Lead	130

Investigating specific heat capacity

A student undertook an investigation by heating 1 kg of an unknown liquid by adding heat energy to it at a steady rate of 150 J s^{-1} for 210 s. The temperature was measured at regular intervals during the heating process and the data recorded was plotted as shown in Figure 2.4.1.

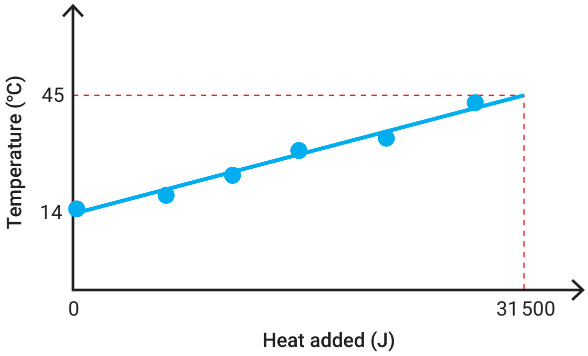


FIGURE 2.4.1 A graph showing that the change in temperature of the liquid is directly proportional to the amount of energy put in

dependent variable the variable that changes as a result of a change in the independent or controlled variable

independent variable a variable on which another variable is dependent; also called the controlled variable

The graph shows that the temperature T of a body (the **dependent variable**) goes up in direct proportion to the amount of heat energy Q (the **independent variable**) put into the liquid: $\Delta T \propto Q$.

The experiment was then repeated using only 0.5 kg of the unknown liquid. All other conditions were kept the same as in the first experiment. The data was recorded and plotted as shown in Figure 2.4.2.

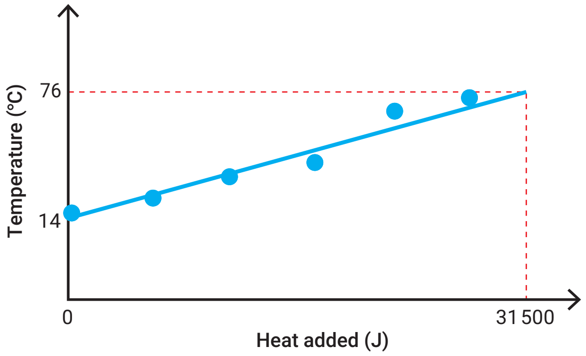


FIGURE 2.4.2 The graph shows that for the same energy input into half the mass, the temperature increase is doubled.

The second graph shows that for the same energy input, *half* the mass increases its temperature (the independent variable) by *twice* as much. Therefore, the change in the temperature of the body is inversely proportional to the mass of the body (a dependent variable):

$$\Delta T \propto \frac{1}{m}$$

Putting these two findings together gives us the relationship:

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

There is always a constant, c, that makes a proportionality an equality, so by rearranging you get:

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

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

The constant c is the specific heat capacity of the substance that is being heated; Q is the quantity of energy supplied; m is the mass of the body being heated and ΔT is the change in temperature. The units of the specific heat capacity can be found by substitution of the units into the last formula:

$$\text{Units of } c = \frac{\text{J}}{\text{kg K}} = \text{J kg}^{-1}\,\text{K}^{-1}$$

The relationships are then expressed in their simplest algebraic form:

$$Q = mc\Delta T$$

This is a good example of how careful experimentation provides useful data to find meaningful relationships (formulas). These relationships can then be used to predict what will happen under a different set of given conditions.

Weblink
Simulation of differences in specific heat capacity

Specific heat capacity of water

Water has the highest specific heat capacity of most commonly occurring substances: 4180 J kg^{-1} K^{-1}. Water:

- heats up more slowly
- cools down more slowly
- stores more internal energy than the same mass of most other substances.

Many cooling and heating systems, from hot water bottles to water-cooled engines, use water's high specific heat capacity. Large bodies of water, such as oceans, seas and lakes, absorb large amounts of energy with only small temperature changes of the water. For the same amount of energy input, landmasses undergo much greater temperature changes. The temperatures inland are much higher than on islands and in coastal regions. During the warmer months, when the sea temperature is less than the average air temperature, the sea acts as a **heat sink**. During the colder months, when the sea is warmer than the average air temperature, it releases the stored energy. This release of energy moderates the temperature of regions close to large bodies of water.

Worksheet
Understanding specific heat capacity

heat sink an object or material that moderates the temperature of its surroundings due to its large specific heat capacity

LEARNING CHECK 2.4

DESCRIBING

1 What does it mean when we say that the specific heat capacity of iron is 450 J kg^{-1} K^{-1}?

2 If 2000 J of heat is required to raise the temperature of an object by 1°C, by how much will the temperature of the same object increase if 4000 J of heat is added to it?

3 If 400 J of heat is required to raise the temperature of 1 kg of a substance by 1°C, how much heat will be required to raise the temperature of 500 g of the same substance by 1°C?

4 Use the specific heat formula $Q = mc\Delta T$ to derive the units of specific heat capacity.

APPLYING

5 **Compare** the specific heat capacities of ice, water and steam, and rank them in increasing order of the heat required to raise each of their temperature by 1°C.

6 **Discuss** why the high specific heat capacity of water is important for its use in heating and cooling systems.

2.5 Solving problems involving specific heat capacity

Worksheet
Hot water systems and heat energy loss

As a general rule, when solving problems for specific heat capacity, it is important to check the given units and if necessary convert them to the SI equivalent. It is also important to note that although the equation for solving specific heat capacity looks simple, it has four terms that require careful application.

The specific heat capacity, *c*, of the substance being investigated will generally be given in the wording of the problem or will be easily accessible in a table such as Table 2.4.1 (page 31). Be sure to use the correct physical state of the substance as the solid, liquid and gaseous phases of a substance will all have different specific heat capacities.

The specific heat capacity should always be used with units of $\text{J kg}^{-1}\,\text{K}^{-1}$, but occasionally will be reported in $\text{J kg}^{-1}\,°\text{C}^{-1}$, $\text{kJ kg}^{-1}\,\text{K}^{-1}$ or even $\text{kcal kg}^{-1}\,\text{K}^{-1}$. If you do see these units in a problem, be sure to convert them to the correct SI units.

In the first instance, since the temperature interval in the Celsius scale is the same as in the Kelvin scale, and it is the change in temperature that we are interested in, the units of $\text{J kg}^{-1}\,°\text{C}^{-1}$ and $\text{J kg}^{-1}\,\text{K}^{-1}$ are entirely equivalent. They can be used interchangeably.

In the second instance, since 1 kJ is equal to 1000 J, to convert $\text{kJ kg}^{-1}\,\text{K}^{-1}$ to the more standard form of $\text{J kg}^{-1}\,\text{K}^{-1}$, we need only to multiply by 1000.

In the final instance, 1 cal = 4.18 J, so 1 kcal = 4180 J. Therefore, to convert $\text{kcal kg}^{-1}\,\text{K}^{-1}$ to $\text{J kg}^{-1}\,\text{K}^{-1}$, we need to multiply by 4180.

In the specific heat equation, ΔT represents the change in temperature and therefore can also be written as $T_{\text{final}} - T_{\text{initial}}$. In the case where an object increases in temperature, T_{final} is greater than T_{initial} and therefore ΔT is a positive number. If this is placed in the equation for specific heat, *Q* will be also be calculated to be a positive number, indicating that heat has been added to the object.

WORKED EXAMPLE 2.5.1

Convert 0.22 $\text{kcal kg}^{-1}\,\text{K}^{-1}$, the specific heat of aluminium, into $\text{J kg}^{-1}\,\text{K}^{-1}$.

ANSWER

1 **Identify the relationship between kcal and J.**

4180 J = 1 kcal so multiplying by $\frac{4180\text{ J}}{1\text{ kcal}}$ is the same as multiplying by 1.

$$= 0.22\,\frac{\text{kcal}}{\text{kg K}} \times \frac{4180\text{ J}}{1\text{ kcal}}$$

2 **Calculate the specific heat capacity in the appropriate units.**

Cancel the kcal in the numerator and denominator.

$$= 0.22\,\frac{\cancel{\text{kcal}}}{\text{kg K}} \times \frac{4180\text{ J}}{\cancel{1\text{ kcal}}}$$

$$= 919.6\text{ J kg}^{-1}\,\text{K}^{-1}$$

3 **Give the answer to the correct number of significant figures.**

$0.22\text{ kcal kg}^{-1}\,\text{K}^{-1} = 920\text{ J kg}^{-1}\,\text{K}^{-1}$

The specific heat of aluminium is 920 $\text{J kg}^{-1}\,\text{K}^{-1}$.

WORKED EXAMPLE 2.5.2

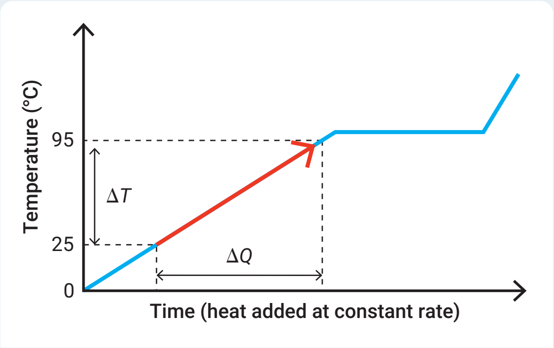
250 mL of pure water at 25°C is heated to 95°C.

a Sketch a graph representing the heating of the water from 0°C to 100°C. On the graph, show the section relevant to this question.

b How much energy is needed to achieve this temperature change?

ANSWERS

a As the temperature of a substance is directly proportional to the heat added, the graph will be linear.



b **1** **Use the correct equation.**

$Q = mc\Delta T$

Substitute known values into the equation and find c for pure water in Table 2.4.1.

$Q = 0.250\text{ kg} \times 4180\text{ J kg}^{-1}\text{ K}^{-1} \times (95°\text{C} - 25°\text{C})$

2 **Calculate the correct answer.**

As Q is positive, heat is added, as it should be.

$Q = 7.3150 \times 10^4\text{ J}$

3 **Give the answer to the correct number of significant figures.**

$Q = 7.3 \times 10^4\text{ J}$

The energy needed to achieve this temperature change is 7.3×10^4 J.

In the case where the temperature of an object decreases, T_{final} will be less than T_{initial} and therefore ΔT will be a negative number. This will result in Q being a negative number, indicating that heat has been lost by the object.

Of course, the specific heat formula can be algebraically rearranged to find any of the variables contained within it.

WORKED EXAMPLE 2.5.3

Calculate the mass of air in a sample if the addition of 48 000 J of heat to the sample results in an increase in temperature of 16°C.

ANSWER

1 **Use the correct equation.**

$Q = mc\Delta T$

2 **Multiply both sides by $\frac{1}{c\Delta T}$ to get m by itself.**

$$Q \times \frac{1}{c\Delta T} = mc\Delta T \times \frac{1}{c\Delta T}$$

3 **Make m the subject.**

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

4 **Substitute known values, retrieving c_{air} from Table 2.4.1.**

$$m = \frac{48000\text{ J}}{1000\text{ J kg}^{-1}\text{K}^{-1} \times 16°\text{C}}$$

5 **Calculate the answer.**

$m = 3$ kg

6 **Give the answer to the correct number of significant figures.**

$m = 3.0$ kg

The mass of air in the sample is 3.0 kg.

calorimeter a highly insulated container that prevents heat energy being lost to the environment, used to measure quantities of heat

power the rate at which work is done by a system, or the rate at which energy is being transferred

watt (W) the unit of power; 1 W = 1 J s^{-1}

Calorimeter

A common piece of experimental equipment used in the field of thermodynamics is the **calorimeter**. A calorimeter has a highly insulating material that ensures that almost no heat is lost to the environment. In this way, any heat added to a liquid held within a calorimeter flows into the calorimeter rather than be released into the environment.

Generally, heat is added to the sample by using a heating element of known **power**. Power is a measure of energy per time and is given the unit of **watt (W)**: 1 watt is equal to 1 J s^{-1}.

Power can also be calculated from the current travelling through and the voltage across the heating element:

$$P = I \times V$$

where:

P = power measured in watts (1 W = 1 J s^{-1})

I = current measured in amperes (A)

V = voltage measured in volts (V)

Using these formulas, the amount of heat added to a substance can be found by multiplying the power by the time over which it is acting: $Q = P \times t$.

KEY FORMULA

Power through a heating element:

$$P = I \times V$$

where:

P = power measured in watts (1 W = 1 J s^{-1})

I = current measured in amperes (A)

V = voltage measured in volts (V)

WORKED EXAMPLE 2.5.4

2.5 A of current passes through a heating element when 2.0 V is applied over it. If this heating element adds heat to a 350 g sample of 5.0°C liquid water in a calorimeter for 30.0 minutes, what temperature will the water reach?

ANSWER

1 **Use the correct equation.**

$Q = mc\Delta T$

2 **Rearrange for the unknown.**

$$T_f = \frac{Q}{mc} + T_i \qquad (1)$$

As $Q = P \times t$ and $P = I \times V$

$$Q = IVt \qquad (2)$$

3 **Substitute equation 2 into equation 1.**

$$T_f = \frac{IVt}{mc} + T_i$$

4 Substitute known values into the equation.

$$T_f = \frac{2.5\ \text{A} \times 2\ \text{V} \times 1800\ \text{s}}{0.35\ \text{kg} \times 4180\ \text{J kg}^{-1}\text{K}^{-1}} + 5°\text{C}$$

5 Calculate the answer.

$T_f = 11.15°\text{C}$

6 Give the answer to the correct number of significant figures.

$T_f = 11°\text{C}$

The water reached a temperature of 11°C.

LEARNING CHECK 2.5

DESCRIBING

1 **Describe** a calorimeter and why it is useful in thermodynamics experiments.

2 **Identify** the SI units for each of these terms.
  - **a** Heat added, *Q*
  - **b** Mass of the sample, *m*
  - **c** Specific heat of the sample, *c*
  - **d** Change in temperature of the sample

3 Rearrange the specific heat equation to make the final temperature, T_f, the subject.

APPLYING

4 If the current passing through a heating element doubles while the voltage over it remains the same, what happens to the power?

5 **Calculate** the amount of heat that needs to be added to 300.0 g of antifreeze to raise its temperature by 15.0°C.

6 **Calculate** the final temperature of a 2.0 kg soil sample at 25°C, when 2500 J of heat is added to it.

7 A current of 5.0 A passes through a heating element when 1.5 V is applied over it. If this heating element adds heat to a 0.20 kg sample of lead at 25°C in a calorimeter for 30.0 minutes, what temperature will the lead reach?

2.6 Interpreting specific heat data

In Practical activity 2.6.1, you will be asked to calculate the specific heat capacity of water by adding heat to it by means of a submersed electric resistor.

During the experiment, you will be able to collect data relating to the amount of heat added (the independent variable) and the resulting temperature change of the water (the dependent variable).

This section will assist you to interpret both the tabulated and graphical data so you can calculate the specific heat capacity of the water and its resulting percentage error.

thermistor temperature-dependent resistor; used to detect changes in temperature

Table 2.6.1 shows the raw data of an experiment in which a **thermistor** with a power rating of 5.0 W was submerged in 500.0 g of water. Temperature readings were taken every 30.0 s for 10.0 min.

TABLE 2.6.1 Experimental data set of time vs temperature of a water sample heated by a 5.0 W thermistor

Time (s)	Temperature (°C)	Time (s)	Temperature (°C)
0.0	24.50	330.0	25.19
30.0	24.56	360.0	25.26
60.0	24.63	390.0	25.32
90.0	24.69	420.0	25.38
120.0	24.75	450.0	25.45
150.0	24.82	480.0	25.51
180.0	24.88	510.0	25.57
210.0	24.94	540.0	25.64
240.0	25.01	570.0	25.70
270.0	25.07	600.0	25.76
300.0	25.13		

The first issue that can be seen is that the table does not contain any reference to heat added to the water. The clue to solving this is the inclusion of the information that the thermistor had a power rating of 5.0 W. Power is a measure of energy per time, and since it can be assumed that all of this energy is being transformed to heat, the thermistor is providing 5.0 J of heat to the water every second.

Using the information in the time column, we can add another 'heat' column in our table using the formula:

$$Q = P \times t = 5.0 \text{ J s}^{-1} \times t \text{ (s)}$$

Even though you may be able to see that the amount of heat added is increasing in regular increments, as would be expected for a constant heat source, it is difficult to make out any relationship between heat added and the temperature of the water source simply by looking at the table (e.g. Table 2.6.2).

The next step is to create a scatterplot of the data. You can do this by hand, or by using a graphics calculator or spreadsheet software.

TABLE 2.6.2 Experimental data set of heat added vs temperature of a water sample

Time (s)	Heat added (J)	Temperature (°C)
0.0	0.0	24.50
30.0	150.0	24.56
60.0	300.0	24.63
90.0	450.0	24.69
120.0	600.0	24.75
150.0	750.0	24.82
180.0	900.0	24.88
210.0	1050.0	24.94
240.0	1200.0	25.01
270.0	1350.0	25.07
300.0	1500.0	25.13
330.0	1650.0	25.19
360.0	1800.0	25.26
390.0	1950.0	25.32
420.0	2100.0	25.38
450.0	2250.0	25.45
480.0	2400.0	25.51
510.0	2550.0	25.57
540.0	2700.0	25.64
570.0	2850.0	25.70
600.0	3000.0	25.76

There are quite a few features that can be seen on this graph **(Figure 2.6.1)**. First, note the inclusion of a graph title and axes titles along with the units of each variable. Note also that the independent variable (heat added) is on the *x*-axis and the dependent variable is on the *y*-axis. Finally, it is evident that there is a linear relationship between the two variables and we can go on and calculate the equation of the line of best fit if we choose to. Many spreadsheet programs will draw graphs of highlighted columns, draw in a regression line and provide a mathematical equation for that line. You should be familiar with how such programs work.

From the specific heat formula, we know the relationship between heat added and temperature is:

$$Q = mc\Delta T$$

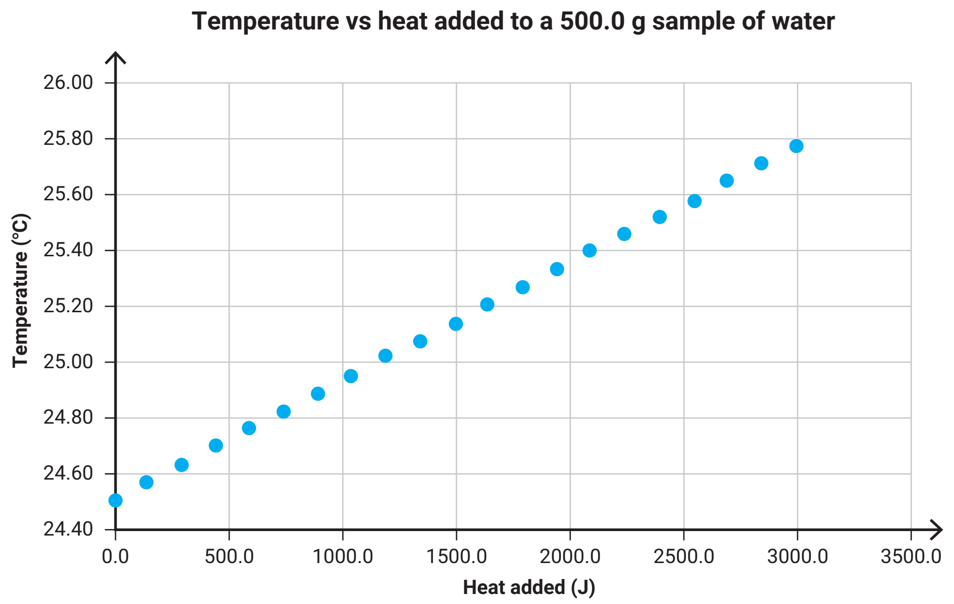


FIGURE 2.6.1 A graphical representation of temperature vs heat added for data from Table 2.6.2

Since temperature is on the y-axis and heat added is on the x-axis, we can rearrange this equation to the more appropriate form:

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

Since $\Delta T = T_f - T_i$, this equation can be written as:

$$T_f - T_i = \frac{Q}{mc}$$

Finally, we can rearrange this into the form:

$$T_f = \frac{Q}{mc} + T_i$$

which is in the form of the linear equation $y = mx + c$, with a y value of temperature, a gradient of $\frac{1}{\text{mass} \times \text{specific heat}}$, an x value of heat added and a y intercept of initial temperature.

We can now find the equation of a line of best fit, knowing that this will yield a valid relationship **(Figure 2.6.2)**.

The equation of the line has been included, but we could just as easily have derived the equation by finding the y intercept of 24.5°C and by calculating the gradient by the rise over run as $0.00042\,\text{J}\,°\text{C}^{-1}$.

The R^2 value of 1 indicates that the line is a perfect fit; it is unlikely that experimental data would achieve such a value.

The y intercept of 24.5°C agrees with the data set in that the water sample did indeed have an initial temperature of 24.5°C.

Finally, the gradient of the line has a value of $0.00042\,\text{J}\,\text{K}^{-1}$, which we can equate to:

$$\frac{1}{\text{mass} \times \text{specific heat}}$$

and since we know the mass of the sample, we can solve for the specific heat capacity.

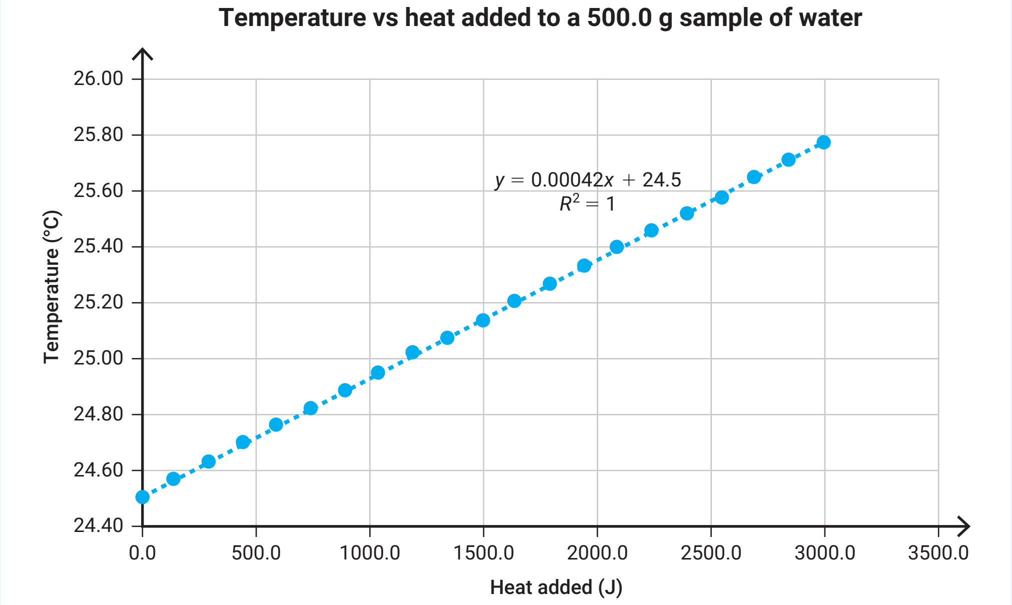


FIGURE 2.6.2 A line of best fit for temperature vs heat added

$$0.000\,42\ \text{J K}^{-1} = \frac{1}{m \times c}$$

$$c = \frac{1}{m \times (0.000\,42\ \text{J K}^{-1})}$$

$$= \frac{1}{(0.5\ \text{kg})(0.000\,42\ \text{J K}^{-1})}$$

$$= 4761.9$$

or correct to two significant figures:

$$c = 4800\ \text{J kg}^{-1}\ \text{K}^{-1}$$

We have calculated the specific heat capacity of water from experimental data and it is time to evaluate our result. To do this, given that we have a commonly accepted 'true' value for the specific heat of water (4180 J kg^{-1} K^{-1}), it makes most sense to calculate the percentage error.

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

$$\%\ \text{error} = \left|\frac{4800 - 4180}{4180}\right| \times 100\%$$

$$\%\ \text{error} = 14.8\%$$

Syllabus link
The digital chapter goes into greater detail about percentage error

PRACTICAL ACTIVITY 2.6.1

SPECIFIC HEAT CAPACITY OF WATER

Introduction

In this experiment, you will be finding an experimental value for the specific heat capacity of water, but you will also use it as practice in writing a report that uses the correct scientific conventions and language as outlined in the previous section.

You should begin by writing an introduction, based on the content of the previous two sections. Remember to use correct referencing protocols.

Research question

What is the relationship between heat added and the temperature of water in a calorimeter?

Aim

To find the specific heat capacity of water

Materials

- calorimeter
- immersion heater
- thermometer or calibrated temperature probe
- sample of water
- galvanometer or voltmeter
- ammeter
- power supply
- $20\ \Omega$ 15 W rheostat
- stopwatch
- electronic scales

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Electrical equipment may cause shocks or electrocution.	Double-check that all electrical equipment is in good working order. Avoid touching the electrical equipment while it is being used.
Hot water can scald.	Wear safety glasses. Avoid spilling or splashing boiling water.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

1. Measure and record the mass of the calorimeter.
2. Add approximately 150 mL of cold water to the calorimeter, and measure and record the mass of calorimeter and water.
3. Suspend the thermometer or temperature probe in the cold water.
4. Connect the power supply (set to approximately 5 V output), rheostat, galvanometer (or voltmeter), ammeter and immersion heater as shown in Figure 2.6.3.
5. Turn on the power supply and adjust the rheostat so that the ammeter reads approximately 2 A.
6. With the voltage properly adjusted, record the voltage and current readings and then turn off the power supply.
7. Measure and record the initial temperature of the water.
8. Switch the power supply back on and start the stopwatch.
9. Stir regularly and record the temperature of the water at 20 s intervals.
10. After 15 min, turn off the power supply and record the final temperature of the water.

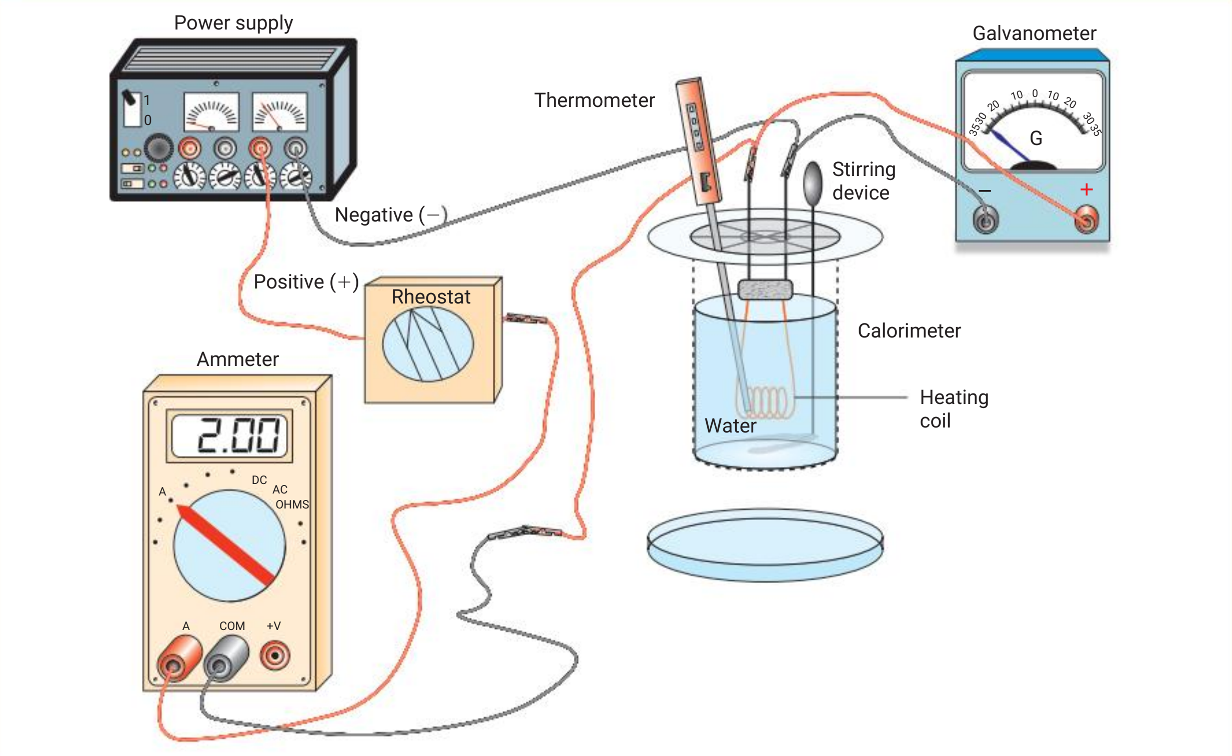


FIGURE 2.6.3 The experimental set-up for determining the specific heat of water

Results

Record your results in tables similar to the tables shown here. Include an estimate of the uncertainty in each measurement. You can calculate heat added as shown in section 2.6.

Table of results part 1

Data	Trial 1	Trial 2
Mass of calorimeter (g)		
Mass of cold water and calorimeter (g)		
Mass of cold water (g)		
Voltage (V)		
Current (A)		
Power output (W) ($P = V \times I$)		

Table of results part 2

Time (s)	Heat added (J)	Temperature (°C)	
		Trial 1	Trial 2
0.0			
30.0			
60.0			
90.0			
120.0			
150.0			
180.0			
210.0			
240.0			
270.0			
300.0			
330.0			
360.0			
390.0			
420.0			
450.0			
480.0			
510.0			
540.0			
570.0			
600.0			

Analysis of results

1 Use the data to graph temperature vs heat added for both trials.
2 Draw a line of best fit for the graph and calculate the equation of the line.
3 Use the equation of the line of best fit to find the specific heat capacity of water for each trial.
4 Use the data to determine the measurement value and the absolute uncertainty in the measurement value.

Interpretation

5 Look up the accepted value of the specific heat capacity of water, including the uncertainty associated with this value. Decide whether the range of your measurement value overlaps the range of the accepted value.
6 Calculate the percentage error in your data.
7 How well does your calculated specific heat capacity of water compare with the accepted true value?

Evaluation

8 Using concepts such as systematic and random error, explain any disparity between your calculated value and the accepted value of the specific heat of water.
9 What elements of the experiment could be improved in order to derive a more precise measurement of the specific heat of water?
10 Write a conclusion to answer your research question.

PRACTICAL ACTIVITY 2.6.2

SPECIFIC HEAT CAPACITY OF METALS

Introduction

Experiments have demonstrated that a small metal block will take about 3–5 min to come to thermal equilibrium with boiling water. Once it has reached this temperature, it can be placed in a known mass of water (specific heat capacity = 4180 $J\ kg^{-1}\ K^{-1}$) at a different temperature. Left for long enough in a calorimeter, the two will reach the same temperature and it can be assumed that the water absorbs all of the heat released by the metal block. From this and the mass of the metal block, the specific heat capacity of the metal can be calculated.

Research question

What is the specific heat capacity of a variety of metals?

Aim

To find the specific heat capacity of one or more metals

Materials

- calorimeter
- thermometer or calibrated temperature probe
- heating equipment
- glass stirring rod
- different metal cubes with dimensions about 2 cm × 2 cm × 2 cm
- strong cotton thread
- paper towel
- electronic scales

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
It is possible to lose control of the hot block while transferring it from beaker to calorimeter or to burn yourself while doing so.	Double-check that the cotton thread is secured. Avoid touching the metal while transferring the block.
Boiling water can scald.	Wear safety glasses. Lower the block gently into the water. Avoid spilling or splashing boiling water.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

1 Set up the equipment as shown in Figure 2.6.4.

2 Heat the water until it is boiling.

3 Determine the mass of the metal cube and securely tie the cotton thread around it.

4 Gently lower the metal cube into the boiling water and leave until it is at 100°C (3–5 min).

5 Measure and record the mass of the calorimeter.

6 Add approximately 150 mL of cold water to the calorimeter and measure and record the mass of calorimeter and water.

7 Suspend the thermometer or temperature probe in the cold water.

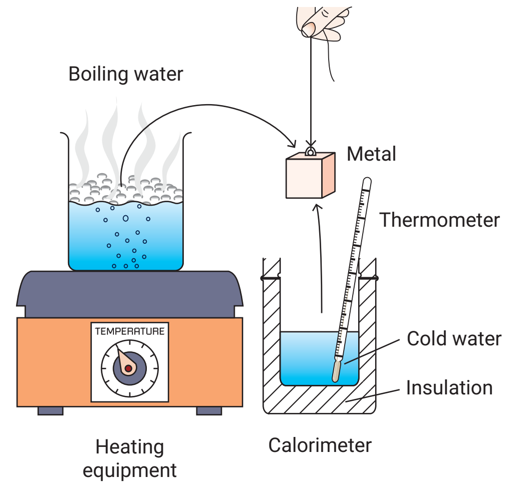


FIGURE 2.6.4 The experimental set-up for the transfer of the hot metal to the cold water

8 Gently stir the water with the stirring rod and wait for the temperature of the water and the thermometer or temperature probe to come to equilibrium. Record this temperature.

9 Carefully lift the hot metal cube out of the boiling water, quickly dry it, then lower it gently into the calorimeter water. Stir the water gently and frequently.

10 Record the temperature of the mixture of the metal block and the water when it reaches its maximum temperature.

11 Repeat the experiment with a second trial.

12 If your teacher directs you to, repeat the experiment with a different metal.

Results

Record your results in a table similar to the table below. Include an estimate of the uncertainty in each measurement.

Results table

Data	Trial 1	Trial 2
Mass of metal block (g)		
Mass of calorimeter (g)		
Mass of cold water and calorimeter (g)		
Mass of cold water (g)		
Initial temperature of cold water and calorimeter (°C)		
Initial temperature of metal cube (°C)		
Final temperature of water and metal cube (°C)		

Analysis of results

1 Use the data to find the specific heat capacity of the metal for both trials.

2 Use the data to determine the measurement value and the absolute uncertainty in the measurement value.

Interpretation

3 Look up the accepted value of the specific heat capacity of the metal, including the uncertainty associated with this value. Decide whether the range of your measurement value overlaps the range of the accepted value.

Evaluation

4 Why were you instructed to dry the metal cube before placing it in the cold water?

5 Why is it desirable to start with the water temperature below room temperature and have a final temperature above room temperature?

6 Why were you asked to do two trials? Does this improve accuracy or precision?

7 Did your best estimate of the specific heat capacity of the metal differ from the accepted value? Explain.

8 Is it meaningful to calculate the percentage error in this experiment? Explain.

9 Write a conclusion to answer your aim.

CHAPTER SUMMARY

Temperature scale

- The Celsius and Kelvin temperature scales are commonly used to measure temperature.
- Conversion between the Kelvin (absolute) and Celsius scales:

$$T_K = T_C + 273$$

where: T_K = temperature in kelvin
T_C = temperature in degrees Celsius

Specific heat capacity

- Specific heat capacity is the amount of energy required to change the temperature of 1 kg of substance by 1°C or 1 K.
- The specific heat formula:

$$Q = mc\Delta T$$

where: Q = the amount of heat added to or removed from the substance (J)
m = the mass of the substance (kg)
c = the specific heat capacity of the substance ($\text{J kg}^{-1}\,{}^\circ\text{C}^{-1}$ or $\text{J kg}^{-1}\,\text{K}^{-1}$)
ΔT = the change in temperature (°C or K)

- The change in temperature is related to the amount of energy added.

Calorimeters and heat

- A calorimeter is a highly insulated apparatus used to measure changes in heat in a liquid.
- Power through a heating element:

$$P = I \times V$$

where: P = power measured in watts ($1\text{ W} = 1\text{ J s}^{-1}$)
I = current measured in amperes (A)
V = voltage measured in volts (V)

- The heat added to a substance can be calculated by:

$$Q = P \times t$$

CHAPTER EXAM

MULTIPLE CHOICE

1. If the temperature of a car's engine is 320°C, what would its temperature be on the Kelvin scale?

A 0 K
B 47 K
C 320 K
D 593 K

2. Which of the following is the SI unit for specific heat capacity?

A $\text{cal kg}^{-1}\,{}^\circ\text{C}^{-1}$
B $\text{cal kg}^{-1}\,\text{K}$
C J kg^{-1}
D $\text{J kg}^{-1}\,\text{K}^{-1}$

3. To which of the following is the heat required to change the temperature of an object not proportional?

A The mass of the object
B The surface area of the object
C Specific heat capacity of the object
D The temperature change of the object

4. Which of the following substances would undergo the greatest increase in temperature for a given input of heat?

A 1 kg of water
B 1 kg of steam
C 1 kg of ice
D 1 kg of soil

5. When 20 kJ of heat is removed from 1.2 kg of ice originally at –15°C, what is its new temperature?

A –35°C
B –26°C
C –23°C
D –18°C

6. Assuming a specific heat capacity of $4.18 \times 10^3\ \text{J kg}^{-1}\,{}^\circ\text{C}^{-1}$, which would require the most energy input?

A $m = 520\ \text{g}, \Delta T = 30^\circ\text{C}$
B $m = 1.2\ \text{kg}, \Delta T = 18^\circ\text{C}$
C $m = 830\ \text{g}, \Delta T = 20^\circ\text{C}$
D $m = 2.5\ \text{kg}, \Delta T = 8^\circ\text{C}$

7. Which statement best describes temperature?

A It is the measure of the heat content of a substance.
B It is the measure of the total internal energy of a substance.
C It is the measure of the specific heat capacity of a substance.
D It is the measure of the average kinetic energy of the particles in a substance.

8. If two substances with different specific heat capacities are heated with the same amount of heat energy, which substance will experience a greater temperature increase?

A The one with higher specific heat capacity will experience a greater temperature increase.
B The one with lower specific heat capacity will experience a greater temperature increase.
C Both will experience the same temperature increase.
D It depends on the initial temperature of the substances.

9. What is the specific heat capacity of a substance that requires 500 J of heat energy to raise the temperature of 2 kg of the substance by 5°C?

A 25 J kg^{-1} K^{-1}

B 50 J kg^{-1} K^{-1}

C 100 J kg^{-1} K^{-1}

D 250 J kg^{-1} K^{-1}

10. What happens to the specific heat capacity of a substance as its temperature increases?

A It decreases.

B It increases.

C It fluctuates.

D It remains constant.

SHORT RESPONSE

11. **Calculate** the heat released when 450 g of molten glass (c_{glass} = 670 J kg^{-1} K^{-1}) at 465°C is cooled to room temperature (25°C). Note: Molten glass and cooled glass are both considered liquids.

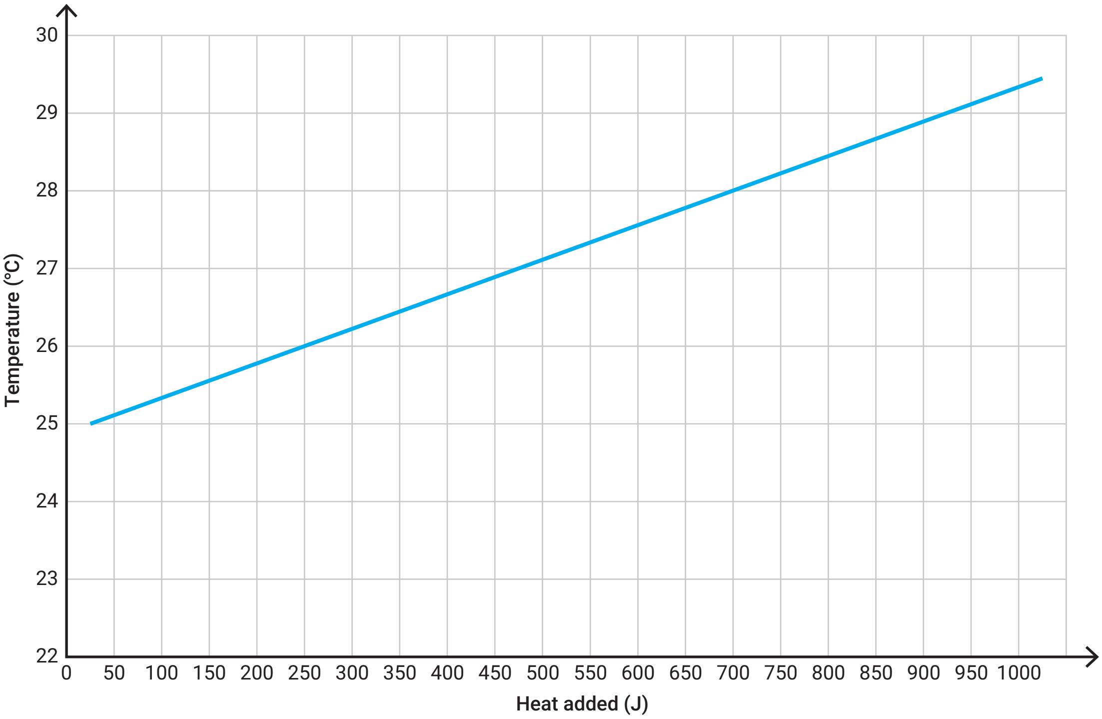
12. If 49 000 J of heat is added to 250 g of cooking oil initially at 25°C, **calculate** its final temperature.

13. What is the specific heat of a 1.8 kg sample of marble if 51 084 J of added heat results in an increase of temperature of 33°C?

DATA ANALYSIS

14. **Analyse data**

Use the graph of temperature change associated with the addition of heat to 0.5 kg of an unknown substance to calculate the specific heat capacity of the substance. **Compare** your result with the values in Table 2.4.1 to suggest what the substance is composed of.



15. Analyse data

A 5.0 W immersion heater was placed in 250 g of a liquid sample and the results were recorded in the table below. Use these results to **calculate** the specific heat capacity of the substance, with the help of a graph.

Time (s)	Temperature (°C)
0.0	12.0
10.0	12.6
20.0	13.2
30.0	13.7
40.0	14.3
50.0	14.9
60.0	15.5
70.0	16.1
80.0	16.7
90.0	17.2
100.0	17.8
110.0	18.4
120.0	19.0
130.0	19.6
140.0	20.1
150.0	20.7
160.0	21.3
170.0	21.9
180.0	22.5
190.0	23.0
200.0	23.6

CHAPTER 3

Phase changes and latent heat

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SYLLABUS DOT POINTS

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 $Q = mL$.

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Introduction

In Chapter 2, the way the temperature of objects changed when heat was added was discussed in terms of the specific heat capacity of the object. It is important to note that this concept only applied to objects that did not change their physical state between solid, liquid or gas.

However, in everyday experience, phase changes occur regularly, such as ice melting in a glass of water, wet clothes drying on a line or condensation forming on the inside of a windscreen.

In this chapter, you will discover what happens to the temperature of a substance as heat is added to it at a transition temperature at which it changes its physical state. This will be done by thoroughly investigating how particles interact when heat is added.

Practicals

- Phase changes
- Estimating the latent heat capacity of water (online-only resource)

Worksheet

- Estimating the latent heat capacity of water
- Measuring the latent heat of water
- Heating graphs

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Particle theory states that matter is made of particles.
- ✓ Substances can transition between phases (solid, liquid, gas).
- ✓ Changing phases involves the absorption or release of heat.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ use the particle model to describe and explain the process of phase change
- ✓ describe and explain melting point, boiling point, melting, vaporisation, condensation, solidification, sublimation, deposition and evaporation
- ✓ interpret heating curves to determine specific heat and latent heat
- ✓ define specific latent heat of fusion and latent heat of vaporisation
- ✓ conduct experiments to quantify energy input, specific heat and latent heat by using data analysis and interpretation
- ✓ solve problems involving energy values, temperature change, specific heat and latent heat.

3.1 The process of state change

When water in the solid phase (ice) is heated, its temperature increases linearly with the amount of heat added. When it reaches 0°C, it undergoes a **phase change** and it melts to form liquid water. If the heating continues, this liquid increases in temperature until it reaches 100°C, when it will undergo another phase change and boil into a gas (steam).

Melting and boiling points

A pure solid starts to change state to a liquid at its **melting point**. A pure liquid starts to change state to a gas at its **boiling point**. Both processes, **melting** and **vaporisation**, require energy input. Removing energy causes gases to undergo **condensation** and liquids to undergo **solidification**.

Some substances can change state (phase) directly from a solid to a gas (**sublimation**) or from a gas to a solid (**deposition**) without going through the liquid state. Solid carbon dioxide (dry ice) does this at –78.5°C. It is primarily used when we require a cooling process that does not leave a liquid residue.

These phase changes are shown in Figure 3.1.1.

Evaporation from a liquid occurs at the surface. Some particles with high kinetic energy escape, as shown in Figure 3.1.2. When these high kinetic energy particles leave the liquid, the average kinetic energy of the liquid is reduced and therefore the temperature decreases. However, vaporisation occurs when the entire liquid changes to gas. No temperature change occurs during vaporisation. Vaporisation can be distinguished from evaporation by the fact that bubbles form below the surface during vaporisation.

phase change	a change in physical state (e.g. solid to liquid)
melting point	the temperature at which a substance undergoes a phase change from solid to liquid (melts)
boiling point	the temperature at which a substance undergoes a phase change from liquid to gas (vaporises)
melting	the phase change from solid to liquid
vaporisation	the phase change from liquid to gas
condensation	the phase change from gas to liquid
solidification	the phase change from liquid to solid
sublimation	the phase change from solid to gas without becoming a liquid
deposition	the phase change from gas to solid without becoming a liquid
evaporation	the process in which some particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point

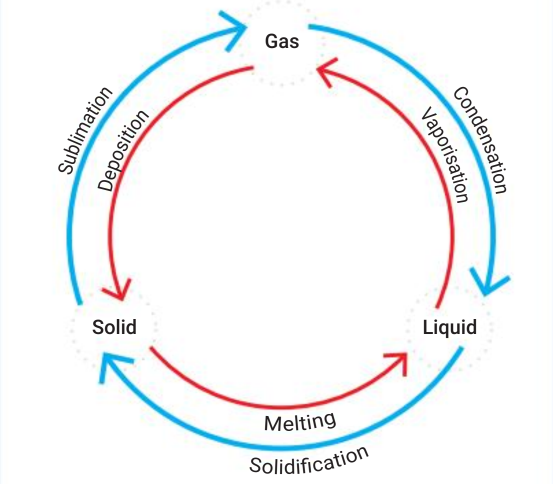


FIGURE 3.1.1 State change cycles. These cycles name each of the phase changes between one physical state and another.

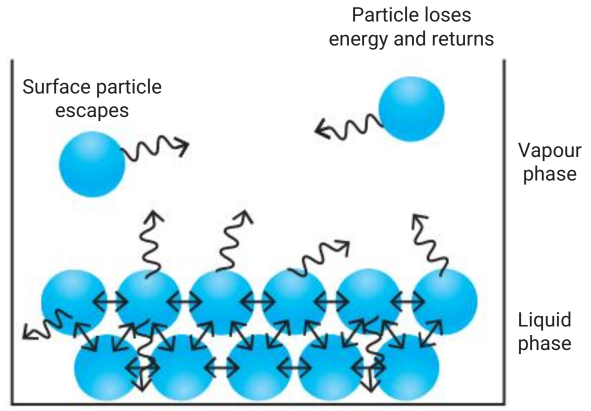


FIGURE 3.1.2 Evaporation occurs at the surface when water molecules that are less tightly bound and have relatively higher kinetic energy than those in the body of the water escape.

Phase changes on a particle level

Particle interactions during phase changes can be illustrated by investigating what happens to a 1.0 kg block of ice as it is heated at a constant rate from −50°C to steam at 100°C at a constant pressure of 1 **atmosphere**.

Figure 3.1.3 shows the **heating curve** of water, which is a graph of temperature versus time or heat added. As can be seen, the temperature of ice rises at a steady rate of about 0.5°C for every kilojoule of heat that is added (section A). During this time, the random motion of the ice molecules increases as they gain more kinetic energy from the heat added.

atmosphere a unit of pressure; 1 atmosphere is the standard pressure at the surface of Earth

heating curve a plot of temperature versus time or heat added

Weblink
Simulation of heat and phases changes

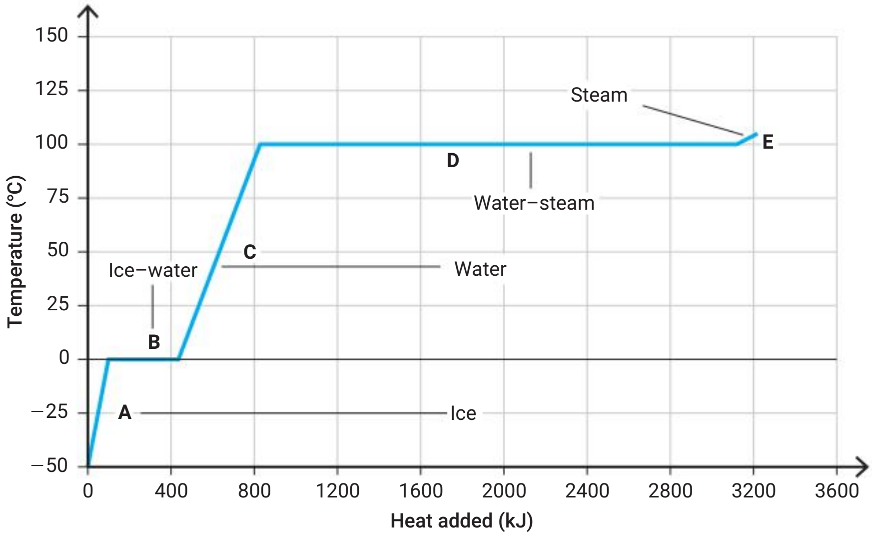


FIGURE 3.1.3 The heating curve of 1.0 kg of pure water. This graph indicates how the temperature of the water changes before, during and after each phase change when heat is steadily being added.

Eventually, some of the molecules gain enough energy to break loose from the bonds that are holding them bound in ice crystals. This is indicated by the plateau in the heating curve, which occurs at 0°C (section B). At this temperature, which is called the melting point, the heat flowing into the ice does not cause an increase in temperature, but disrupts the ice structure of individual molecules. These molecules collide with other molecules and transfer energy to them, in turn allowing them to break free from the ice-forming bonds. Although there is an increase in the internal energy of the sample, this process does not result in an increase in the average kinetic energy of the molecules (otherwise, there would be an increase in temperature). Instead it results in an increase in the potential energy of the molecules.

The melting process continues at a constant temperature until all the molecules break free from the bonds and the phase change is complete. As can be seen from the heating curve, about 330 kJ of energy is required to turn 1 kg of ice at 0°C to water at 0°C.

As shown in section C of Figure 3.1.3, when the sample is in the liquid phase, the temperature of the water increases at a steady rate of about 0.25°C for every 1 kJ of energy added, until it reaches its boiling point at 100°C. At this point, the temperature of the sample once again remains constant, as all the heat added is used to increase the potential energy of the molecules by making them energetic enough to break free from the bonds holding them together as liquid water (section D). In this way, the internal energy of the sample once again increases while the average kinetic energy of its particles (and therefore its temperature) does not.

The whole process of turning 1.0 kg of water at 100°C to steam at 100°C requires about 2260 kJ of energy. In the steam phase, the temperature of the 1.0 kg sample increases linearly with heat added at a rate of about 0.5°C kJ^{-1} of heat added (section E).

Both of these phase changes are reversible. For example, steam loses energy to its surroundings, cooling until it reaches its boiling point, remaining at a constant temperature while the water molecules get closer together. Energy is being released to the surroundings during the condensation process. This energy comes from a reduction of the internal energy of the molecules as they draw closer together to form liquid water. This is why steam at 100°C will cause much more severe burns than the same mass of water at 100°C.

Condensation and heat exchange occur in cloud formation. A pocket of moist air surrounded by dry air rises because it is less dense. It ascends into a cooler region, causing the water vapour to condense as clouds. The latent heat of vaporisation is released to the surrounding air, which becomes warmer. Warm air, being less dense than cooler air, continues to rise. Eventually, the moist air hits the ‘roof’ of the weather zone, the troposphere. Cloud formation then continues horizontally rather than vertically. Distinctive anvil-shaped clouds **(Figure 3.1.4)** form at the tops of thunderclouds, especially in the tropics.

PhotoStock-Israel/Alamy Stock Photo

FIGURE 3.1.4 Distinctive anvil-shaped clouds are often seen at the tops of thunderclouds.

LEARNING CHECK 3.1

DESCRIBING

1 **Distinguish** between vaporisation and evaporation.

2 Order the following processes for the heating of 1 kg of lead.

- I Lead vaporises at 2296°C.
- II Solid lead increases in temperature at a rate of 7.7°C per kilojoule of heat added.
- III Liquid lead increases in temperature at a rate of 7.1°C per kilojoule of heat added.
- IV Lead melts at 873°C.

APPLYING

3 **Discuss** why the temperature of a liquid at its boiling point remains constant when it is changing state.

4 The line on a heating curve for a pure substance that is being heated between state changes has a constant linear slope. What does this imply about the heat supply?

5 The lines on a heating curve for a pure substance that is receiving a constant heat energy input during state changes are parallel to the horizontal axis. What does this imply?

ANALYSING

6 Different substances have different melting points and boiling points, but the shapes of their heating curves are very similar. Solid iron is heated constantly from its solid state to its gaseous state in a furnace. The heating curve for the duration of this process is shown in Figure 3.1.5. Use the curve to **determine** the:

- a melting point of iron
- b boiling point of iron.

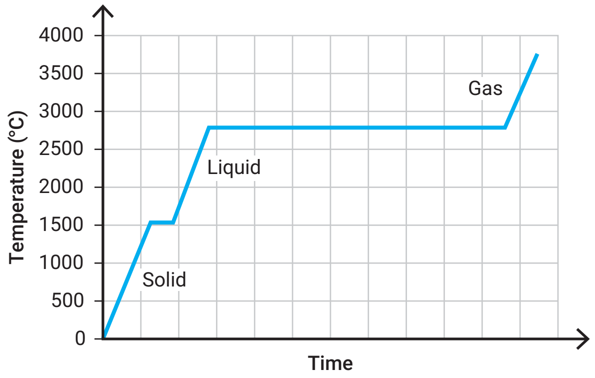


FIGURE 3.1.5 The heating curve for iron

3.2 Defining specific latent heat

During a change of state, energy is added or removed. The energy added or removed during a state change is called the **latent heat**.

latent heat the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: J kg^{-1}

Specific latent heat of fusion

The **specific latent heat of fusion** of a substance is the energy required to change the state of 1 kg of the substance from its solid state to its liquid state without any change in temperature. It is also the energy that is released when 1 kg of the same substance solidifies from liquid to solid. Table 3.2.1 gives the latent heat of fusions for some common substances. The latent heat of fusion has the units of J kg^{-1}.

specific latent heat of fusion the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

Worksheet
Estimating the latent heat capacity of water

TABLE 3.2.1 Latent heats of fusion and vaporisation for some common substances. Unlike specific heat (J kg^{-1} K^{-1}), latent heat is given in J kg^{-1}

Substance	Specific latent heat of fusion (J kg^{-1})	Specific latent heat of vaporisation (J kg^{-1})
Aluminium	390 000	10 500 000
Alcohol (ethanol)	105 000	841 000
Copper	205 000	4 800 000
Iron	276 000	6 340 000
Lead	25 000	860 000
Silver	105 000	2 350 000
Water	334 000	2 260 000

Specific latent heat of vaporisation

The **specific latent heat of vaporisation** of a substance is the heat required to change the state of 1 kg of the substance from its liquid to gaseous state. The specific latent heat of vaporisation of water is 2 260 000 J kg^{-1} (2.6×10^6 J kg^{-1}). You can see from the very large value that a huge amount of energy is required to separate the particles from each other. This is the same amount of energy that is released when 1 kg of the same substance condenses from gas to liquid. Table 3.2.1 also shows the latent heat of vaporisations for some common substances.

specific latent heat of vaporisation the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

The concept of latent heat can be described in the following example.

Students completed an investigation in which they heated different masses of ice at 0°C that had been dried to remove any liquid water from its surface. The heat energy was supplied at a steady rate of 1000 J s^{-1} until the ice had just melted. The time was recorded and precautions were taken to minimise any external heat gains or losses. The data was recorded in Table 3.2.2, and graphed in Figure 3.2.1.

TABLE 3.2.2 Data from student investigation

Mass of ice at 0°C (g)	Time for melting (s)	Total energy input (J)
0.10	33	33 000
0.22	72	72 000
0.39	88	88 000
0.52	175	175 000
0.64	217	217 000
0.90	300	300 000

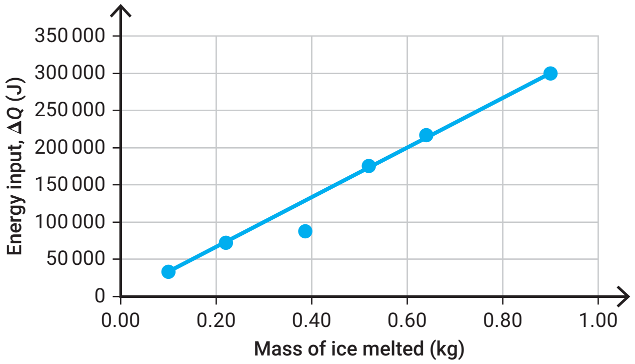


FIGURE 3.2.1 Finding the relationship between energy input and mass of ice melted. The equation of the line is $Q = m \times 334\,000$.

Worksheet
Measuring the latent heat of water

The graph indicates that there is a direct proportionality. In general:

$$Q \propto m$$

There is always a constant that makes a proportionality an equality; in this case L is used as the constant:

$$Q = mL$$

where:
Q = heat required or released during a state change (J)
m = mass of the object undergoing the state change (kg)
L = specific latent heat of the substance and state change (J kg^{-1})

Rearranging the equation gives:

$$L = \frac{Q}{m}$$

L, the specific latent heat, is the gradient of the graph.

The units of $L = \frac{\text{J}}{\text{kg}} = \text{J kg}^{-1}$

This gives the algebraic expression of the relationship between state changes and energy required to change the state.

KEY FORMULA

The latent heat equation

$$Q = mL$$

where:
Q = heat required or released during a state change (J)
m = mass of the object undergoing the state change (kg)
L = specific latent heat of the substance and state change (J kg^{-1})

LEARNING CHECK 3.2

DESCRIBING

1 **Describe** and **explain:**
   - a latent heat
   - b specific latent heat of fusion
   - c specific latent heat of vaporisation.

APPLYING

2 Rank the substances listed in Table 3.2.1 (page 58) in order of increasing latent heat of vaporisation. **Discuss** what this says about the heat required to boil 1 kg of water compared to the amount of heat required to boil 1 kg of aluminium.

3 If 205 kJ of energy is released when 1.0 kg of liquid copper at its melting point fully solidifies into solid copper, **calculate** the energy that would be released if 3.0 kg of liquid copper at the same temperature were to fully solidify.

3.3 Solving problems involving specific latent heat

The specific latent heat, L in the latent heat equation, is specific and unique for every substance and every type of phase change. It can be replaced with L_f, the specific latent heat of fusion, if the substance is undergoing a phase change between solid and liquid, and L_v, the specific latent heat of vaporisation, if the state change is between liquid and gas.

$$L_f = \text{latent heat of fusion}$$

$$L_v = \text{latent heat of vaporisation}$$

When solving problems involving the latent heat equation, it is once again important to make sure that all variables have standard SI units.

WORKED EXAMPLE 3.3.1

How much heat must be added to 15 g of solid tungsten at its melting point to completely liquefy it? Tungsten has a latent heat of fusion of 44 kcal kg^{-1}.

ANSWER

1 **Convert values to the appropriate units.**

$$44\,\frac{\text{kcal}}{\text{kg}} \times \frac{4186\text{ J}}{1\text{ kcal}} = 184\,184\text{ J kg}^{-1} \qquad (1)$$

2 **Use the specific latent heat of vaporisation equation.**

$$Q = mL_v \qquad (2)$$

3 **Substitute equation (1) into equation (2).**

$$Q = 0.015\text{ kg} \times 184\,184\text{ J kg}^{-1}$$

4 **Calculate the answer.**

$Q = 2762.76\ \text{J}$

5 **Give the answer to the correct number of significant figures.**

$Q = 2700\ \text{J}$

2700 J of heat must be added.

WORKED EXAMPLE 3.3.2

If 250 g of gaseous chlorine at its boiling temperature releases 1.44×10^5 J of energy when it liquefies, calculate the specific latent heat of vaporisation for chlorine gas. Give the answer in kJ kg^{-1}.

ANSWER

1 **Apply the specific latent heat of vaporisation equation since condensation is involved.**

$Q = mL_v$

2 **Rearrange for the required unknown.**

$$L_v = \frac{Q}{m}$$

3 **Substitute the values.**

$$L_v = \frac{1.44 \times 10^5\ \text{J}}{0.25\ \text{kg}}$$

4 **Calculate the answer.**

$L_v = 576\,000\ \text{J kg}^{-1}$

5 **Give the answer with the correct units and number of significant figures.**

$L_v = 580\ \text{kJ kg}^{-1}$

Solving for multiple temperature and state changes

Many real-life situations involve temperature and state changes occurring in a process that is being studied. For example, cooling down a hot barbecue plate with water and perspiring to remove excess heat from your body both involve liquid to gas phase changes. The heating curve of a substance becomes a very handy tool when solving problems that involve multiple temperature and state changes.

Different sections of the curve require different calculations to find the energy input needed to heat and change the temperature or state of ice, water or steam. Cooling requires the release to the surroundings of the same amounts of energy. The calculations used depend on whether the water remains in its state or its state is changing.

Weblink
Heating curve of water

Worksheet
Heating graphs

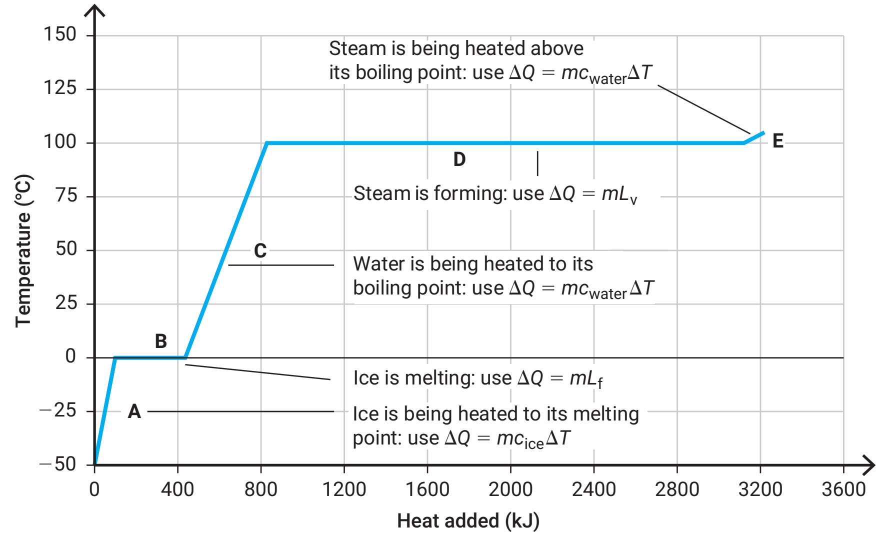


FIGURE 3.3.1 The heating curve for 1 kg of pure water

WORKED EXAMPLE 3.3.3

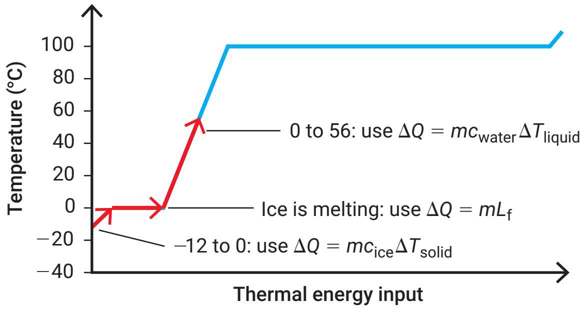
A 430.0 g sample of ice at –12°C is heated to water at 56°C.

a Sketch the heating curve for water and identify the section of the curve that the problem covers.

b How much thermal energy is required?

ANSWERS

a



b 1 **Use the latent heat and the specific heat formulas together because the problem involves a phase change and a change in temperature.**

$Q_{total} = mc_{ice}\Delta T_{solid} + mL_f + mc_{water}\Delta T_{liquid}$

2 **Substitute the known values.**

$Q_{total} = [0.430 \text{ kg} \times 2.10 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \times (0 - -12)] + (0.430 \text{ kg} \times 3.34 \times 10^5 \text{ J kg}^{-1}) + [0.430 \text{ kg} \times 4.2 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \times (56 - 0)]$

3 **Calculate the answer.**

$Q_{total} = 255\ 592 \text{ J}$

4 **Give the answer to the correct number of significant figures.**

$Q_{total} = 2.6 \times 10^3 \text{ kJ}$

PRACTICAL ACTIVITY 3.3.1

PHASE CHANGES

Introduction

The fact that the temperature of a material does not change during a phase change despite heat being added can seem counterintuitive. During this experiment, you will investigate the temperature change of ice during a phase change to verify this claim.

Research question

What is the temperature change of water as it changes from solid ice to liquid water?

Aim

To observe the changes in temperature that a sample of ice undergoes before, during and after a phase change into liquid water

Materials

- calorimeter
- immersion heater
- thermometer or calibrated temperature probe
- electronic scales
- sample of crushed ice
- power supply
- stopwatch

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Heating equipment can cause burns.	Avoid touching the equipment. Wait for the equipment to cool before you put it away.
Electrical equipment may cause shocks or electrocution.	Double-check that all electrical equipment is in good working order. Avoid touching the electrical equipment while it is being used.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

1. Place the crushed ice, thermometer and heating element into the calorimeter, ensuring that the heating element and thermometer are not in contact with each other or with the walls of the calorimeter.
2. Measure the temperature of the ice and record this and any observations that you have in the 0 minutes row of the results table.
3. Connect the heating element to the power supply and turn the power on.
4. After 2 minutes, record the temperature of the sample and your observations.
5. Continue measuring the temperature and making observations at 2-minute intervals, making sure to stir the contents just before taking your measurements.
6. Continue to record your data until the temperature of the sample is 5°C above the point at which it completely liquefied.

Results

Copy and complete the results table.

Time (s)	0	120	240	360	480	600	720	840	960	1080	1200	1320	1440	1560	1680	1800
Temperature (°C)																

Analysis of results

Construct a graph from your experimental data.

Interpretation

1 What did your observations of the physical state of the ice reveal as it went through its phase transition?

2 What happened to the temperature of the sample before, during and after the phase change?

3 Why does the temperature of the sample remain constant during the phase change?

Evaluation

4 How could you improve the experiment to obtain more precise data?

5 What other substances could you investigate?

6 How could you refine the experiment to be able to measure the latent heat of fusion of water?

LEARNING CHECK 3.3

DESCRIBING

1 **Identify** the correct units of each of the following variables.

- a Heat added, *Q*
- b Mass, *m*
- c Specific latent heat, *L*

2 For each of the following scenarios, state whether you would use the latent heat of fusion, L_f, or the latent heat of vaporisation, L_v.

- a Ice becomes liquid water.
- b Steam becomes liquid water.
- c Liquid water becomes ice.
- d Liquid water becomes steam.

APPLYING

3 How much heat (kJ) is required to completely melt 330 g of solid silver that is at its melting point?

4 If it takes 52.8 kcal to vaporise a 160 g sample of liquid ammonia that is at its boiling point, what is the latent heat of vaporisation of ammonia?

5 A 3.2 kg sample of copper is at 975°C and is heated until it completely liquefies at its melting point of 1085°C.

Sketch the heating curve of copper for the temperature region that the problem covers.

6 A scientist would like to obtain 2.5 kg of liquid nitrogen at –210°C from an equal amount of nitrogen gas at 25°C. How much energy must be removed from the gas to achieve this if the boiling point of nitrogen is –210°C? ($c_N = 0.248$ kcal kg^{-1} °C^{-1} and $L_{v,N} = 199$ kJ kg^{-1})

7 A 330 g sample of ice at 0°C is heated until it completely vaporises as steam.

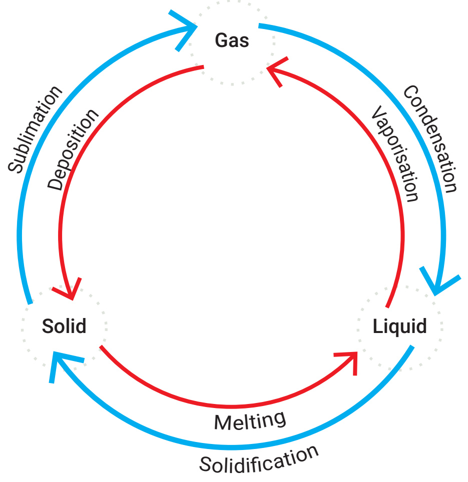
- a **Sketch** the heating curve of water that covers the temperature range of the problem.
- b How much heat must be added for the ice to become steam?

CHAPTER SUMMARY

Phase changes

- State change cycles name each of the phase changes between one physical state and another.
- Substances can change physical states depending on the availability of heat.

Phase changes



Latent heat

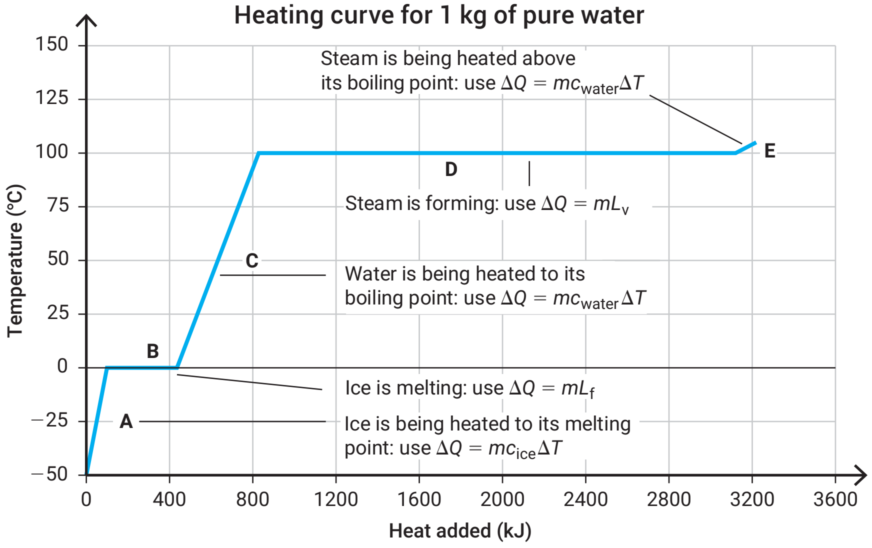
- Latent heat is the heat required to change the state of a substance.
- The latent heat equation:

$$Q = mL$$

where: Q = heat required or released during a state change (J)
m = mass of the object undergoing the state change (kg)
L = specific latent heat of the substance and state change (J kg^{-1})

- Different substances require different amounts of energy to change phases. The latent heat of vaporisation describes the energy needed to convert a liquid substance to its gaseous form, whereas the latent heat of fusion is the energy required to convert a solid into its liquid state.

Heating curve for 1 kg of pure water



CHAPTER EXAM

MULTIPLE CHOICE

1. Which of the following processes does not result in particles of a liquid entering a different phase?

A Deposition
B Evaporation
C Solidification
D Vaporisation

2. What happens to the temperature of a liquid during vaporisation?

A It increases.
B It decreases.
C It stays the same.
D It remains unchanged.

3. The latent heat of a phase change is dependent on the:

A mass of the substance.
B surface area of the substance.
C electrical conductivity of a substance.
D temperature change undergone by the substance.

4. Which of the following is the SI unit for the specific latent heat of vaporisation?

A $\text{J}\,°\text{C}^{-1}$
B $\text{cal}\,\text{kg}^{-1}$
C $\text{J}\,\text{kg}^{-1}$
D $\text{cal}\,\text{kg}^{-1}\,°\text{C}^{-1}$

5. If 3 MJ of heat is removed from 1 kg of steam at 200°C, the result is:

A ice.
B water.
C water and ice.
D water and steam.

6. The latent heat of vaporisation of water describes the amount of heat:

A added to melt 1 kg of ice to liquid.
B removed to melt 1 kg of ice to liquid.
C added to condense 1 kg of steam to liquid.
D removed to condense 1 kg of steam to liquid.

7. The melting point for a substance is the:

A temperature at which it solidifies.
B temperature at which it vaporises.
C temperature at which it condenses.
D amount of energy required to melt the substance.

8. For a particular material:

A the latent heat of vaporisation is larger than latent heat of fusion.
B the latent heat of vaporisation is the same as latent heat of fusion.
C the latent heat of vaporisation is smaller than latent heat of fusion.
D it depends on the substance whether the latent heat of vaporisation or the latent heat of fusion is larger.

9. What is the amount of energy that needs to be added to evaporate 520 g of liquid water at 100°C?

A 1.74×10^5 J
B 1.17×10^6 J
C 4.35×10^6 J
D 1.74×10^8 J

10. What is the amount of energy that would need to be removed from 280 g of steam at 100°C to condense it to liquid?

A 9.35×10^4 J
B 6.33×10^5 J
C 1.19×10^6 J
D 6.33×10^8 J

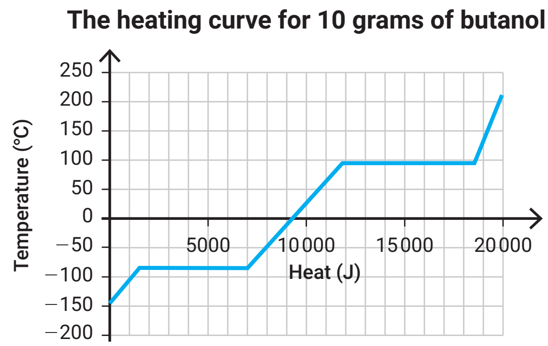
SHORT RESPONSE

11. **Calculate** the mass of copper that would liquefy if 135 kJ of heat is added.

12. **Calculate** the mass of ice transformed, when 380 kJ of heat in total is used to transform solid ice at –12°C to liquid water at 56°C.

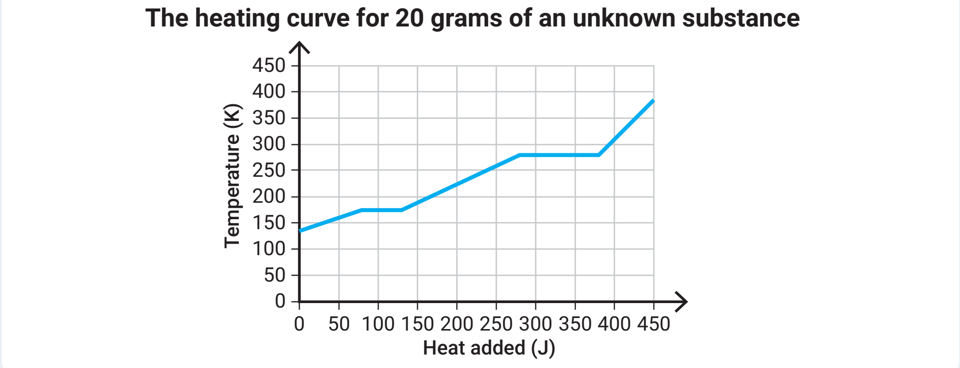
CROSS-CHAPTER QUESTION

13. The graph shows the temperature of a 10 g sample of butanol as heat is added to it at a constant rate.



a **Identify** the boiling point of butanol.
b **Identify** the melting point of butanol.
c **Determine** the specific heat of butanol in the solid state in J kg^{-1} °C^{-1}.
d **Determine** the specific heat of butanol in the liquid state in J kg^{-1} °C^{-1}.
e **Determine** the specific heat of butanol in the gaseous state in J kg^{-1} °C^{-1}.
f **Determine** the latent heat of fusion of butanol in:
  i J g^{-1}
  ii kJ kg^{-1}.
g **Determine** the latent heat of vaporisation of butanol in:
  i J g^{-1}
  ii kJ kg^{-1}.

14. The graph shows the temperature of a 20 g sample of an unknown substance as heat is added to it at a constant rate.



a **Identify** the boiling point of the substance.

b **Identify** the melting point of the substance.

c **Determine** the specific heat of the substance in the solid state in $J\,g^{-1}\,K^{-1}$.

d **Determine** the specific heat of the substance in the liquid state in $J\,g^{-1}\,K^{-1}$.

e **Determine** the specific heat of the substance in the gaseous state in $J\,g^{-1}\,K^{-1}$.

f **Determine** the latent heat of fusion of the substance in:

- **i** $J\,g^{-1}$
- **ii** $kJ\,kg^{-1}$.

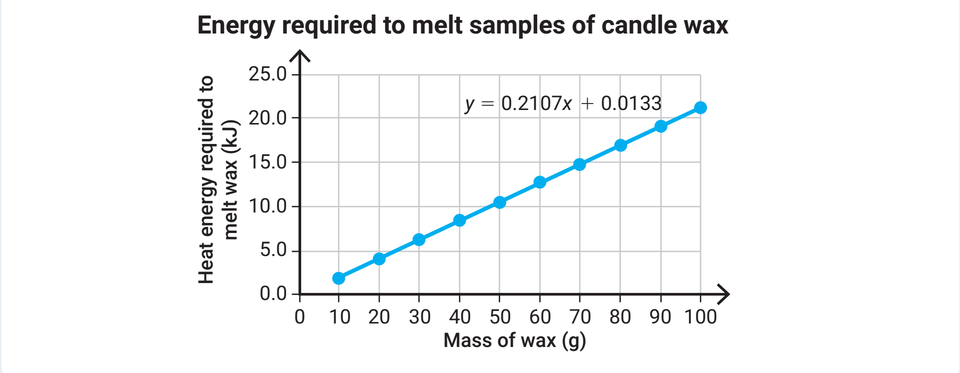
g **Determine** the latent heat of vaporisation of the substance in:

- **i** $J\,g^{-1}$
- **ii** $kJ\,kg^{-1}$.

DATA ANALYSIS

15. Analyse data

A student conducted an experiment to answer the following research question:
‘What is the experimental value of the latent heat of fusion of candle wax?’
To answer this question, the student measured how much heat energy was required to melt various masses of the wax. A graph of the student’s results is shown below.



a Using the graph, **determine** the experimental value for the latent heat of fusion of the candle wax in $kJ\,kg^{-1}$.

b Using your response to part **a**, **predict** how much energy would be required to melt 6 kg of the candle wax.

CHAPTER
4

Energy conservation in calorimetry

Agencja Fotograficzna Caro/Alamy Stock Photo

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- 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 this as the zeroth law of thermodynamics.
- Solve problems involving specific heat capacity, specific latent heat and thermal equilibrium.

SCIENCE INQUIRY

- Investigate specific heat capacity of a substance.
- Explore why it is possible to boil water in a paper cup on a campfire.
- Investigate percentage error by comparing the theoretical and measured temperatures of a mixture of two liquids.

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Introduction

So far, we have investigated the thermodynamic behaviour of objects when heat is added to them during a phase change and between phase changes. But where does this energy come from or go to?

Naturally, it must have come from another object.

In this chapter, we will investigate the thermodynamics of mixtures, both from a conceptual and a mathematical perspective, and what happens when two objects are placed into thermal contact and heat is transferred between them.

Worksheets

- Heat transfer

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ The law of conservation of energy states that energy cannot be created or destroyed, only transferred or transformed.
- ✓ Heat flows from a region of higher temperature to a region of lower temperature.
- ✓ Materials that are good insulators help to reduce heat loss/transfer of heat.
- ✓ Conduction is the process where heat is transferred between particles through direct contact.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain thermal equilibrium in terms of heat flow and the kinetic particle model
- ✓ recall the zeroth law of thermodynamics
- ✓ compare and contrast open, closed and isolated thermodynamic systems
- ✓ solve problems involving thermal equilibrium, the spontaneous transfer of heat and the conservation of energy in closed systems (calorimetry)
- ✓ solve problems requiring the use of latent and specific heats.

4.1 Thermal equilibrium and the energy of particles

Two objects at different temperatures will eventually reach the same temperature when they are put into thermal contact (when thermal energy can transfer between them) **(Figure 4.1.1)**. For example, if you place a hot stone in a container of cold water, heat energy is transferred from the hot stone to the cold water and container. The heat lost by the stone is equal to the heat gained by the water and the container. The stone gets cooler and the water and its container gets warmer. This transfer continues until the stone and the water reach the same temperature. They are now said to be in **thermal equilibrium**.

thermal equilibrium
the condition in which the particles of two or more objects in physical contact have the same temperature and average kinetic energy as each other

Weblink
Thermal equilibrium

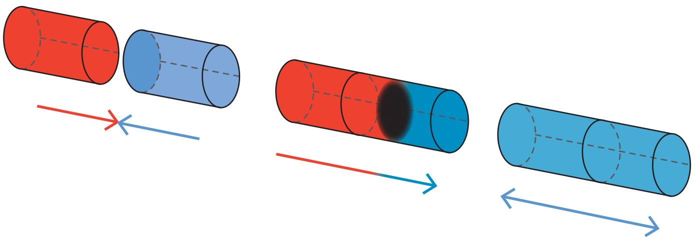


FIGURE 4.1.1 Hot and cold objects reach thermal equilibrium because of the transfer of energy by particle collisions. Eventually, the average kinetic energy of particles in the two objects is the same.

When they are at thermal equilibrium, heat is still being transferred between the water particles and the stone particles; however, the amount of heat going from the water into the stone exactly balances the amount of heat leaving the stone and going into the water. There is no longer a net transfer of heat from one to the other. Therefore, another condition necessary to be able to state that two objects are in thermal equilibrium is that there is no net transfer of energy between them.

LEARNING CHECK 4.1

DESCRIBING

1 **Describe** the temperature condition for two objects if they are in thermal equilibrium.
2 **Describe** the energy condition for two objects if they are in thermal equilibrium.

APPLYING

3 **Explain** in terms of heat flow what happens when an ice tray full of liquid water is placed in the freezer compartment of a refrigerator.
4 **Explain** what happens in terms of heat flow when an ice tray full of solid ice is taken out of the freezer and placed on the counter in a room at 25°C.

4.2 Achieving thermal equilibrium

Recall that the temperature of an object is a measure of the average kinetic energy of the particles in a system. When two objects at different temperatures are placed in thermal contact, the kinetic energy of the particles in the hotter object begins to be transferred into the colder object through the process of elastic collisions between the particles. This continues until the average kinetic energy of the two objects is equal.

In the case of a pot of water on a stove, the particles of the hot element have a large average kinetic energy. At the boundary with the saucepan, they undergo collisions with the particles of the pan and transfer some of this kinetic energy to them, causing the temperature of the saucepan to increase until the particles of the pan and the element have the same average kinetic energy. The same process occurs at the boundary between the saucepan and the water. This can be seen in **Figure 4.2.1a**.

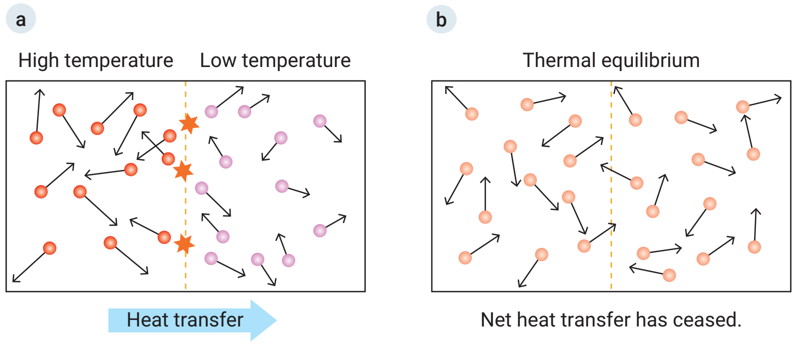


FIGURE 4.2.1 The particles of two substances collide when (**a**) they are at different temperatures when heat is being transferred, and (**b**) at thermal equilibrium when no net heat is transferred.

Once the particles of both objects have the same average kinetic energy, they must have the same temperature and are therefore in thermal equilibrium. Collisions between particles of the two systems still occur, with a concurrent transfer of kinetic energy; however, the likelihood of the particles in the saucepan transferring kinetic energy to the particles of the stove element is equal to the likelihood of the particles in the stove element transferring energy to the particles in the saucepan. This is why there is no net heat flow between objects at thermal equilibrium. This can be seen in Figure 4.2.1b.

Syllabus link
Chapters 1 and 2 discuss the first and second laws of thermodynamics.

zeroth law of thermodynamics if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other

Experiments have shown that if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other. This observation is the basis of the **zeroth law of thermodynamics**. This unusual name is a result of the fact that it was not until scientists had worked out the first and second laws of thermodynamics that they realised that this obvious law needed to be defined.

As well as being a measure of the average kinetic energy of an object, temperature is also a property that determines whether an object is in thermal equilibrium with other objects. If two systems are in thermal equilibrium, then they must have the same temperature and no net thermal energy will flow between them. Therefore, the importance of the zeroth law is that it gives a useful definition of temperature that agrees with our everyday experience that when a hot object and a cold object are put into contact, they will eventually reach the same temperature.

LEARNING CHECK 4.2

DESCRIBING

1 **Explain**, using the kinetic particle model, how two objects at thermal equilibrium maintain equal temperatures if their particles are still colliding and transferring kinetic energy.

APPLYING

2 **Explain**, on a particle level, what happens when an ice tray full of solid ice is taken out of the freezer and placed on the counter in a room at 25°C.

3 **Explain** what is happening on a particle level when a saucepan of cold water is placed on a hot stove element.

4 A bottle of water is at thermal equilibrium with the air in a room and is also at thermal equilibrium with the benchtop on which it is standing. **Compare** the kinetic energy of the particles of all three objects.

4.3 Solving problems involving thermal equilibrium and the spontaneous transfer of heat

system any object or set of objects under investigation

When solving problems involving thermal equilibrium and the spontaneous transfer of heat between objects as they approach thermal equilibrium, scientists often speak about specific systems. A **system** can be considered as any object or set of objects that we are investigating. There are several types of systems.

Open, closed and isolated systems

An **open system** is any system in which mass and energy can enter or leave. Most real-life systems would be considered open. Many idealised systems that are studied in physics are said to be **closed systems** – systems in which no mass can enter or leave, but from which energy can be transferred. A closed system is said to be an **isolated system** if no mass or energy can cross its boundaries.

open system a system that can lose mass and energy to its surroundings

closed system a system that can lose energy but not mass to its surroundings

isolated system a system in which no matter or energy transfers into or out of and in which no energy is created or destroyed

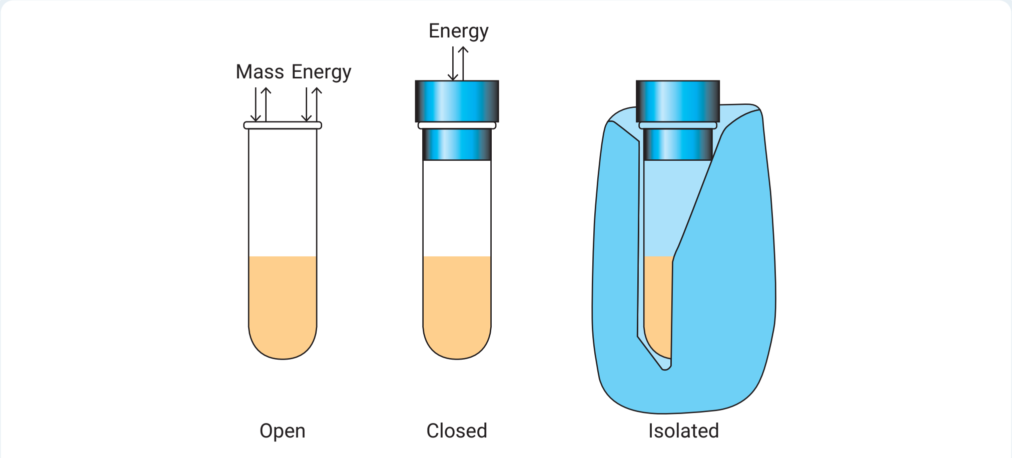


FIGURE 4.3.1 Open, closed and isolated systems

When studying real-life situations involving heat flow, we often need to include the source of the heat and the temperature and phase changes in our calculations, as well as the heat flow in or out and the resultant temperature and state changes.

It is often useful to consider many systems in thermodynamics as being isolated and therefore the law of conservation of energy can be applied. The first law of thermodynamics (the law of conservation of energy) states that in an isolated system, energy can neither be created nor destroyed. Energy can be transferred or transformed, but the total energy of an isolated system remains constant. The total change in energy is zero. Therefore, if an isolated system contains two parts that are at different temperatures and all the heat energy from the hotter object is transferred into kinetic energy of the particles of the colder substance, then we can assume that the heat lost by one object is equal to the heat gained by the other.

For example, when a barbecue plate is cooled down by throwing ice on it, all the heat that is released by the hot plate will be absorbed by the ice, which will turn to water, continue to absorb heat as a liquid and, most likely, turn into steam.

KEY FORMULA

Heat transfers in an isolated system

$$-Q_{\text{lost}} = Q_{\text{gained}}$$

where:

Q_{lost} = heat lost by objects in the system (J)

Q_{gained} = heat gained by objects in the system (J)

WORKED EXAMPLE 4.3.1

If 350 g of water at 10°C is added to 0.40 kg of water at 75°C, what final temperature will the mixture reach?

ANSWER

1 **Assume the hot and cold water are an isolated system.**

heat lost by hot water = heat gained by cold water

2 Apply conservation of energy.

$-Q_{\text{hot}} = Q_{\text{cold}}$

3 Apply the specific heat equation (it can be assumed there will be no phase changes).

$-m_{\text{hot}}c\Delta T_{\text{hot}} = m_{\text{cold}}c\Delta T_{\text{cold}}$

4 Cancel the *c* on both sides, since they are identical (water), and multiply both sides by −1.

$m_{\text{hot}}\Delta T_{\text{hot}} = -m_{\text{cold}}\Delta T_{\text{cold}}$

5 Expand Δ*T* on both sides, noting that T_f is the same for both.

$m_{\text{hot}}(T_f - T_{\text{i, hot}}) = -m_{\text{cold}}(T_f - T_{\text{i, cold}})$

6 Expand the brackets on both sides.

$m_{\text{hot}}T_f - m_{\text{hot}}T_{\text{i, hot}} = -m_{\text{cold}}T_f + m_{\text{cold}}T_{\text{i, cold}}$

7 Gather the like terms.

$m_{\text{hot}}T_f + m_{\text{cold}}T_f = m_{\text{cold}}T_{\text{i, cold}} + m_{\text{hot}}T_{\text{i, hot}}$

8 Factorise T_f on the left-hand side.

$(m_{\text{hot}} + m_{\text{cold}})T_f = m_{\text{cold}}T_{\text{i, cold}} + m_{\text{hot}}T_{\text{i, hot}}$

9 Rearrange the equation to have T_f as the subject.

$$T_f = \frac{m_{\text{cold}}T_{\text{i, cold}} + m_{\text{hot}}T_{\text{i, hot}}}{m_{\text{hot}} + m_{\text{cold}}}$$

10 Substitute known values.

$$T_f = \frac{0.35\,\text{kg} \times 10°\text{C} + 0.4\,\text{kg} \times 75°\text{C}}{0.4\,\text{kg} + 0.35\,\text{kg}}$$

11 Calculate the answer.

$T_f = 44.66667°\text{C}$

12 Give the answer to the correct number of significant figures.

$T_f = 45°\text{C}$

WORKED EXAMPLE 4.3.2

250 g of boiling hot coffee (100.0°C) is poured into a 150 g copper cup initially at 30.0°C.

What will the final temperature of the coffee and the cup be? Assume $c_{\text{coffee}} = 4180\ \text{J kg}^{-1}\,°\text{C}^{-1}$ and $c_{\text{copper}} = 380\ \text{J kg}^{-1}\,°\text{C}^{-1}$

ANSWER

1 Assume coffee and coffee cup are an isolated system and apply the conservation of energy equation.

$-Q_{\text{coffee}} = Q_{\text{cup}}$

2 Apply the specific heat equation to both sides as there is no phase change.

$-m_{\text{coffee}}c_{\text{coffee}}\Delta T_{\text{coffee}} = m_{\text{cup}}c_{\text{cup}}\Delta T_{\text{cup}}$

3 Substitute known values and use T_f as the final temperature for both.

$$-(0.25\,\text{kg})\left(4180\frac{\text{J}}{\text{kg}\,°\text{C}}\right)(T_f - 100°\text{C}) = (0.15\,\text{kg})\left(380\frac{\text{J}}{\text{kg}\,°\text{C}}\right)(T_f - 30°\text{C})$$

4 Expand the brackets.

$-(1045\ \text{J}\,°\text{C}^{-1})T_f + 104\,500\ \text{J} = (57\ \text{J}\,°\text{C}^{-1})T_f - 1710\ \text{J}$

5 **Gather like terms.**

$(1045\ \text{J}\ ^\circ\text{C}^{-1})T_f + (57\ \text{J}\ ^\circ\text{C}^{-1})T_f = 1710\ \text{J} + 104\,500\ \text{J}$

6 **Factorise T_f.**

$(1102\ \text{J}\ ^\circ\text{C}^{-1})T_f = 106\,210\ \text{J}$

7 **Calculate the answer.**

$T_f = 96.380^\circ\text{C}$

8 **Give the answer to the correct number of significant figures.**

$T_f = 96^\circ\text{C}$

WORKED EXAMPLE 4.3.3

A nurse prepares a bath that needs to be at 41°C for a patient. First he adds 53 L of water at 23°C from the cold tap.

a What four assumptions must be made to calculate part **b**?

b How much water needs to be added from the hot tap at 68°C to achieve the required temperature of 41°C?

ANSWERS

a Assumptions:

- No energy is lost to the surroundings such as the taps, the air and the bath.
- The mixing process does not add energy to the water.
- The water is pure.
- 1 L of water has a mass of 1 kg.

b 1 **Assume it is an isolated system and apply the conservation of energy equation.**

$-Q_{\text{hot}} = Q_{\text{cold}}$

2 **Apply the specific heat equation to both sides.**

$-m_{\text{hot}}c\Delta T_{\text{hot}} = m_{\text{cold}}c\Delta T_{\text{cold}}$

3 **Rearrange to make m_{hot} the subject.**

$$m_{\text{hot}} = \frac{m_{\text{cold}}c\Delta T_{\text{cold}}}{-c\Delta T_{\text{hot}}}$$

4 **Cancel c because it is common (water).**

$$m_{\text{hot}} = \frac{m_{\text{cold}}\Delta T_{\text{cold}}}{-\Delta T_{\text{hot}}}$$

5 **Substitute known values.**

$$m_{\text{hot}} = \frac{53\,\text{kg} \times (41^\circ\text{C} - 23^\circ\text{C})}{-(41^\circ\text{C} - 68^\circ\text{C})}$$

6 **Calculate the answer.**

$m_{\text{hot}} = 35.3\ \text{kg}$

7 **Give the answer to the correct number of significant figures.**

$m_{\text{hot}} = 35\ \text{kg}$

The nurse needs to add 35 kg or 35 L of hot water.

WORKED EXAMPLE 4.3.4

Two 50.0 g ice cubes at 0.0°C are placed into a full 3.0 L jug of water at 25°C.
Calculate the final temperature of the mixture.

ANSWER

1 **Assume it is an isolated system and apply the conservation of energy equation.**

$Q_{\text{ice}} = -Q_{\text{water}}$

2 **Apply the specific heat and latent heat equations since the ice will undergo a phase change.**

$m_{\text{ice}}L_{\text{f, ice}} + m_{\text{ice}}c_{\text{water}}\Delta T_{\text{water}} = -m_{\text{water}}c_{\text{water}}\Delta T_{\text{water}}$

3 **Substitute known values and expand T_f on both sides.**

$0.1\text{ kg} \times 334\,000\text{ J kg}^{-1} + 0.1\text{ kg} \times 4180\text{ J kg}^{-1}\,°\text{C}^{-1}(T_f - 0°\text{C}) = -3\text{ kg} \times 4180\text{ J kg}^{-1}\,°\text{C}^{-1}(T_f - 25°\text{C})$

4 **Expand the brackets.**

$33\,400\text{ J} + 418\text{ J }°\text{C}^{-1} \times T_f = -12\,540\text{ J }°\text{C}^{-1} \times T_f + 313\,500\text{ J}$

5 **Gather terms containing T_f on the left and factorise.**

$(418\text{ J }°\text{C}^{-1} + 12\,540\text{ J }°\text{C}^{-1})T_f = 313\,500\text{ J} - 33\,400\text{ J}$

$12\,958\text{ J }°\text{C}^{-1} \times T_f = 280\,100\text{ J}$

$$T_f = \frac{280\,100\text{J}}{12\,958\text{JC}^{-1}}$$

6 **Calculate the answer.**

$T_f = 21.616°\text{C}$

7 **Give the answer to the correct number of significant figures.**

$T_f = 22°\text{C}$

The final temperature of the mixture is 22°C.

WORKED EXAMPLE 4.3.5

A 2.5 kg iron barbecue plate at 328°C is too hot for cooking and needs to be cooled to 200°C. If this is to be done by placing a block of ice on the plate, how much ice at 0°C will be required?

ANSWER

If the final temperature is to be 200°C and only just enough ice is to be used to achieve this heat transfer, the particles of ice will go through the melting phase change, through the entire liquid phase, and finally through the vaporisation phase change. Once again, we will assume the system is isolated and therefore all the heat absorbed by the ice in its transformation will come from the heat lost by the iron (Fe).

1 **Assume it is an isolated system and apply the conservation of energy equation.**

$-Q_{\text{Fe}} = Q_{\text{ice}}$

2 **Apply the latent heat of fusion and the latent heat of vaporisation equations together with the specific heat equations.**

$-m_{\text{Fe}}c_{\text{Fe}}\Delta T_{\text{Fe}} = m_{\text{ice}}L_f + m_{\text{water}}c_{\text{water}}\Delta T_{\text{water}} + m_{\text{water}}L_v$

Since the mass of ice and water is the same:

$-m_{\text{Fe}}c_{\text{Fe}}\Delta T_{\text{Fe}} = m_{\text{ice}}(L_f + c_{\text{water}}\Delta T_{\text{water}} + L_v)$

3 Rearrange to make m_{ice} the subject.

$$m_{\text{ice}} = \frac{-m_{\text{Fe}}c_{\text{Fe}}\Delta T_{\text{Fe}}}{L_{\text{f}} + c_{\text{water}}\Delta T_{\text{water}} + L_{\text{v}}}$$

4 Substitute known values.

$$m_{\text{ice}} = \frac{-2.5\,\text{kg} \times 450\,\text{J kg}^{-1}(200°\text{C} - 328°\text{C})}{3.34 \times 10^5\ \text{J kg}^{-1} + 4.18 \times 10^3\ \text{J kg}^{-1}\,°\text{C}^{-1} \times (100°\text{C} - 0°\text{C}) + 2.26 \times 10^6\ \text{J kg}^{-1}}$$

5 Calculate the answer.

$m_{\text{ice}} = 0.047\,808\ \text{kg}$

6 Give the answer to the correct number of significant figures.

$m_{\text{ice}} = 4.78 \times 10^{-2}\ \text{kg}$

The calorimeter

The experimental device called a calorimeter, which was introduced in Chapter 2, is a way in which scientists can simulate the conditions of an isolated system. It uses a highly insulating material to ensure that almost no heat is lost to the environment. This is similar in design to the Dewar flask, described in Chapter 1. A major use of the calorimeter is to determine the unknown specific heat capacity of a substance by immersing the substance at a known temperature in cooled water in the calorimeter. Since the heat lost by the substance will be gained by the water and the calorimeter, by measuring the final temperature of the water (which is the same as the temperature of the substance and the calorimeter), the specific heat capacity of the substance can be found.

Weblink
Calorimeters and calorimetry

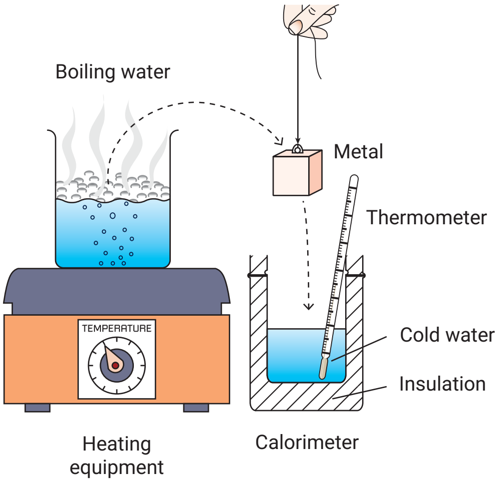


FIGURE 4.3.2 A calorimeter is used to calculate the unknown specific heat capacity of a substance.

WORKED EXAMPLE 4.3.6

A chemical engineer wants to determine the specific heat capacity of a 150 g sample of an unknown substance. To do this, he initially heats the alloy to 540°C by placing it in a precision temperature-controlled oven long enough for thermal equilibrium to be reached. He then quickly removes it from the bath, dries it and places it into 400.0 g of water at 10.0°C, which is held in a 250 g aluminium calorimeter. The final temperature of the system is 30.5°C.

Calculate the specific heat of the unknown substance. Assume $c_{\text{aluminium}} = 900\ \text{J kg}^{-1}\ °\text{C}^{-1}$

ANSWER

1. **The system is isolated.**

   heat lost by substance = (heat gained by water) + (heat gained by calorimeter)

2. **Apply the conservation of energy equation.**

   $-Q_s = Q_w + Q_{cal}$

3. **Apply the latent and/or specific heat equations.**

   $-m_s c_s \Delta T_s = m_w c_w \Delta T_w + m_{cal} c_{cal} \Delta T_{cal}$

4. **Rearrange for the unknown.**

   $$c_s = \frac{m_w c_w \Delta T_w + m_{cal} c_{cal} \Delta T_{cal}}{-m_s \Delta T_s}$$

5. **Substitute known values.**

   $$c_s = \frac{(0.4\ \text{kg})\left(4180\frac{\text{J}}{\text{kg °C}}\right)(30.5°\text{C} - 10.0°\text{C}) + (0.25\ \text{kg})\left(900\frac{\text{J}}{\text{kg °C}}\right)(30.5°\text{C} - 10.0°\text{C})}{-(0.15\ \text{kg})(30.5°\text{C} - 540°\text{C})}$$

6. **Simplify.**

   $$c_s = \frac{34\,276\ \text{J} + 3690\ \text{J}}{76.425\ \text{kg°C}}$$

7. **Calculate the answer.**

   $c_s = 496.77\ \text{J kg}^{-1}\ °\text{C}^{-1}$

8. **Give the answer to the correct number of significant figures.**

   $c_s = 5 \times 10^2\ \text{J kg}^{-1}\ °\text{C}^{-1}$

The specific heat of the unknown substance is $5 \times 10^2\ \text{J kg}^{-1}\ °\text{C}^{-1}$.

Worksheet
Heat transfer

LEARNING CHECK 4.3

DESCRIBING

1. **Describe** the structure and thermodynamic properties of a calorimeter.
2. **Explain** why the equation $Q_{\text{lost}} = -Q_{\text{gained}}$ is another way of writing the conservation of energy principle.
3. **Compare** the thermodynamic properties of the following three types of systems.
   - **a** Open
   - **b** Closed
   - **c** Isolated

APPLYING

4 **Classify** the following systems as open, closed or isolated.

- **a** The universe
- **b** A saucepan with a lid
- **c** A lake of water
- **d** A saucepan of water
- **e** A thermos flask of hot water
- **f** Gas in a balloon

5 If 2.0 L of hot water at 65.0°C is added to 1.0 L of cold water at 10.0°C, at what temperature will the mixture reach thermal equilibrium?

6 A 5.0 L tub of water contains 3.0 L of water at 23°C. The tub is then filled to the top with hot water. The final temperature of the water in the tub is 26°C. **Calculate** the initial temperature of the hot water.

7 A 60 kg bushwalker suffering from hypothermia has an average body temperature of 33.5°C. When rescued, she is wrapped in a blanket and given two 310 mL cups of warm tea each at a temperature of 60.0°C. **Calculate** the maximum rise in the bushwalker's temperature due to the heat of the tea. ($c_{\text{human body}} = 3.5 \times 10^3$ J kg^{-1} K^{-1})

8 When a 1.23 kg sample of an unknown material at 98.0°C is added to a 150 g aluminium calorimeter containing 250 g of water at 10.0°C, the final temperature is observed to be 38.0°C. **Calculate** the specific heat of the unknown material and suggest what the material might be.

9 When a cook pours 100.0 mL of water at 65°C into a 5.0 kg iron saucepan at 140°C, it is observed that all the water is converted to steam. What is the final temperature of the saucepan?

10 How much steam at 100°C must be added to 1.0 kg of ice at 0°C such that the final mixture consists of liquid water at 22°C?

CHAPTER SUMMARY

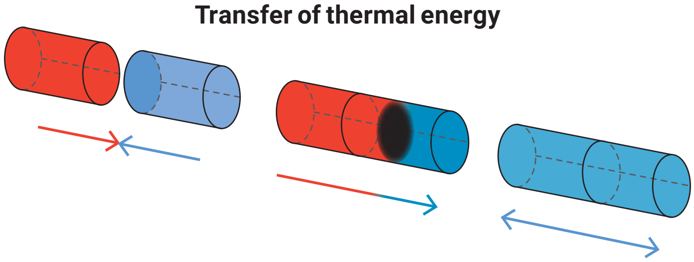
Transfer of heat between objects

- Objects at different temperatures that are put in contact will eventually reach the same temperature.
- Heat transfers in an isolated system:

$$-Q_{\text{lost}} = Q_{\text{gained}}$$

where: Q_{lost} = heat lost by objects in the system (J)
Q_{gained} = heat gained by objects in the system (J)

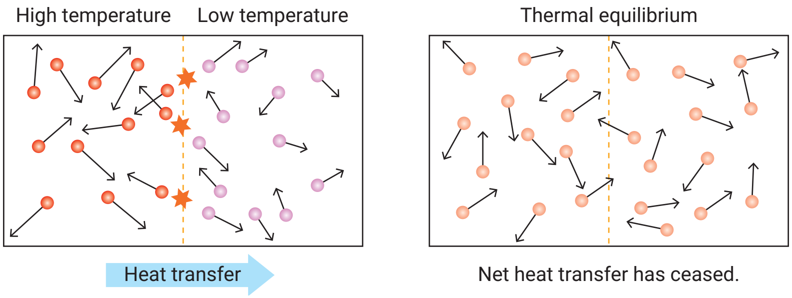
Transfer of thermal energy



Reaching thermal equilibrium

- Hot and cold objects reach thermal equilibrium due to the transfer of energy by particle collisions.
- Eventually, the average kinetic energy of particles in the two objects is the same. At this point, thermal equilibrium has been reached.

Particle collision to achieve thermal equilibrium



MULTIPLE CHOICE

1. Which of the following options is indicative of two objects at thermal equilibrium?

A They have different temperatures.
B Their particles have equal average kinetic energies.
C They have equal amounts of potential energy.
D There is a net heat flow from one object to the other.

2. What type of system is the calorimeter an experimental example of?

A Closed
B Insulated
C Isolated
D Open

3. A hot liquid at 80°C is added to 600 g of the same liquid originally at 10°C. When the mixture reaches 30°C, the total mass of liquid is:

A 825 g.
B 840 g.
C 857 g.
D impossible to calculate without knowing the specific heat capacity of the liquid.

4. If 400 g of water at 10°C is poured into a 600 g jug ($c = 0.80\,\text{kJ kg}^{-1}\,°\text{C}^{-1}$) at 20°C, what is the final temperature of the water?

A 11°C
B 12°C
C 14°C
D 17°C

5. A 1.0 kg iron bar ($c = 460\,\text{J kg}^{-1}\,°\text{C}^{-1}$) at 100°C, is placed in 3.0 kg of water at 15°C. What does the temperature of the water approximately increase by?

A 0.7°C
B 3°C
C 5°C
D 18°C

6. When 4.536 kg of water at 10°C is poured over 0.4536 kg of ice at –17.8°C, what is the temperature of the resulting mixture?

A –7.2°C
B –0.56°C
C 0°C
D 1°C

7. Which one or more of the following combinations will result in water at 50°C?

A 1 kg each of ice at 0°C and steam at 100°C
B 1 kg each of ice at 0°C and water at 100°C
C 1 kg each of water at 0°C and steam at 100°C
D 1 kg each of water at 0°C and water at 100°C

8. The zeroth law of thermodynamics states:
   - **A** in an open system, there is no gain or loss of total energy.
   - **B** in any closed system, there is no gain or loss of total energy.
   - **C** when two objects come into contact, cold flows from the body of lower temperature to higher temperature.
   - **D** when two objects come into contact, heat flows from the body of higher temperature to lower temperature.

9. Which one of the following everyday items is designed to most closely resemble a closed system?
   - **A** Hot water system
   - **B** Insulated drink cooler
   - **C** Oven
   - **D** Refrigerator

10. A heated piece of metal is placed in a beaker of water at room temperature. Which of the following would occur?
    - **A** The temperature of the water and metal stay the same.
    - **B** The metal ends up at a lower temperature than the water.
    - **C** The temperature of the metal decreases and the temperature of the water increases until they are the same temperature.
    - **D** The temperature of the water decreases and the temperature of the metal increases until they are the same temperature.

SHORT RESPONSE

11. 0.20 L of water at 100°C is poured onto a 3.0 kg iron barbecue plate at 180°C. **Calculate** the final temperature of the hot plate once all of the water has vaporised, if it is assumed no heat is lost to the surroundings.

12. A 30 g copper cup ($c = 380\,\mathrm{J\,kg^{-1}\,°C^{-1}}$) contains 180 g of water is at 18°C. A 120 g lump of lead ($c = 130\,\mathrm{J\,kg^{-1}\,°C^{-1}}$) which was at 98°C is added to the cup. **Determine** the final temperature of the water in the cup.

CROSS-CHAPTER QUESTION

13. River water at 10°C is used to condense spent steam at 120°C to water at 50°C in an electricity generating plant. If the cooling water leaves the condenser at 30°C, **calculate** how many kilograms of river water are needed per kilogram of spent steam.

DATA ANALYSIS

14. **Analyse data**

An experiment was conducted to determine the specific heat capacity of an unknown metal cube by calorimetry. The 10 g metal cube was placed in boiling water for 5 minutes before being placed in an insulated cup of water. The results of the experiment are shown below.

Mass of empty copper cup	158.0 g
Mass of copper cup + water	210.4 g
Initial temperature of water and copper cup	26.9°C
Final temperature of water, copper cup and cube	28.6°C

a Use the data above to **calculate** the specific heat capacity of the unknown cube of metal.

b **Compare** your result to the following list of specific heat capacities of some common metals to determine what the cube was most likely made of.

Metal	Specific heat capacity (J kg^{-1} $°C^{-1}$) (approximate)
Aluminium	920
Brass	400
Copper	380
Lead	130
Nickel	500
Tin	215

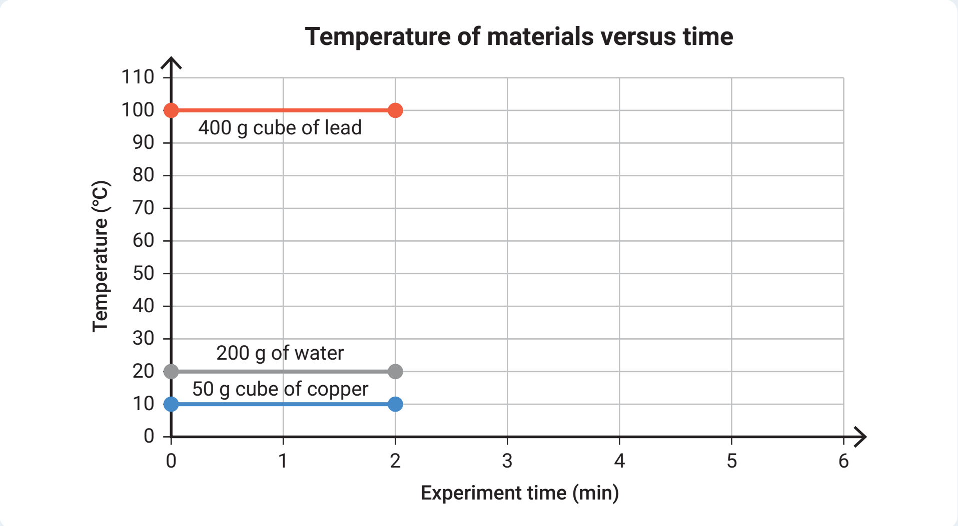
15. Interpret evidence

A student set up an experiment to answer the following research question.

'What will the temperature be at thermal equilibrium when a 50 g cube of copper and a 400 g cube of lead are added to 200 g of water if all of their initial temperatures are known?'

At the beginning of the experiment, the student started a stopwatch. Using an infrared non-contact thermometer, they initially monitored the temperature of each material to ensure stability, then added them together in a calorimeter at 2 minutes.

The following graph includes the data from the first 2 minutes of the experiment.



Given that the specific heat capacity of copper is 380 J kg^{-1} K^{-1} and the specific heat capacity of lead is 130 J kg^{-1} K^{-1}, copy the graph to **predict** and **sketch** what the trend lines will look like from 2 minutes to 5 minutes if thermal equilibrium is reached at 4 minutes.

CHAPTER 5

Energy in systems – mechanical work and efficiency

Peter Gudella/Shutterstock.com

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- 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 $\eta = \frac{\text{energy output}}{\text{energy input}} \times 100\%$.

SCIENCE INQUIRY

- Consider the energy contained within a cup of coffee versus a swimming pool.
- Consider why you feel colder when you are wearing wet clothes.

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Introduction

The field of thermodynamics was developed in the 19th century as a direct result of the technological advancements of the Industrial Age. During this time of great invention, new industries across the world were finding ways to use the energy within objects to complete tasks that would previously have been carried out by hand.

In this chapter, we will investigate, from a physics standpoint, just how the world was changed forever by the fact that the internal energy of a substance can be used to perform useful work. In addition, we will explore the transformations that take place in some common engines and discuss factors that impact their efficiency.

Worksheets

- Increasing energy efficiency

Nelson MindTap

To access resources above, visit
cengage.com.au/nelsonmindtap

ASSUMED KNOWLEDGE

- ✓ To operate everyday devices, energy needs to transform from one form to another, e.g. electrical to mechanical.
- ✓ Mechanical energy is the energy that an object has due to its motion or position.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ explain how a system with thermal energy has the capacity to do mechanical work
- ✓ calculate work done in terms of a force acting over a distance
- ✓ determine the rate at which work is done in terms of power
- ✓ compare internal and external combustion engines
- ✓ describe and explain how energy transfers and transformations in mechanical systems always result in some heat loss so that the amount of usable energy is reduced
- ✓ recall the concept of internal energy
- ✓ perform calculations involving changes in the internal energy of a system
- ✓ interpret the diagrammatical representation of the energy flow associated with a heat engine
- ✓ describe and explain heat-exchange systems and heat-conversion systems
- ✓ recognise the principles of thermodynamics that are evident in the operation of a reverse-cycle air conditioner, heat pump or refrigerator
- ✓ describe the concept of energy efficiency
- ✓ determine the energy efficiency of common devices.

5.1 The capacity to do work

work the energy transferred due to the action of a force over a distance

Weblink
How does work work?

Heat is one way in which energy can be transferred from one object or system to another. The other way in which energy can be transferred to another object or system is through the action of a force. **Work**, W, is defined as the energy transferred by the action of a force over a distance. When a force, F, acts on an object and moves the object through some distance, s, in the same direction as the force, the energy transferred to the object is equal to:

$$W = F \times s$$

where: $W =$ work (J)
$F =$ force (N)
$s =$ distance (m)

This equation calculates the work done by the object applying the force. But it can also show the work done on an object by the application of a force. Work has units of newton metres (N m), which is equivalent to $\text{kg}\,\text{m}^2\,\text{s}^{-2}$. As work is a form of energy, this unit is also equivalent to the joule (i.e. $1\,\text{N m} = 1\,\text{J}$).

KEY FORMULA

Work defined

$$W = F \times s$$

where:
$W =$ work (J)
$F =$ force (N)
$s =$ distance (m)

It is important to differentiate between heat and work, as they are both ways in which energy can be transferred. Remember that work is energy transferred by the action of a force, whereas heat is energy transferred as a result of a temperature difference.

The rate at which energy is transferred, either by heat or work, is called power. Power, P, is energy, E, transferred per unit time. If the only energy transferred is in the form of work, then this can also be written as the work, W, performed per unit time.

$$P = \frac{E}{t} = \frac{W}{t}$$

where: P = power (W)

E = energy transferred (J)

t = time (s)

W = work (J)

KEY FORMULA

$$P = \frac{E}{t} = \frac{W}{t}$$

where:

P = power (W)

E = energy transferred (J)

t = time (s)

W = work (J)

Power has the unit of J s^{-1}, which is given the name watt (W) after the Scottish engineer James Watt (1736–1819), who did important work on developing steam engines.

The power of steam drove the Industrial Revolution of the 18th and 19th centuries, making mining, manufacturing, travel and transport much more effective. For example, water was pumped from mines more efficiently, so mines could be dug deeper; long-distance travel and transport by rail and water improved markedly; and mass production of goods in factories concentrated employment in cities.

Demand for fuels for the energy needs of steam engines rose sharply. Employment patterns changed as new jobs were created, replacing traditional forms of work, particularly in the field of transportation. Steam continues to be used today to produce electricity and in manufacturing.

Many of the models and theories of thermodynamics, such as the three laws of thermodynamics, were also developed in parallel with the development of the steam engine. This is an example of the interplay between theory, experiment and technology. Advances in any one of these usually leads to advances in the other two.

Science & Society Picture Library/Getty Images

FIGURE 5.1.1 George Stephenson (1781–1848) built one of the first efficient steam engines – 'Stephenson's Rocket' – in 1829. The steam engine is used in this chapter to explore the concept of work.

Weblink
Steam engine

Worksheet
Work and energy

Useful systems

external combustion engine a device to produce work through the expansion of a fluid that is heated by the combustion of an external fuel source

Consider the steam engine of a train as an example of a useful system. Steam engines are **external combustion engines**. Coal or wood or some other fuel is burnt (combusted) outside the engine and the engine does work and makes the train move **(Figure 5.1.2)**. If we define our system as the engine, then the engine is not an isolated system – energy both enters and leaves the system. However, since mass is not entering or leaving the system, it can be considered a closed system.


Roger Bamber/Alamy Stock Photo

FIGURE 5.1.2 Coal heats the boiler to produce the steam that drives the train engine's pistons.

Energy enters the system as heat, *Q*, due to the temperature difference between the combustion chamber (firebox) and the boiler in the engine. This increases the energy of the system.

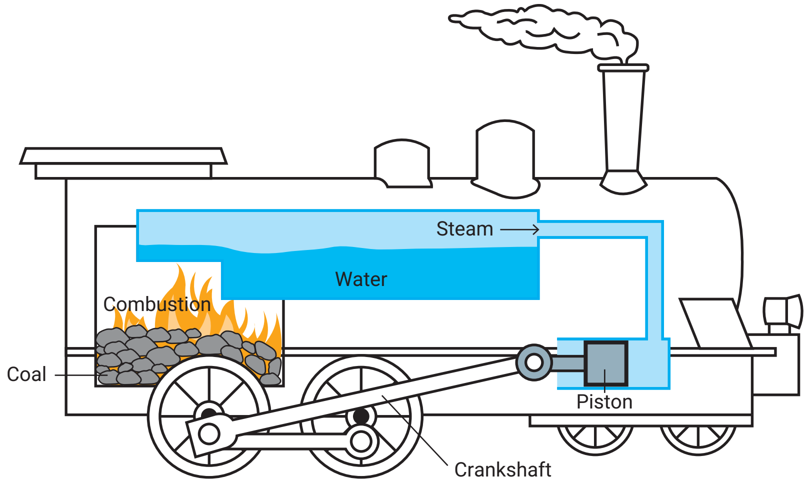

FIGURE 5.1.3 A diagrammatic representation of an external combustion steam engine

This heat is then used to boil water in the boiler, which creates steam. The steam is hot and at high pressure. It pushes on pistons that, in turn, push on the wheels, which push on the ground and make the engine move, pulling the carriages behind it. Hence, energy is leaving the system through work because a force is being applied over some distance.

LEARNING CHECK 5.1

DESCRIBING

1 **Recall** the ways in which energy can be lost from a thermodynamic system.
2 **Define** 'work' as it relates to a thermodynamic system.
3 **Define** 'power' as it relates to a thermodynamic system.
4 Use the equations for work and power to show that the units of power could be given as N m s^{-1}.

APPLYING

5 **Explain** how the heat from a combustion chamber in a steam engine can be used to do work on its carriages.
6 **Calculate** the power rating of an engine that does 3.0 kJ of work in 15 s.
7 If a system has a power rating of 5.0×10^3 W, how much work can it do in 2.5 minutes?
8 If a 1500 W engine pulls a carriage with a 120 N force over 225 m, for how long was the engine working?

5.2 Change in internal energy

Syllabus link
Chapter 1 discusses internal energy.

The sum of all the kinetic and potential energies in a substance is defined as the *internal energy* of that substance. This can be expanded to an entire system of different parts to say that the total internal energy of a system is equal to the sum of its total kinetic and potential energy.

If a system loses heat to its surroundings, the internal energy of that system must decrease, and if heat is added to a system, its internal energy must increase. Similarly, since work is also a transfer of energy, it is reasonable to assume that if work is done by a system on its surroundings, the internal energy of the system will decrease, and if work is done on a system, the internal energy of the system will increase.

This work–energy principle can be stated as 'the change in internal energy of a closed system, ΔU, is equal to the energy added to the system in the form of heat minus the work done by the system on its surroundings'.

The work–energy principle is a mathematical representation of the first law of thermodynamics and its validity has never been called into question through any experimental observation. It is one of the great laws of physics and, as it shows that as energy is transferred out of a system in the form of heat or work, then the internal of energy of the system must accordingly decrease; it is effectively a formulation of the conservation of energy.

When the work–energy principle is applied, it is important to be careful and to consistently follow the sign conventions for Q and W. If heat is added to the system, Q is positive; if heat is removed from the system, Q is negative. If work is done *by* the system on its surroundings, W is positive and U decreases; if work is done *on* a system, W is negative and U increases.

The work–energy principle:

$$\Delta U = Q - W$$

where: ΔU = change in internal energy of a closed system (J)
Q = heat added to the system from its surroundings (J)
W = work done by the system on its surroundings (J)

KEY FORMULA

The work–energy principle

$$\Delta U = Q - W$$

where:
ΔU = change in internal energy of a closed system (J)
Q = heat added to the system from its surroundings (J)
W = work done by the system on its surroundings (J)

Closed systems

When the energy enters the system in the form of heat from the combustion chamber that boils the water, the internal energy of the system increases by an amount:

$$\Delta U = {}^{+}Q_{\text{in}}$$

When the steam does work to push the pistons into motion and ultimately the wheels, engine and carriages as well, the system is doing work. Energy is being transferred out of the system and therefore the change in internal energy can be represented by:

$$\Delta U = -\,{}^{+}W$$

The positive sign of W, which is negated by the minus sign in the equation, indicates that energy is lost from the system. If no energy is lost as heat, then the total energy change is:

$$\Delta U = Q_{\text{in}} - W$$

In an ideal engine with 100% efficiency, the work done would equal the heat input. However, there is no such thing as an ideal engine. There is always some heat lost from the system to the environment, $-Q_{\text{out}}$. Hence, we can write our energy equation for any real engine as:

$$\Delta U = Q_{\text{in}} - Q_{\text{out}} - W = Q - W$$

This tells us that the change in energy of the system is equal to the net heat added to the system minus the work done by the system. If the net heat in, Q $(= Q_{\text{in}} - Q_{\text{out}})$, and the work done ($W$) are equal, then the total change in internal energy is zero. This is the case for an engine working at constant temperature; in other words, once it has reached its stable operating temperature.

Figure 5.2.1 shows these energy transfers. The heat source (the firebox) supplies heat to boil the water to make steam. Heat energy Q_{in} moves from here into the engine. Work is done by the engine; this is energy leaving the system. Heat is also lost by the system to its surroundings; this is Q_{out}. We call a system that converts heat into work a **heat engine**. Steam engines and petrol and diesel car engines, as well as the petrol engines that power generators and pumps, are all heat engines.

heat engine a system that converts heat energy to work

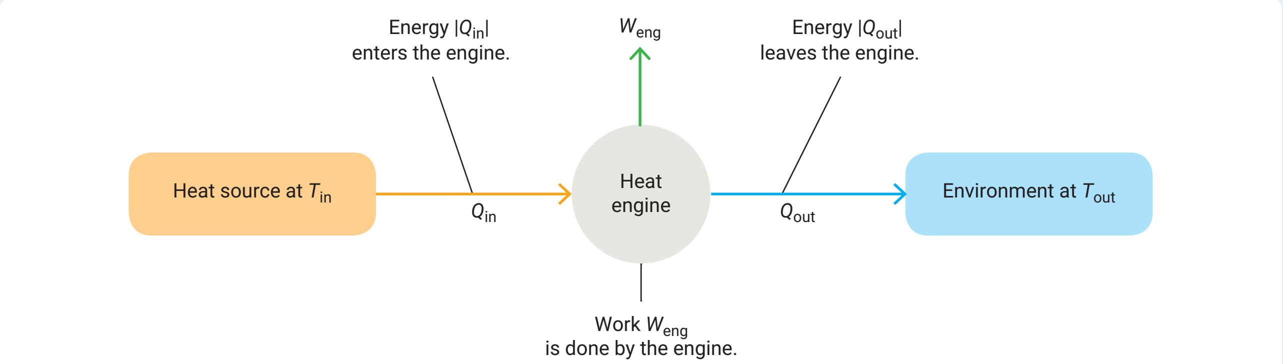

FIGURE 5.2.1 A schematic representation of a heat engine

Now consider another system – one of the carriages. The carriage, to a first approximation, is not gaining or losing heat. However, if it is being pulled by the engine, then a force is applied to it and work is done on it. In this case, the change in energy is positive, energy is coming into the system. Hence, the sign of the work is negative (which is made positive by the minus in the equation):

$$\Delta U = -\,{}^{-}W = {}^{+}W$$

In general, any energy change, whether it is heat or work, is positive for energy coming into a system and negative for energy leaving the system.

It is important to carefully define our system boundaries so that we know which sign to use. If we define our system as the universe, which is an isolated system, then the total energy change must always be zero. The heat going into the steam engine must have come from somewhere. It came from the internal energy of the fuel that was burnt. This loss of internal energy to the environment outside the engine is equal to the gain in heat inside the engine. The total energy of the universe is conserved.

WORKED EXAMPLE 5.2.1

If 2500 J of heat is added to a system and 1800 J of work is done on the system, what is the total change in internal energy of the system?

ANSWER

1 **Apply the work–energy principle.**

$\Delta U = Q - W$

2 **Substitute known values.**

Q is positive since it is added to the system and W is negative because work is done on the system.

$\Delta U = 2500\ \text{J} - (-1800\ \text{J})$

Both are now positive, indicating that they are both processes that result in an increase in internal energy.

$\Delta U = 2500\ \text{J} + 1800\ \text{J}$

3 **Calculate the answer with correct number of significant figures.**

$\Delta U = 4300\ \text{J}$

WORKED EXAMPLE 5.2.2

When 250 kJ of heat is added to a steam engine that has reached its stable operating temperature, 180 kJ of work is done by the engine.

Calculate the amount of heat lost by the system to its surroundings.

ANSWER

1 **Apply the work–energy principle.**

$\Delta U = Q - W$

$\Delta U = 0$ since the engine is at its stable operating temperature.

$0 = Q - W$

Q (net heat) is equal to $Q_{\text{in}} - Q_{\text{out}}$.

$0 = (Q_{\text{in}} - Q_{\text{out}}) - W$

2 **Rearrange for the unknown.**

$Q_{\text{out}} = Q_{\text{in}} - W$

3 **Substitute the known values.**

$Q_{\text{out}} = 250\,000\ \text{J} - 180\,000\ \text{J}$

4 **Calculate the answer.**

$Q_{\text{out}} = 70\,000\ \text{J}$

5 **Give the answer to the correct units and number of significant figures.**

$Q_{\text{out}} = 7.0 \times 10^4\ \text{J}$

LEARNING CHECK 5.2

DESCRIBING

1 **Define** the work–energy principle.
2 **Define** the purpose of a heat engine.
3 **Identify** the stable operating temperature of a heat engine.
4 If heat is added to a system, what sign will Q in the work–energy principle have?
5 If heat is removed from a system, what sign will Q in the work–energy principle have?
6 If work is done on a system, what sign will W in the work–energy principle have?
7 If work is done by a system, what sign will W in the work–energy principle have?

APPLYING

8 If 2.5 kJ of heat energy is added to a system and, in turn, it does 1200 J of work, **calculate** the change in internal energy of the system.
9 The combustion chamber of a steam engine delivers 5.0 kJ of heat to the boiler and the expanding steam does 3.0 kJ of work on the piston. If 1.5 kJ of heat is lost as waste, **calculate** the change in internal energy of the system.
10 If a heat engine at its stable operating temperature does 323 kJ of work when 440 kJ of heat is added to the system, **calculate** the amount of heat lost to the external surroundings.

5.3 Heat loss and usable energy

usable energy energy that can be used to perform a desired result; usually in the form of energy to do work

You only have to rub your hands together to realise that it is relatively easy to produce thermal energy by doing work. The reverse process, that of producing **usable energy** in the form of work, is much more difficult. This is the primary role of the heat engine and the first practical device that achieved this was the steam engine, which was not developed until the 18th century.

The basic idea behind any heat engine is that mechanical work can be extracted from a process in which thermal energy is transferred from an area of high temperature to one of low temperature (Figure 5.2.1).

This temperature difference is a necessary component of any heat engine. For example, consider what would happen if the region of low temperature, the boiler, were at the same temperature as the combustion engine. In this case, no heat would flow and the water in the boiler would not produce steam to push the pistons and no work would be done.

There are many types of engines, but they all work by converting heat from a fuel source into useful work. All real engines will also lose energy in the form of heat to their surroundings. This may be due to mechanical friction of the moving parts of the engine, turbulence of the expanding gases or other factors. Heat lost in this way reduces the overall usable energy available to the engine.

Heat exchange and conversion systems

heat-exchange system any system that transfers heat from a warmer to a cooler place

A **heat-exchange system** transfers heat from a warmer to a cooler location. For example, numerous capillaries in the human nasal passages maintain a temperature below core temperature. This means that air leaving the nose is cooled and air entering the nose is warmed.

A **heat-conversion system** transforms the internal energy of a system. For example, air expelled from a person's wide-open mouth feels warm, but air blown through a smaller hole feels cooler. The decrease in hole size increases pressure in the mouth. When the air is released through a small hole, it undergoes cooling as it expands rapidly, does work on the surrounding air, transfers its energy and cools rapidly. Try it yourself.

Heat exchange and evaporative cooling are common in nature and are used to regulate body temperature. Many modern-day cooling and heating systems use heat exchange, state change, energy release and capture, and energy conversion systems. These processes can control temperature and do useful work.

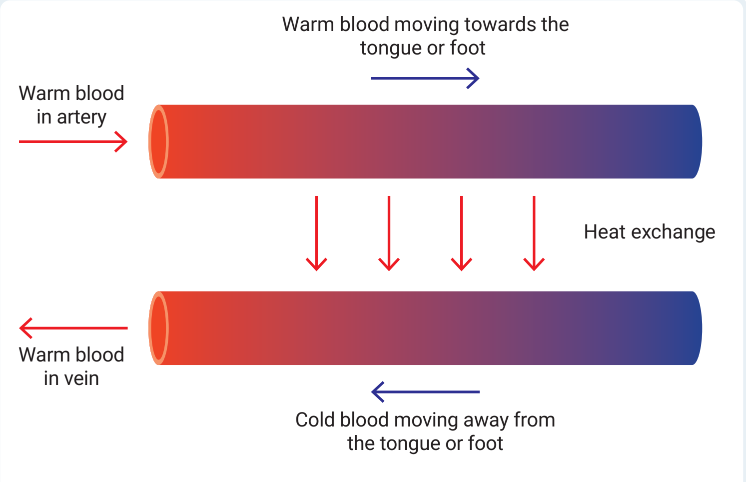

FIGURE 5.3.1 Countercurrent heat exchange between blood vessels reduces heat loss in some animals.

Countercurrent heat exchange

'Countercurrent' heat exchange occurs naturally in the circulation systems of fish, whales and other marine mammals (Figure 5.3.1). Arteries carrying warm blood from the heart to the skin are intertwined with veins carrying cool blood from the skin to the heart. This allows the warm arterial blood to exchange heat with the cooler blood in the veins. This reduces the overall heat loss in cold waters.

heat-conversion system a system that transforms the internal energy of a system

Reverse-cycle heating and cooling

During winter, a reverse-cycle air conditioner extracts heat from the outside air, even on very cold nights. The evaporator coil inside the air conditioner is maintained at a much colder temperature than outside. Energy is transferred from the warmer, though very cold, outside air to the colder evaporator coil. This energy is then transferred into the house. The clever design means that, in summer, this cycle can be reversed and heat is extracted from the house and transferred outside. These systems are fully contained and are relatively cost efficient.

As the cold gas refrigerant passes through an external copper coil (the evaporator) between (2) and (4) in Figure 5.3.2, it absorbs heat by collision with the cool outside air particles. The refrigerant gas is then pumped through a compressor (4), where it is compressed and turns from a cool gas into a hot liquid. The compressor has transferred energy to the particles of the refrigerant by forcing them closer together. This increases the internal energy of the compressed refrigerant in the pump. Its temperature increases.

The hot liquid passes into a copper coil with a large surface area, the **condenser** (1). The hot liquid in the condenser radiates heat energy into the room. The cooler refrigerant liquid continues to pass along the condenser's copper coil until it reaches a constriction, called an expansion valve, at (2). As the refrigerant passes through the constriction, it expands rapidly into the evaporator. This expansion means that the internal energy is re-balanced so that potential energy increases while the kinetic energy, hence temperature, decreases.

condenser a vessel that removes heat from a gas by allowing it to turn back into a liquid

The expansion of the vapour in the expansion coil causes rapid cooling of the refrigerant. The cold expansion coil again absorbs heat energy from the outside, warming the coil and refrigerant. The refrigerant is then pumped back into the condenser, starting another heat-exchange cycle. The cycle will continue as long as the compressor continues to operate.

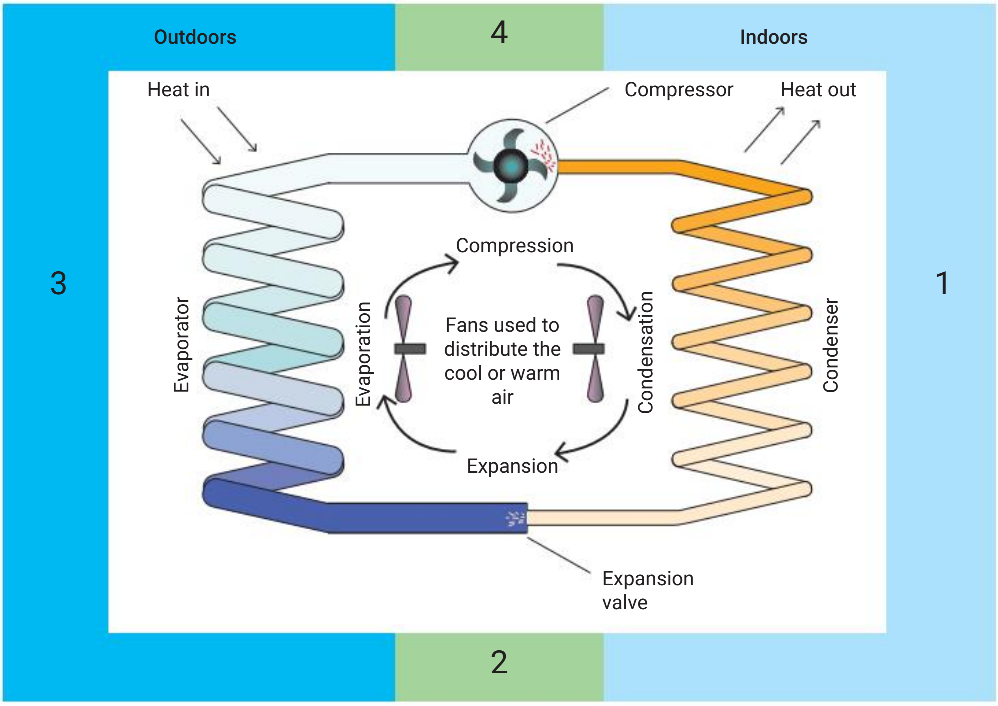

FIGURE 5.3.2 The heating cycle of a reverse-cycle air conditioner. This schematic diagram shows the energy transfers from the outdoor set of coils to the indoor set of coils by a repeating cycle of compression and expansion of a refrigerant.

Figure 5.3.3 shows the energy transfers that occur in this system. Heat, Q_{in}, enters the system and heat, Q_{out}, leaves the system. Work, *W*, is done *on* the system.

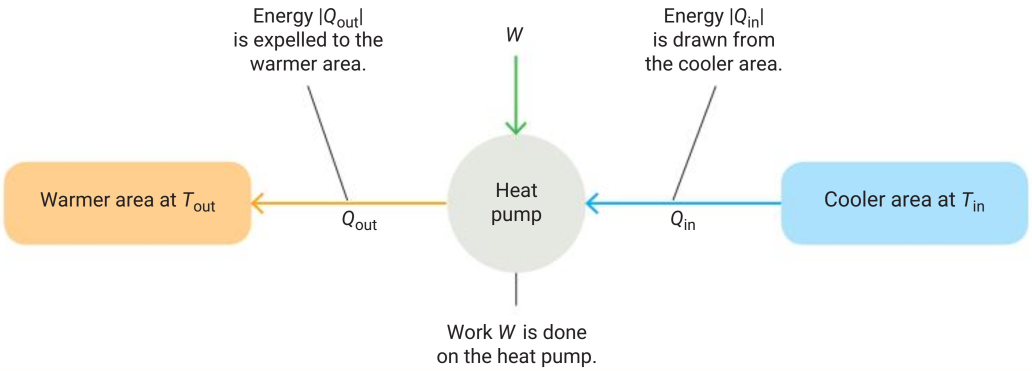

FIGURE 5.3.3 This schematic representation of a heat pump indicates the heat and work transfers taking place.

The net effect is that heat is moved from a cooler area to a warmer area. This is impossible without some energy being used to accomplish it. This energy is supplied by the compressor. Work is done on the system by the compressor. This work is used to move the heat energy from the cooler area to the warmer area. The energy supplied to the compressor for a refrigerator or reverse-cycle heater is usually the electric potential energy that powers the motor.

heat pump a system that moves thermal energy from one place to another

This sort of system is called a **heat pump** because it moves energy (heat) from one place to another.

The refrigerator as a heat pump

A refrigerator is a heat pump that cools the inside volume, including the food and containers. Work must be done to remove heat from inside the refrigerator. The work is done by an electric motor that compresses the refrigerant gas that passes through external coils. This causes the temperature in the coils to rise so that they radiate energy away into the cooler room (**Figure 5.3.4**). The gas next passes through an expansion valve into coils in the refrigerator, where it becomes cooler than the materials inside the refrigerator. Heat is transferred to the refrigerant, which cycles back via compression to the outside, and so on. The temperature is kept at an appropriate level by a sensor circuit.

Reverse-cycle heat pumps can act in the same way as refrigerators: they cool the room in summer and send the heat outside, or heat the room in winter by cooling the air outside. Coolers that use this process often drip water because the expansion coil gets very cold, causing water vapour in the surrounding air to condense.

FIGURE 5.3.4 The back of a household refrigerator. The air surrounding the coils is a heat sink.

External combustion engine

An external steam combustion engine is a heat engine that uses **superheated steam** under pressure as the working fluid to drive a piston. The water is heated outside the piston cylinder to temperatures well above boiling point. The rapidly expanding high-pressure steam transfers energy to the piston to move it. The steam is then expelled from the cylinder, where it is condensed, reheated back into steam and recycled.

superheated steam
steam that is held under high pressure and heated to a temperature above the boiling point of water

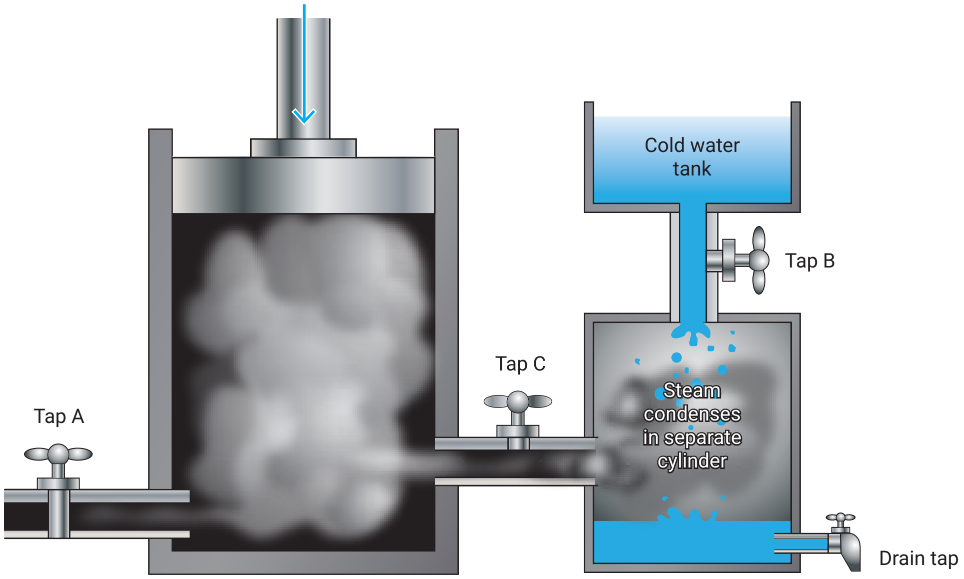

FIGURE 5.3.5 James Watt's external combustion engine with an external condenser

Figure 5.3.5 shows how an early James Watt external condenser steam engine worked. Taps B and C are closed and steam is introduced into the cylinder through tap A, which is open. This pushes the piston up the cylinder. Then tap A is closed and tap C is opened, allowing steam to escape under pressure into the condenser. This reduces the pressure under the piston, and air pressure and gravitational force cause the piston to fall. This expels all the steam into a separate, external cylinder. Cold water is then added into this steam through tap B to condense it.

The piston's cylinder was always hot under these conditions, so fuel was not required to heat it again before steam was reintroduced. This also meant that the steam could be allowed to expand into the cylinder to do work, rather than continuously feeding in steam. This was a saving on the volume of steam needed and, hence, the amount of fuel used. This early design has been developed into the highly efficient engines that are used today, mainly in the generation of electrical energy.

Internal combustion engine

Most cars currently use what is called a four-stroke internal combustion cycle to convert the chemical energy in the petrol into motion. The four-stroke engine was invented in 1867 by Nikolaus Otto (1832–91). The four strokes are the intake stroke, the compression stroke, the combustion stroke and the exhaust stroke **(Figure 5.3.6)**. High-energy fuels, such as petrol, contain large amounts of chemical energy. When they combust with oxygen, this energy is released, mainly in the form of heat. When small amounts of petrol are ignited with oxygen in a confined space, large amounts of energy are released by the hot expanding gases. These expanding gases can do work if they are produced in the cylinders of a piston-driven engine.

The piston is connected to the crankshaft by a rod. As the crankshaft revolves, it uses lifters to open and close the valves at the correct time during each cycle. The engine can complete the cycle thousands of times per minute.

Let us follow the four strokes of the engine cycle, starting with the piston at the top. The intake valve opens and the petrol–air mixture is drawn in as the piston moves down. The second step begins as the piston moves up, compressing the mixture. When the piston reaches the top, the third stage begins. In this stage, the compressed mixture is ignited by the spark plug or electronic ignition system, causing a powerful explosion that pushes the piston down. This is known as the power stroke. Once the piston reaches the bottom of its stroke, the exhaust valve opens. The exhaust gases are then expelled into the exhaust pipe as the piston moves up. This completes the cycle.

Weblink
Animated engines – four stroke

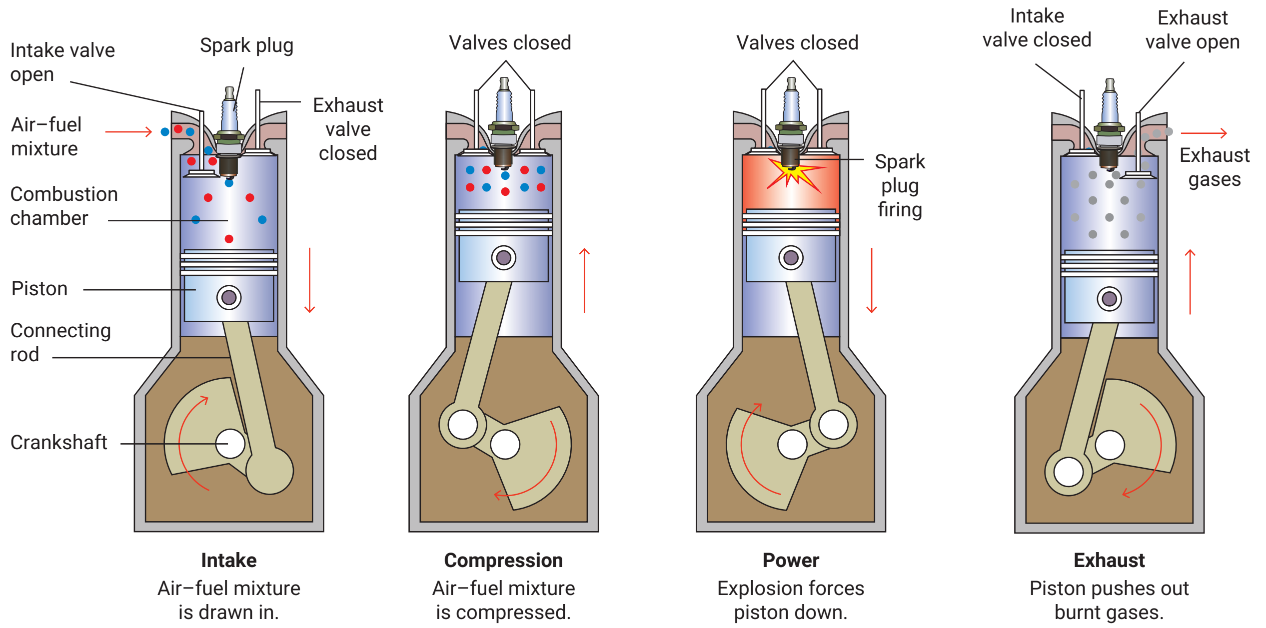

FIGURE 5.3.6 The four-stroke cycle internal combustion engine

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LEARNING CHECK 5.3

DESCRIBING

1 **Define** 'usable energy'.
2 **Describe** a heat-exchange system.
3 **Describe** how a heat-exchange system is different from a heat-conversion system.
4 **Describe** the difference between an internal combustion engine and an external combustion engine.

APPLYING

5 **Explain** why opening a refrigerator door will not cool the room it is in.
6 Use diagrams to explain how a four-stroke engine works.

5.4 Efficiency

The **energy efficiency**, η (the Greek letter 'eta'), of any system is the fraction of the input energy that produces a useful output. It is usually represented as a percentage.

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

where: η = energy efficiency

energy efficiency the fraction of input energy that is converted in a thermodynamic process to useful output energy

Science, driven by the quest for efficiency and innovation, has shaped technological advancements, particularly evident in the evolution from early steam engines to modern internal combustion engines and now electric vehicles. The need to enhance the efficiency of early steam engines spurred both technological and scientific progress. Engineers sought ways to improve these engines, leading to more efficient designs and the internal combustion engine, revolutionising transportation and industry. Through rigorous experimentation, they formulated laws governing energy conversion, known as thermodynamics principles. This deeper understanding not only optimised engine efficiency but also laid the foundation for modern physics and engineering principles.

KEY FORMULA

Efficiency of a system

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

where: η = energy efficiency

WORKED EXAMPLE 5.4.1

A system produces 3.3 kJ of usable energy output when 5.8 kJ of energy is put into it. Calculate the efficiency of the system.

ANSWER

1 **Use the equation for efficiency of a system.**

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

2 **Substitute known values.**

$$\eta = \frac{3.3\text{ kJ}}{5.8\text{ kJ}} \times \frac{100\%}{1}$$

3 **Calculate the answer.**

$\eta = 56.897\%$

4 **Give the answer to the correct number of significant figures.**

$\eta = 57\%$

The system has an efficiency of 57%.

WORKED EXAMPLE 5.4.2

A car with an efficiency of 22% produces a usable output energy of 28 kJ.
Calculate the amount of chemical energy that must have been input into the engine from the fuel.

ANSWER

1 **Use the efficiency equation.**

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

2 **Rearrange for the unknown.**

$$\text{Energy input} = \frac{\text{energy output}}{\eta} \times \frac{100\%}{1}$$

3 **Substitute known values.**

$$\text{Energy input} = \frac{28\,000\ \text{J}}{22\%} \times \frac{100\%}{1}$$

4 **Calculate the answer.**

Energy input = 127 272.727 J

5 **Give the answer to the correct number of significant figures.**

Energy input = 130 kJ

In the case of heat engines, the input energy is equal to the heat input, Q_{in}, and the output energy is equal to the work, W, done by the system. As a result, efficiency can be rewritten as:

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

If the heat engine is at its operating temperature, $\Delta U = 0$ and $W = Q_{in} - Q_{out}$, so efficiency can then be written as:

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1} = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times \frac{100\%}{1}$$

KEY FORMULA

The efficiency of a heat engine

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

KEY FORMULA

The efficiency of a heat engine at its operating temperature

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1} = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times \frac{100\%}{1}$$

Worksheet
Increasing energy efficiency

WORKED EXAMPLE 5.4.3

A steam engine working at its operating temperature uses 5.6 kJ of heat energy every second and has an efficiency of 27%.

a Calculate the amount of usable mechanical energy that will be produced every second.

b Determine the amount of waste heat that is radiated from the engine every second.

ANSWERS

a **1 Use the heat engine equation.**

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

2 Rearrange for the unknown value.

$$W = \frac{\eta \times Q_{in}}{100\%}$$

3 Substitute known values.

$$W = \frac{27\% \times 5600 \text{ J}}{100\%}$$

4 Calculate the answer.

$W = 1512$ J

5 Give the answer to the correct number of significant figures.

$W = 1.5$ kJ

b **1 Use the operating temperature equation.**

$$\eta = 1 - \frac{Q_{out}}{Q_{in}} \times \frac{100\%}{1}$$

2 Rearrange for the unknown value.

$$Q_{out} = Q_{in}\left(1 - \frac{\eta}{100\%}\right)$$

3 Substitute known values.

$$Q_{out} = 5.6\left(1 - \frac{27\%}{100\%}\right)$$

4 Calculate the answer.

$Q_{out} = 4.088$ kJ

5 Give the answer to the correct number of significant figures.

$Q_{out} = 4.1$ kJ

Note: As the problem involves a heat engine working at its operating temperature, part **b** could have been solved by realising that:

$Q_{out} = Q_{in} - W$

LEARNING CHECK 5.4

DESCRIBING

1 **Define** 'efficiency'.

APPLYING

2 An engine has an energy output of 35 kJ when 105 kJ of energy is input into the system.
  - a **Calculate** the efficiency of the engine.
  - b What happened to the remaining 70 kJ of energy?

3 If 900 J of energy is input into a system with an efficiency of 25%, **calculate** its energy output.

4 If a car can do 350 kJ of work when 1700 kJ of heat is added to it, **calculate** its efficiency.

5 A heat engine that is 19% efficient at its stable operating temperature releases 115 kJ of energy to the surroundings.
  - a **Calculate** the energy that must have been input into the system.
  - b **Calculate** the amount of work done by the system.

Work

- Work is defined as the energy transferred by the action of a force over a distance, and is represented as:

$$W = F \times s$$

where: W = work (J)
F = force (N)
s = distance (m)

$$P = \frac{E}{t} = \frac{W}{t}$$

- Power is the rate at which energy is transferred. This can be by heat or work.

where: P = power (W)
E = energy transferred (J)
t = time (s)
W = work (J)

The work–energy principle

- The work–energy principle states that the change in internal energy of a closed system is due to the heat added to the system minus the work done by the system.
- The work–energy principle:

$$\Delta U = Q - W$$

where: ΔU = change in internal energy of a closed system (J)
Q = heat added to the system from its surroundings (J)
W = work done by the system on its surroundings (J)

- When heat is added, Q is positive. When heat is removed, Q is negative
- When work is done by the system, W is positive. When work is done on the system, then W is negative.

Energy efficiency

- Energy efficiency is a measure of the amount of energy that is used to produce a useful output.
- The efficiency of a system:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

where: η = energy efficiency

- The efficiency of a heat engine:

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

- If the heat engine is at its operating temperature, $\Delta U = 0$ and $W = Q_{in} - Q_{out}$, so efficiency can then be written as:

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1} = \left(1 - \frac{Q_{out}}{Q_{in}}\right) \times \frac{100\%}{1}$$

CHAPTER EXAM

MULTIPLE CHOICE

1. Which of the following results in a decrease in the internal energy of a system?

A Heat is added to the system.
B Work is done on the system.
C Work is done by the system.
D Kinetic energy is added to the system.

2. Which of the following is not a unit for work?

A watt
B joule
C newton metre
D $kg\,m^2\,s^{-2}$

3. An increase in which of the following terms would result in an increase in the efficiency of a heat engine?

A Q_{in}
B Q_{out}
C U
D W

4. What is the value of the change in internal energy when an external combustion engine is working at its stable operating temperature?

A W
B 0
C Q_{in}
D Q_{out}

5. What is the work done by a 300 W electric grinder in 5.0 min?

A 1 kJ
B 1.5 kJ
C 25 kJ
D 90 kJ

6. An electric kettle has an input of 1500 J of electrical energy and the water within gains 1260 J of thermal energy. What is the efficiency of an electric kettle?

A 0.84%
B 84%
C 100%
D 119%

7. A car's combustion engine uses 480 kW of energy from fuel. 120 kW of this energy goes to powering the wheels and 360 kW gets converted into heat. The energy efficiency of the combustion energy would be calculated as:

A $\frac{120}{480} \times 100\%$

B $\frac{360}{480} \times 100\%$

C $\frac{120 + 360}{480} \times 100\%$

D $\frac{120}{360} \times 100\%$

8. Usable energy is the:
   - **A** total energy consumed by a device.
   - **B** total energy transformed by a device.
   - **C** useful energy transformed by a device.
   - **D** energy lost to the surroundings during the transformation.

9. A beaker containing 1200 g of water at 25°C is placed on a Bunsen burner for 1 minute where $\eta = 30\%$. The output of a Bunsen burner is 588 kJ per minute. The final temperature of the water is approximately:
   - **A** –10°C.
   - **B** 25.5°C.
   - **C** 60°C.
   - **D** 142°C.

10. A petrol-fuelled car engine becomes hot. This is because:
   - **A** the engine is close to being 100% efficient.
   - **B** not all the energy in the fuel is converted to heat energy.
   - **C** not all the energy in the fuel is converted to kinetic energy.
   - **D** the kinetic energy of the car is being converted to heat energy.

SHORT RESPONSE

11. **Calculate** the efficiency of an engine that performs 1.6 kJ of work for every 8.5 kJ of heat that is added.

12. Use the example of the steam engine to **explain** how an external combustion engine can be used to do useful work. Include a diagram in your answer.

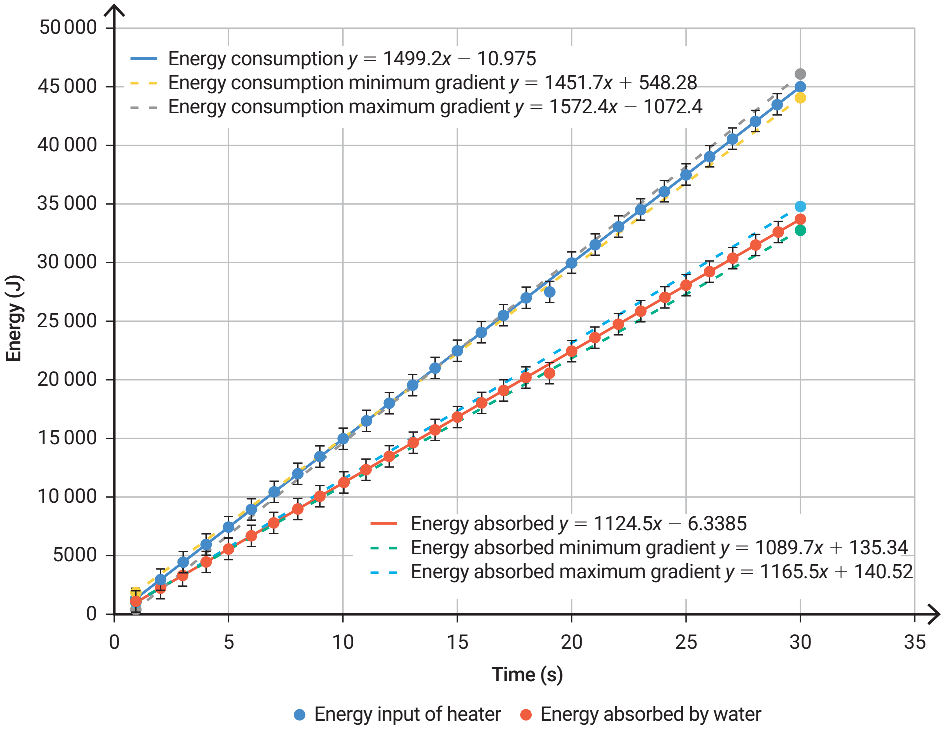
13. A refrigerator consumes 5000 J of energy per second to maintain a temperature difference of 20°C between its interior and the surroundings. If the heat transferred from the refrigerator to the surroundings is $2000\,\text{J}\,\text{s}^{-1}$, **calculate** the energy efficiency (η) of the refrigerator and the percentage efficiency of the refrigerator.

DATA ANALYSIS

14. **Analyse data**

   The energy consumption of a water heater and the energy absorbed by the water it was heating were monitored over time. The data collected was used to produce the following graph, which includes the energy consumption and absorption experimental trend lines, as well as the corresponding maximum and minimum gradient lines derived using the error bars of the measurement devices used.
   - **a** **Explain** why the line for energy absorbed by the water is lower than the line for energy consumed by the water heater.
   - **b** Using the equation for the line for energy consumption, **determine** the average power consumption of the heater (to one decimal place).
   - **c** Using the maximum and minimum gradients of the line for the heater's energy consumption, **determine** the uncertainty for the value of the average power consumption (to one decimal place).
   - **d** Using the equation for the line for energy absorption, **determine** the average rate of energy absorption of the water. State your answer in watts (to one decimal place).

e Using the maximum and minimum gradients for the line for absorbed energy, **determine** the uncertainty for the value of the water's absorption (to one decimal place).

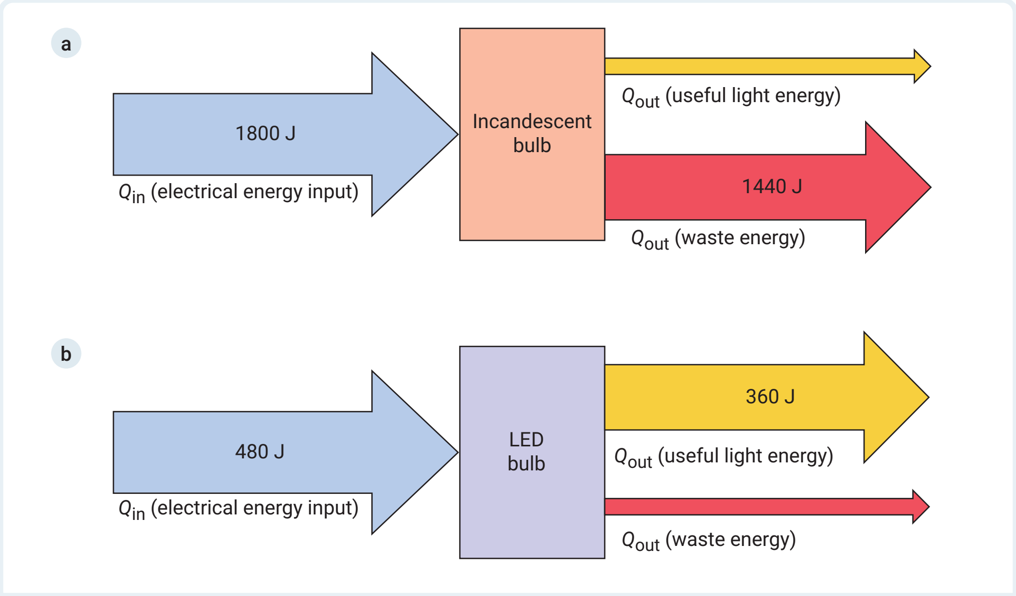


Energy consumption of a water heater and the energy absorbed by the water over time

f Write a conclusion about the percentage efficiency of the water heater. Include any specific values from relevant calculations.

15. Analyse data

Incandescent light bulbs are an old technology in which an electrical current heats a conductor called a filament so that it glows. Recently, light bulbs using light emitting diodes (LEDs) have become more common. LEDs rely on light being produced from the quantum effects of an electrical current flowing through special materials called semiconductors. The following diagrams represent the energy flow through each type of light over a period of 1 minute.



- **a** Both bulb types do not convert all their input electrical energy into useful output light energy. **Identify** the most likely form of the waste energy.
- **b** Quantify the waste energy for the LED bulb.
- **c** **Determine** the percentage efficiency of each bulb type and compare them. Write a conclusion about why LED bulb technology is becoming more prevalent.
- **d** **Calculate** the power consumption of the incandescent bulb.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- 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.

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The physics of anthropogenic climate change

Advancements in understanding heating processes and the development of new technologies have shaped our ability to predict global temperatures and comprehend the impact of human-induced climate change.

The role of climate modelling

Climate modelling plays a pivotal role in understanding and mitigating climate change. It provides us with a window into the future, allowing us to explore various scenarios and assess their consequences. Two influential physicists, Klaus Hasselmann and Syukuro Manabe, pioneered climate modelling, bridging fundamental research with societal relevance. They were recently honoured with the Nobel Prize in Physics for their contributions to quantifying variability and reliably predicting global warming.

The physics principles behind climate modelling

To appreciate anthropogenic climate change, we must grasp key physics principles.

- **Conservation laws:** Fundamental principles such as the conservation of energy, momentum and mass underpin climate models. These laws guide our understanding of how energy flows through Earth's system.
- **Radiative forcing:** Climate scientists use the concept of radiative forcing to quantify the effect of increased greenhouse gas concentrations. Radiative forcing measures the change in Earth's energy balance relative to pre-industrial times. It is expressed in watts per square metre.

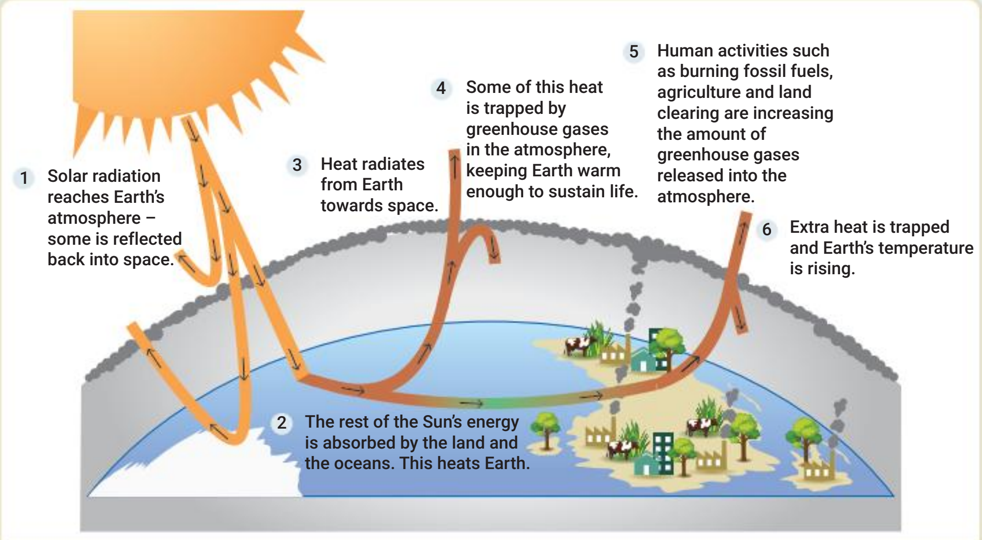


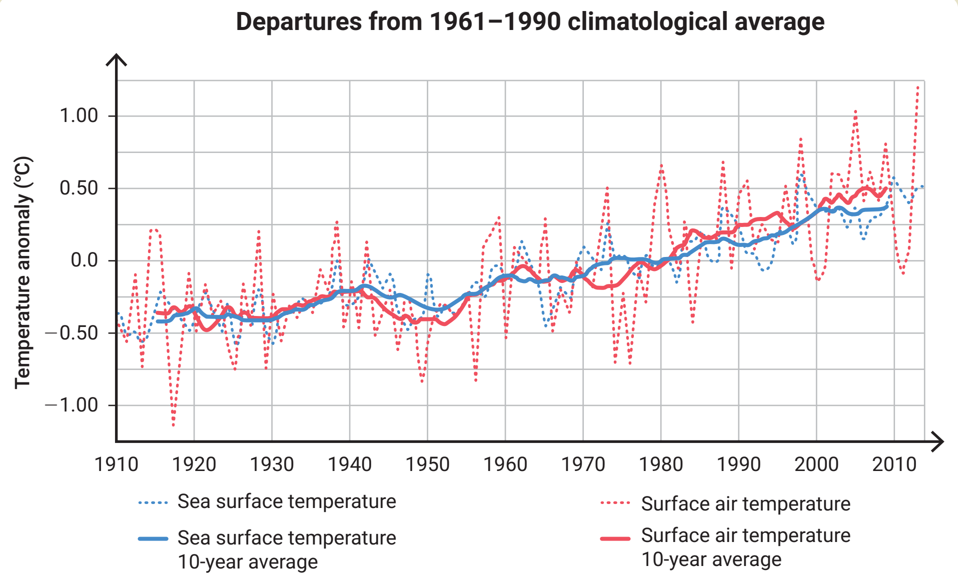
FIGURE 1 The enhanced greenhouse effect

Environmental Biology. Authored by: Matthew R. Fisher, Editor.

- **Quantum mechanics and quantum field theory:** In 1900, Max Planck introduced the idea of quanta – discrete packets of energy emitted by light. The Planck constant, central to quantum mechanics, sets the stage for understanding energy transitions.

Predicting global patterns

Advancements in technology, particularly machine learning, have revolutionised climate prediction. Researchers now use unique data sets from existing climate model simulations to learn relationships between short-term and long-term temperature responses. This approach helps us project global climate changes based on different forcing scenarios.



Australian Academy of Science

FIGURE 2 Deviations from the 1961–1990 average sea surface temperature and temperatures over land in the Australian region

Conclusion

Physics, technology and climate science converge to address one of humanity's most pressing challenges: anthropogenic climate change. As we continue to refine our models and deepen our understanding, the contributions of physicists past and present remain essential in shaping a sustainable future.

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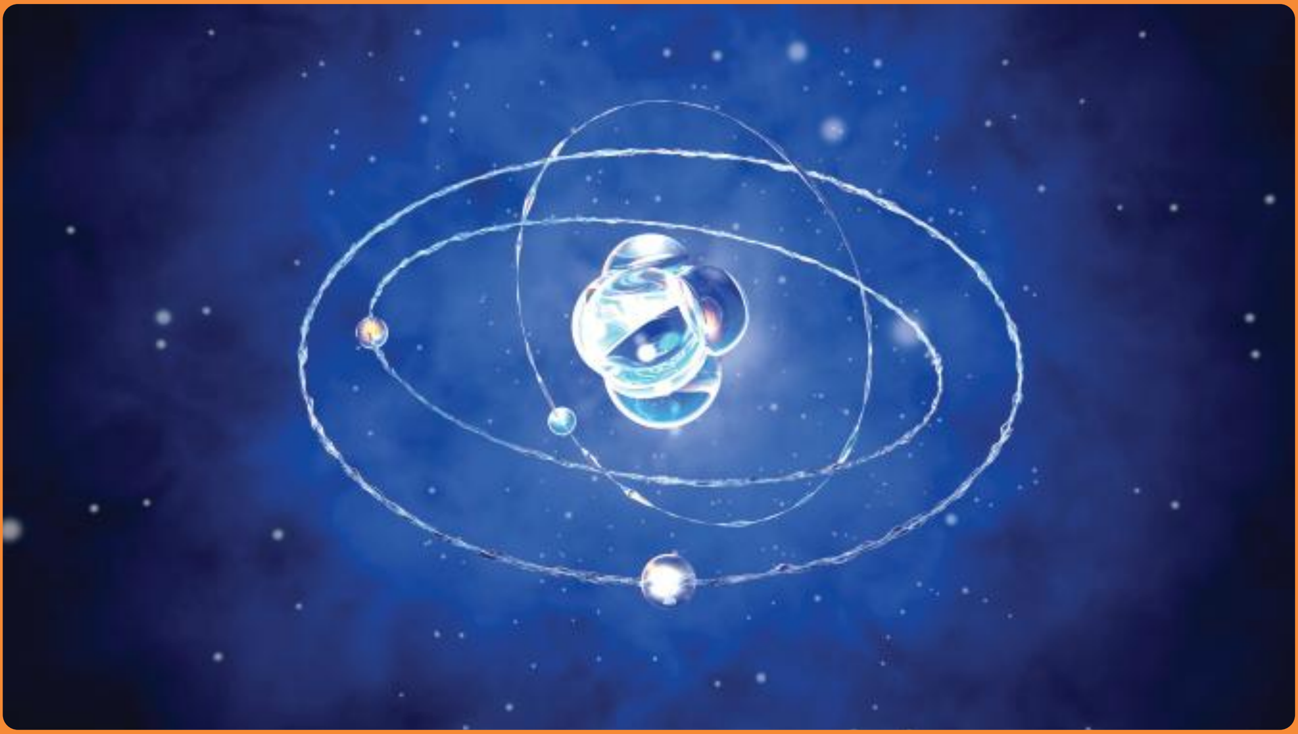
CHAPTER 6

Nuclear model and stability



Spectral-Design/Shutterstock.com

SYLLABUS DOT POINTS

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.
- Explain natural radioactive decay in terms of stability.

SCIENCE AS A HUMAN ENDEAVOUR

- Appreciate the significant contributions of scientists such as Marie Curie, Irene Curie-Joliot, Lise Meitner and Otto Hahn who furthered our understanding of radiation and nuclear stability.
- 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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Introduction

All matter, living or not, is composed of nothing more than millions and trillions of atoms. Different atoms have uses in different fields, from construction materials to nuclear power and radiation treatments for medical purposes. Recently, scientists have been able to photograph shadows of atoms, and, surprisingly, the major constituent of these small particles, once believed to be indivisible, is just empty space.

Practical

- Atomic scale

Worksheet

- The atom and isotopes

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ The atom consists of protons, neutrons and electrons.
- ✓ Protons, neutrons and electrons have different relative masses and charges.
- ✓ Particles with opposite charges are attracted to each other by electrostatic forces.
- ✓ Particles with the same charge repel each other.
- ✓ Different elements consist of different types of atoms.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe the nuclear model of the atom, including the characteristics of subatomic particles
- ✓ appraise the various historical models of the atom
- ✓ describe nuclides using nomenclature or notation conventions mass number and atomic number
- ✓ define ‘element’, ‘isotope’, ‘isobar’, ‘isomer’ and ‘nuclide’
- ✓ determine the number of neutrons of a nuclide
- ✓ explain the concept of atomic weight
- ✓ describe and explain the strong nuclear force
- ✓ explain the effect of Coulomb’s law within the atom
- ✓ contextualise the strong nuclear force within the four fundamental forces
- ✓ compare the four fundamental forces
- ✓ analyse and interpret the stability curve
- ✓ describe and explain radioactive decay and link it to the stability curve
- ✓ analyse data pertaining to Coulomb’s law to investigate its proportionality via linearisation.

6.1 The nuclear model

The **nucleus** lies at the centre of the **atom** and contains the **subatomic particles** that distinguish elements and isotopes from one another. The discoveries that led to the current understanding of the nucleus of the atom have been the life-consuming work of many scientists. After many experiments and years of development, a common understanding of the atom has come to light: there is an extremely small nucleus at the centre of an atom, and this nucleus contains the vast majority of the atom’s mass.

nucleus the centre of an atom; comprises most of an atom’s mass

atom a particle; originally thought to be indivisible, but now known to comprise numerous smaller particles

subatomic particle a particle within an atom

The atomic model

Democritus (460–370 BCE) was the first to propose the idea of the atom as the smallest, indivisible particle of matter. At the time, this was a powerful idea, but it has never entirely been accepted. The idea of something this small and fundamental was groundbreaking and provoked many scientists to work towards developing a deeper understanding of the atom.

Thomson's 'plum pudding' model

In 1897, J.J. Thomson (1856–1940) discovered the **electron** by applying a high voltage across a gas at very low pressure. This discovery gave support to the idea that within an atom there were more fundamental particles. Thomson proposed a model for the atom, consisting of a uniformly positive region of charge within which negatively charged electrons were distributed. The model was dubbed the 'plum pudding' model (Figure 6.1.1), because the electrons appeared to be like raisins stuck in a plum pudding.

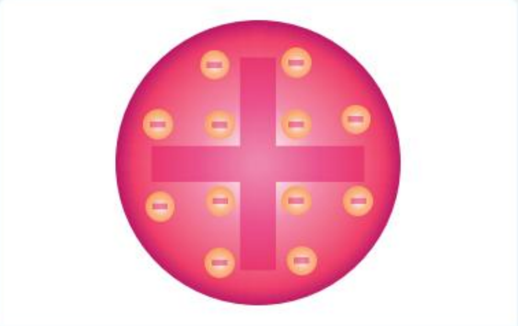


FIGURE 6.1.1 Thomson's plum pudding model of the atom shows electrons in a positively charged sphere of electrification producing a neutrally charged atom overall.

Rutherford's model

In 1909, Ernest Rutherford (1871–1937) designed an experiment to test Thomson's plum pudding model. Famously called the gold foil experiment, it involved Rutherford firing positively charged **alpha particles** (helium nuclei) at an extremely thin piece of gold foil. If Thomson's model was correct, the particles would pass through the foil as though uninterrupted. However, when the experiment was carried out, it was noticed that some alpha particles were deflected slightly from a straight path, and a small number bounced almost directly backwards from the foil (1 in 20000 reflected back straight towards the source). This revolutionary result prompted Rutherford to develop his own atomic model, refined from the plum pudding model. He suggested that, rather than a uniformly positively charged region, there was a dense region of positive charge (explaining the deflection and reflection of alpha particles – termed 'scattering') and that there was a light, negatively charged space in which the electrons circulated. He analogised these circulating electrons to planets orbiting the Sun, in which the Sun represented a dense, positively charged nucleus.

electron a negatively charged subatomic particle with mass 9.11×10^{-31} kg

alpha particle a particle made up of two neutrons and two protons; a helium nucleus

Weblink
Discovery of electron and nucleus

Rutherford–Bohr model

Unfortunately, the idea that negatively charged electrons could orbit freely while maintaining all their energy was a serious violation of the laws of classical electrodynamics. James Clerk Maxwell (1831–79) developed equations that effectively describe, explain and predict a vast array of electromagnetic phenomena. For example, as a charged particle (e.g. an electron) orbits or passes other charged objects (e.g. a positively charged nucleus), it should slow down, and spiral into the centre. There was no evidence that this was happening in Rutherford's planetary model (Figure 6.1.2).

Niels Bohr (1885–1962) worked extensively with Rutherford, and suggested that electrons could only have specific energies, and within those energy states the electrons could not radiate or lose any energy. Within this model, all laws of physics are maintained, whereby electrons occupy discrete energy levels and the nucleus is located at the centre of the atom.

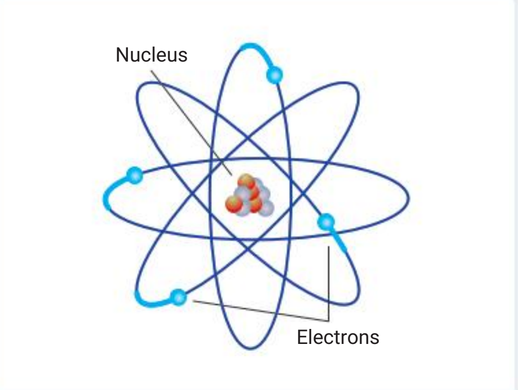


FIGURE 6.1.2 Rutherford's planetary model of the atom

The nuclear conclusion

The percentage of mass contained in the nucleus and the volume of the nucleus as a percentage of the size of the atom are summarised in **Table 6.1.1**.

TABLE 6.1.1 The percentage mass and volume of the nucleus of an atom

Component of atom	Percentage mass of atom	Percentage volume of atom
Nucleus	>99%	<1%
Remainder of atom (space and electrons)	<1%	>99%

The properties of the Rutherford–Bohr model are as follows:

- The nucleus contains most of the mass.
- The nuclear charge is positive and equal in size to the total electronic charge.
- Electrons exist in orbitals that correspond to allowed energy states.
- The atom is much bigger than the nucleus.

This is our current understanding of the model of the atom.

PRACTICAL ACTIVITY 6.1.1

ATOMIC SCALE

The nucleus is very small and dense, and comprises a small part of the atom. This practical aims to give some idea of how much space there is between the electrons orbiting a nucleus, and the nucleus itself. The ratio of the diameter of the nucleus to the diameter of the hydrogen atom is approximately 1 : 100 000.

Materials

- small round object such as a pea or small ball bearing
- trundle wheel

Procedure

1. Measure the diameter of the pea and record it in metres.
2. Calculate the radius of an atom if it had a nucleus the size of the pea.
3. Go outside and have a group member hold the pea in the centre of a large space, such as an oval.
4. Have each student measure the scale radius for an atom as calculated in step 2. This gives an idea of how large each atom is compared to a nucleus.

Alternative materials

- large piece of butcher’s paper

Alternative procedure

1. It may help to cover a large area of floor space with butchers paper for this activity. In the centre of a large piece of butchers paper, make a dot with the tip of your pen. This dot should be approximately 1 mm in diameter.
2. Determine the diameter of an atom if the nucleus was 1 mm in diameter. Measure this length across the dot at several points, until a circle can be sketched.
3. Sketch the circle, and note that the pencil or pen you are drawing the atom boundary with is thicker than the nucleus you drew in the centre.

LEARNING CHECK 6.1

DESCRIBING

1 Name the scientists who have been integral in developing the model of the atom.

2 **Explain** why the model of the atom keeps changing over time.

APPLYING

3 **Distinguish** the key differences between Rutherford's model of the atom and the Rutherford–Bohr model. Discuss how Bohr's model was different and why it is currently accepted as the model of the atom.

6.2 Protons

Now that we have seen the model for the atom, we can begin to further explore the nucleus. As stated earlier, the nucleus contains most of an atom's mass, suggesting that the subatomic particles that make up the nucleus are relatively heavy compared to the electrons surrounding the nucleus. These subatomic particles are **protons** and **neutrons**. Protons and neutrons are collectively called **nucleons**.

Rutherford discovered the proton in 1919. He found that protons are positively charged, equal in charge to an electron, but approximately 1800 times more massive.

Protons are positively charged, so being too close together in a nucleus causes them to repel each other. This called into question how atoms stayed together. In 1932, Sir James Chadwick (1891–1974) discovered the neutron. Neutrons have a slightly greater mass than a proton and carry zero charge (neutrally charged), so having neutrons between the positively charged protons helps combat this repulsive electrostatic force by increasing the distance between protons and by providing a 'gluing' force to maintain the stability of the nucleus. This will be explored later in the chapter.

proton a positively charged subatomic particle within the nucleus of an atom

neutron a neutrally charged subatomic particle within the nucleus of an atom

nucleon a proton or neutron; a particle that makes up the nucleus of an atom

Elements, isotopes and nuclides

The difference between different types of atoms depends on what is in the nucleus. Because electrons are in energy shells **(Figure 6.2.1)** that are far away from the centre of the atom, it is easy for electrons to be lost or gained depending on the atom's surroundings. This is known as ionisation. When an atom has more electrons than protons or fewer electrons than protons, it is said to be a negatively or positively charged ion respectively. It is important to recognise that this exchange of electrons and the overall charge of an atom has nothing to do with the *nucleus*.

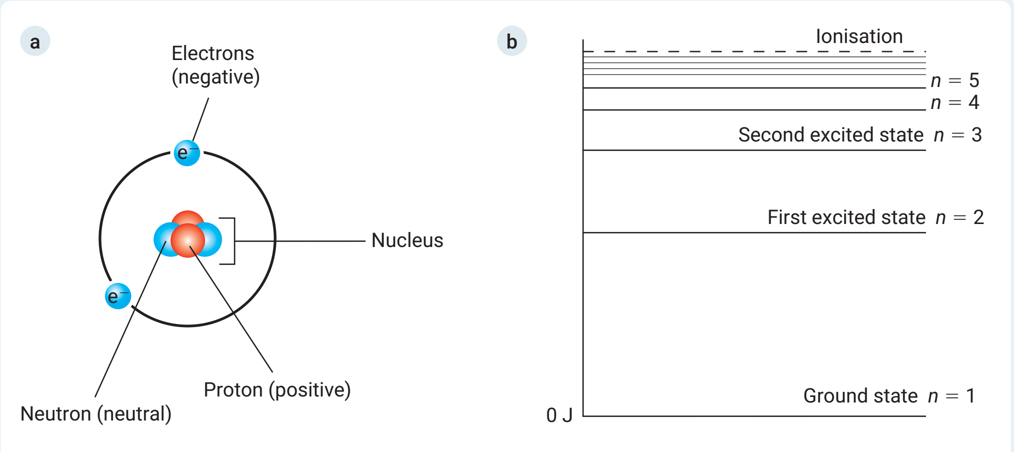


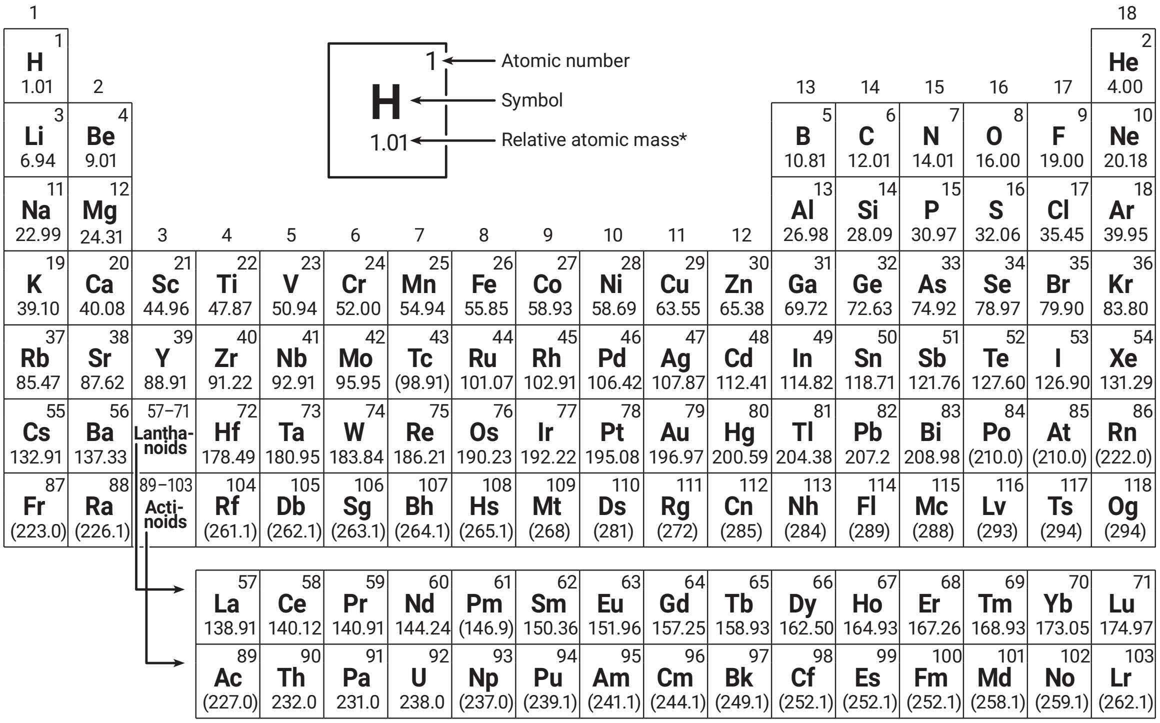
FIGURE 6.2.1 (**a**) The Rutherford–Bohr model of the atom, in which the nucleus is composed of protons and neutrons, and the outer shells contain the electrons. (**b**) The Rutherford–Bohr energy level model. Each state represents how much energy an electron needs to absorb to move to a state higher than $n = 1$.

Elements

The number of protons in the nucleus *defines* an **element**. Elements are not affected by the ionic charge of an atom. The periodic table arranges the known elements according to the number of protons in the nucleus (**Figure 6.2.2**). For example, hydrogen has one proton in its nucleus, and sulfur has 16.

element a substance made up of atoms with the same number of protons

Periodic table of the elements



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H 1.01																	2 He 4.00
3 Li 6.94	4 Be 9.01											5 B 10.81	6 C 12.01	7 N 14.01	8 O 16.00	9 F 19.00	10 Ne 20.18
11 Na 22.99	12 Mg 24.31											13 Al 26.98	14 Si 28.09	15 P 30.97	16 S 32.06	17 Cl 35.45	18 Ar 39.95
19 K 39.10	20 Ca 40.08	21 Sc 44.96	22 Ti 47.87	23 V 50.94	24 Cr 52.00	25 Mn 54.94	26 Fe 55.85	27 Co 58.93	28 Ni 58.69	29 Cu 63.55	30 Zn 65.38	31 Ga 69.72	32 Ge 72.63	33 As 74.92	34 Se 78.97	35 Br 79.90	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.91	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc (98.91)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
55 Cs 132.91	56 Ba 137.33	57–71 Lanthanoids	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (210.0)	85 At (210.0)	86 Rn (222.0)
87 Fr (223.0)	88 Ra (226.1)	89–103 Actinoids	104 Rf (261.1)	105 Db (262.1)	106 Sg (263.1)	107 Bh (264.1)	108 Hs (265.1)	109 Mt (268)	110 Ds (281)	111 Rg (272)	112 Cn (285)	113 Nh (284)	114 Fl (289)	115 Mc (288)	116 Lv (293)	117 Ts (294)	118 Og (294)

57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (146.9)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.05	71 Lu 174.97
89 Ac (227.0)	90 Th 232.0	91 Pa 231.0	92 U 238.0	93 Np (237.0)	94 Pu (239.1)	95 Am (241.1)	96 Cm (244.1)	97 Bk (249.1)	98 Cf (252.1)	99 Es (252.1)	100 Fm (252.1)	101 Md (258.1)	102 No (259.1)	103 Lr (262.1)

Groups are numbered according to IUPAC convention 1–18.

*Values in brackets are for the isotope with the longest half-life.

QCAA

FIGURE 6.2.2 The periodic table

Isotopes

Although each element has a unique number of protons, there are different *versions* of these elements. An **isotope** has the same number of protons but a different number of neutrons in the nucleus. This does not change the element, but it changes the size of the nucleus of the element and, in turn, the mass of the element. Different isotopes of elements occur naturally and in different abundances. Some isotopes that have high numbers of neutrons or protons are unstable; these are called radioisotopes.

isotopes elements with the same number of protons, but a different number of neutrons in the nucleus

Nuclides

A **nuclide** is a species of atom classified according to the number of protons and neutrons *as well as* its energy state. There are different energy levels within a nucleus, and an atom is most stable when the nucleus is in its lowest energy level – its **ground energy state**. As the number of protons in a nucleus increases, more and more neutrons are required to overcome the electrostatic force. This works only up to a certain point at which there are simply not enough neutrons to hold the nucleus together (e.g. uranium). In these cases, a nuclide would not be in its ground state, but rather it would have a lot of energy, and would need to decay in order to be stable.

The term 'nuclide' is used to describe all possible elements and isotopes in the periodic table. 'Isotope' is used to distinguish elements with different numbers of nucleons in their nucleus, due to different numbers of neutrons, whereas the term 'element' refers exclusively to proton number.

nuclides elements with the same number of protons and neutrons with the nucleus in the same energy state

ground energy state the state in which a nucleus has absorbed no energy, and requires no additional energy to maintain its state

Syllabus link
Chapter 7 discusses radioisotopes, spontaneous decay and half-life.

Atomic number and mass number

Nuclides are named according to the number of nucleons they have. Carbon has six protons and six neutrons; it is called carbon-12 because there are 12 nucleons. This differs for other isotopes of carbon. Carbon that has seven neutrons is called carbon-13; if it has eight neutrons, it is called carbon-14. Thus, we write different nuclides according to their **atomic number** (Z) and **atomic mass number** (A). The atomic number Z is the number of protons in the nucleus, and the mass number A is the number of nucleons the element has (protons + neutrons). The number of neutrons is denoted N.

atomic number the number of protons in a nucleus (Z)

atomic mass number the total number of protons and neutrons in a nucleus (A)

KEY FORMULA

$$N = A - Z$$

where:
N = number of neutrons
A = mass number denoting the number of protons and neutrons within the nucleus
Z = atomic number, denoting the number of protons

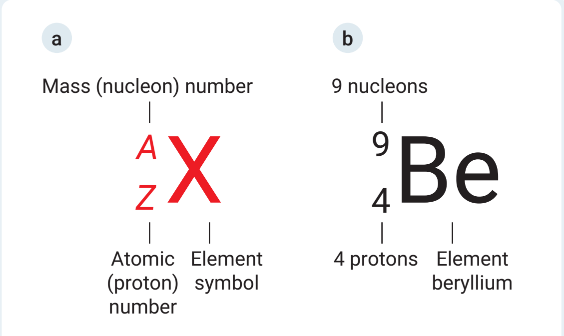


FIGURE 6.2.3 (**a**) The international standard notation for representing a nuclide. (**b**) The standard notation for the element beryllium.

Notation

In addition to writing carbon-12 for the isotope of carbon with six protons and six neutrons, there is a universal notation for showing the atomic number and mass number of the element, based on its symbol in the periodic table. Figure 6.2.3 shows the international standard notation for representing nuclides. The chemical symbol has the atomic mass (A, the nucleon number) as a left superscript, and the atomic number (Z, the number of protons) as a left subscript. Look at the periodic table in Figure 6.2.2 and, from the symbols given, work out the atomic and mass numbers of iron, platinum and gold.

Worksheet
The atom and isotopes

Nuclide families

Nuclides are sorted into families in a number of ways, further to those shown in the periodic table. They can be sorted by the number of protons (isotopes), the number of nucleons (isobars), the number of neutrons (isotones) and energy states (isomers). This is summarised in **Table 6.2.1**.

TABLE 6.2.1 Nuclear families

Families	Nuclides with the same:
Isotopes	atomic (proton) number, *Z*
Isobars	mass (nucleon) number, *A*
Isotones	number of neutrons, *A* – *Z*
Isomers	*Z* and *A*, but different energy states

If a nuclide can exist in an energy state above its ground state for more than 10^{-12} s, then it is called a **metastable** nuclide.

metastable able to remain in a higher energy state for a certain period

Atomic weight

Within a sample of an element, there is normally more than one isotope of the element. The **atomic weight** (or **relative atomic mass**) is the weighted average of the masses of the different nuclides in a pure, naturally occurring sample of the element. This is scaled according to the natural abundance of each isotope. For example, the relative atomic mass of silver is 107.96. This is calculated from the knowledge that pure silver naturally is made up of 51.84% Ag-107 and 48.16% Ag-109. The atomic weight should not be confused with the mass number of a nuclide.

atomic weight (relative atomic mass) the weighted average of all the masses of the different nuclides in a pure, naturally occurring sample of the element

WORKED EXAMPLE 6.2.1

Pure silver contains 51.84% of isotope ${}^{107}_{47}\text{Ag}$ and 48.16% of ${}^{109}_{47}\text{Ag}$. Determine the atomic weight of silver.

ANSWER

1 **Multiply the mass number of each isotope by the percentage, and add the two.**

Weighted average = $107 \times 0.5184 + 109 \times 0.4816$

2 **Give the answer.**

Atomic weight of silver = 107.96 amu

LEARNING CHECK 6.2

DESCRIBING

1 For the general nuclide ${}_{Z}^{A}\text{X}$, what do *A*, X and *Z* represent?

2 **Describe** and **explain**:

- a element
- b isotope
- c nuclide.

3 List the three subatomic particles and their respective charges.

4 **Compare** atomic mass and atomic weight.

5 Does the number of electrons define an element? **Explain** your answer.

APPLYING

6 Find the number of neutrons in ${}_{57}^{136}\text{La}$.

7 Europium occurs as two different isotopes, ${}_{63}^{153}\text{Eu}$ (52.18%) and ${}_{63}^{151}\text{Eu}$ (47.82%). Find the atomic weight (relative atomic mass) of europium.

ANALYSING

8 An isotope of an element is sometimes referred to as 'the element'. Highlight how this can cause confusion between these terms.

9 Molybdenum-99 is formed when a nuclide absorbs a neutron. What is that nuclide?

6.3 Strong nuclear force

As stated earlier, protons have positive charge and positive charges repel each other. This repulsion is caused by the electrostatic force. The electrostatic force becomes relatively large when the protons are close together. In a nucleus, protons come to within 2×10^{-15} m of each other. This causes an electrostatic force of about 60 N between two protons within the nucleus. This value is calculated using **Coulomb's law**. This law states that the force between two charges is inversely proportional to the square of the distance between them:

$$F = \frac{kqQ}{r^2}$$

where: F = force between the two charges q and Q in newtons (N)

k = the constant 9.0×10^9 N m^2 C^{-2}

q = charge in coulombs of one charge (C)

Q = charge in coulombs of the other charge (C)

r = distance that separates the charges, measured from their centres (m)

Weblink
Strong nuclear force

Coulomb's law states that the force of attraction or repulsion between two charges is inversely proportional to the square of its distance

KEY FORMULA

Coulomb's law

$$F = \frac{kqQ}{r^2}$$

where:

F = force between the two charges q and Q in newtons (N)

k = the constant 9.0×10^9 N m^2 C^{-2}

q = charge in coulombs of one charge (C)

Q = charge in coulombs of the other charge (C)

r = distance that separates the charges, measured from their centres (m)

WORKED EXAMPLE 6.3.1

a If protons in a nucleus come within 2×10^{-15} m of each other, and each proton has a charge of 1.6×10^{-19} C, what is the electrostatic force of repulsion between them?

b If the distance between the protons doubled, what would happen to the electrostatic force between the protons?

ANSWERS

a 1 Use Coulomb's law.

$$F = \frac{kqQ}{r^2}$$

2 Substitute the known values and calculate the answer.

$$F = \frac{9.0\times10^{9}\times1.6\times10^{-19}\times1.6\times10^{-19}}{(2\times10^{-15})^{2}}$$

$$= \frac{2.3\times10^{-28}}{4\times10^{-30}}$$

3 Give the answer with the correct unit and to the appropriate number of significant figures.

$$F = 57.6\,\text{N}$$

b We know $F = \frac{kqQ}{r^2}$ and that the distance has doubled. So the new force will be calculated by:

$$F_2 = \frac{kqQ}{(2r)^2}$$

$$= \frac{kqQ}{4r^2}$$

$$= \frac{1}{4}\times\frac{kqQ}{r^2}$$

$$= \frac{1}{4}\times F_1$$

Therefore, if the distance between protons doubles, the force decreases by a factor of 4.

Protons have mass and masses attract each other. This is called gravitational force. The gravitational force between two masses can be calculated with Newton's universal law of gravitation. For the scenario in Worked example 6.3.1, if two protons are 2×10^{-15} m away from each other and each has a mass of 1.67×10^{-27} kg, the gravitational force between them can be calculated as approximately 4.65×10^{-35} N of attraction. This is nowhere near enough attractive force to overcome the 60 N of electrostatic repulsion they experience! So how do protons in a nucleus stay together?

Syllabus link
Chapter 8 discusses Newton's universal law of gravitation.

strong nuclear force
the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons

Protons stay together in the nucleus because of the **strong nuclear force**. The strong nuclear force is produced between nucleons by the exchange of particles called mesons. Neutrons provide the means by which protons are kept far enough apart so that they don't repel each other but can also participate in meson exchange, which contributes to increased strong nuclear force. The strong nuclear force is essentially independent of whether the nucleons are protons or neutrons.

The strong nuclear force overcomes the electrostatic force of repulsion and provides the 'glue' that keeps the protons, neutrons and atoms – the building blocks of the universe – together. Over the small distances involved, the strong nuclear force is the strongest of the four fundamental forces in the universe **(Figure 6.3.1)**.

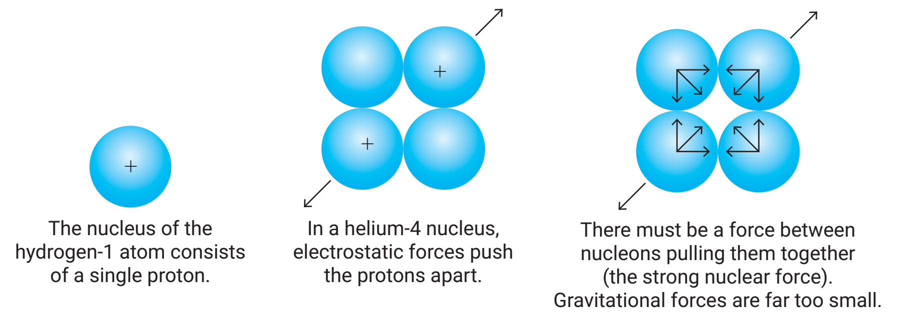


FIGURE 6.3.1 A representation of the strong nuclear force holding a nucleus together

Four fundamental forces

Physicists have identified four fundamental forces that are key to understanding the universe. At the nuclear level, the strong nuclear force has the greatest effect on keeping nucleons in the nucleus, overcoming the smaller electrostatic force. The gravitational force is a distant last in terms of strength. There is a fourth force, the weak nuclear force, which acts within nucleons. At the nuclear level, the gravitational force has much less effect than the other three forces.

It is important to note that the size of a charge, mass or distance between two objects determines which force is stronger. For example, over extremely small distances such as within a nucleus, the strong nuclear force is stronger than the gravitational force between protons. However, over astronomical distances, the gravitational force between planets (very large masses) is much larger than the other forces (Table 6.3.1).

Weblink
The four fundamental forces

Syllabus link
Chapter 8 discusses the four fundamental forces in more detail.

TABLE 6.3.1 Comparing the effect of the four fundamental forces within a nucleus

	Gravitational force	Weak nuclear force	Electromagnetic force	Strong nuclear force
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Infinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

LEARNING CHECK 6.3

DESCRIBING

1 List the four forces that act within the nucleus, in order of strength.

2 **Recall** why the strong nuclear force is considered the strongest force in the universe.

APPLYING

3 **Discuss** what would happen if there was no strong nuclear force.

4 If two protons are 6×10^{-15} m apart, what is the electrostatic force of repulsion between them?

5 In the last part of Figure 6.3.1, there are arrows on the four nucleons, showing the direction of the strong nuclear force between them. Draw a vector diagram for one of these nucleons, showing all the forces it is experiencing. Be sure to include the gravitational, electrostatic and strong nuclear forces.

6 From the forces calculated in this chapter, and your vector diagram from Question 5, **calculate** the strong nuclear force required to keep all the four nucleons together in a helium-4 nucleus.

6.4 Nuclear stability

Scientists such as Marie Curie, Irene Curie-Joliot, Lise Meitner and Otto Hahn played pivotal roles in advancing our understanding of radiation and nuclear stability. Marie Curie's groundbreaking work on radioactivity earned her two Nobel Prizes. Irene Curie-Joliot continued her mother's legacy, making significant contributions to nuclear physics and radiochemistry. Lise Meitner's collaboration with Otto Hahn led to the discovery of nuclear fission, with far-reaching implications for both science and society. These scientists overcame discrimination and adversity to unravel the mysteries of the atom and pave the way for transformative discoveries in nuclear science and technology.

The stability of a nucleus is determined by several different factors. These include operation of the strong nuclear force over very short distances, electrostatic repulsion, and the relative number of protons and neutrons in the nucleus.

The more neutrons in the nucleus, the stronger the force that helps glue the nucleus together. As nuclei become larger, specifically as the atomic number becomes greater than 82, the strong force is no longer enough to keep the nucleus together. In these cases, there is simply so much electrostatic repulsion from the protons in the nucleus that it cannot be contained. Once this is the case, we say that a nucleus is **unstable**.

unstable describes a nucleus that is likely to decay because the strong nuclear force is not large enough to overcome the electrostatic repulsion force

Stability curve

The stability of a nuclide is described by the stability curve (Figure 6.4.1). Each dot on this curve represents a stable nuclide, with a corresponding number of protons and neutrons in the nucleus. Note that, as the atomic number increases, there must be more neutrons in the nucleus for the nuclide to be considered stable (where the nucleus is still in its ground energy state).

Weblink
Band of stability

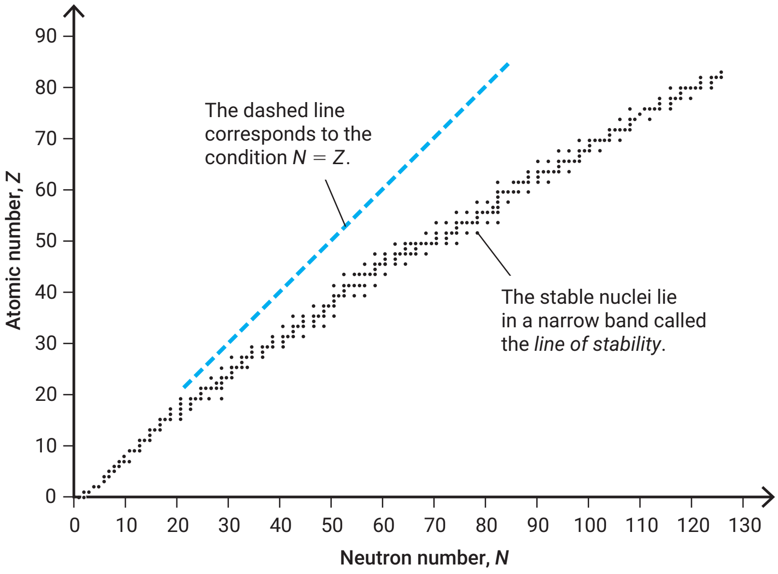


FIGURE 6.4.1 The stability curve. Each dot represents a stable nuclide. Note that the more neutrons there are in the nucleus, the greater the neutron-to-proton ratio.

An unstable nucleus (one that is not a dot on the line of stability curve) undergoes **radioactive decay** and emits radiation. *How* the nucleus is unstable determines the type of decay it will undertake. Instability in nuclides is the result of too many protons, too many neutrons, or too many of both within the nucleus. The strong nuclear force and the electrostatic force must be balanced in order for the nucleus to remain in its ground state. The types of decay that nuclei undergo will be discussed in Chapter 7.

radioactive decay when a nucleus breaks apart; it can happen naturally or be forced by impact from subatomic particles outside the nucleus

LEARNING CHECK 6.4

DESCRIBING

1 **State** what it means for a nucleus to be stable.

2 **Describe** and **explain** the 'line of stability'.

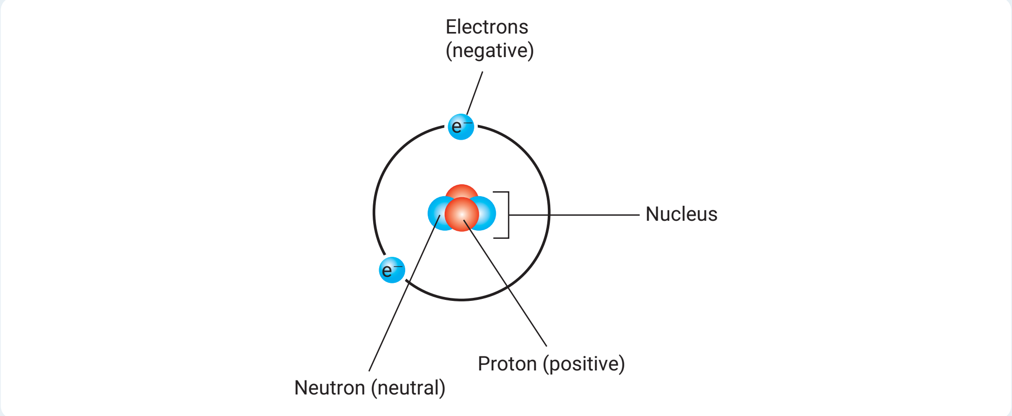
APPLYING

3 If a nuclide has 10 protons and 90 neutrons, would it be considered stable? **Explain** your answer.

CHAPTER SUMMARY

Nuclear model

- The basic structure of an atom includes a nucleus that contains protons and neutrons, which is surrounded by electrons.



Notation

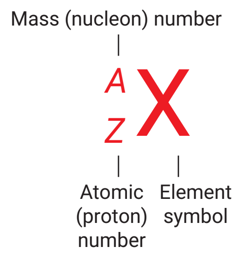
- The ${}^{A}_{Z}X$ nomenclature is used to represent information about each type of atom.

$$N = A - Z$$

where: N = number of neutrons

A = mass number denoting the number of protons and neutrons within the nucleus

Z = atomic number denoting the number of protons

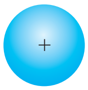


Nuclear force

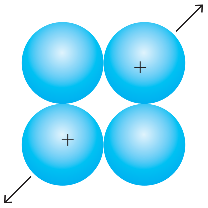
- Protons in the nucleus repel each other. The neutrons and nuclear force within the nucleus help to hold the nucleus together.
- Coulomb's law:

$$F = \frac{kqQ}{r^2}$$

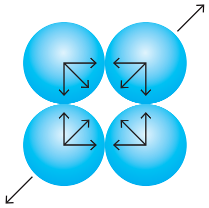
where: F = force between the two charges q and Q (N)
k = the constant $9.0 \times 10^9\,\mathrm{N\,m^2\,C^{-2}}$
q = charge, in coulombs, of one charge (C)
Q = charge, in coulombs, of the other charge (C)
r = distance (m)



The nucleus of the hydrogen-1 atom consists of a single proton.



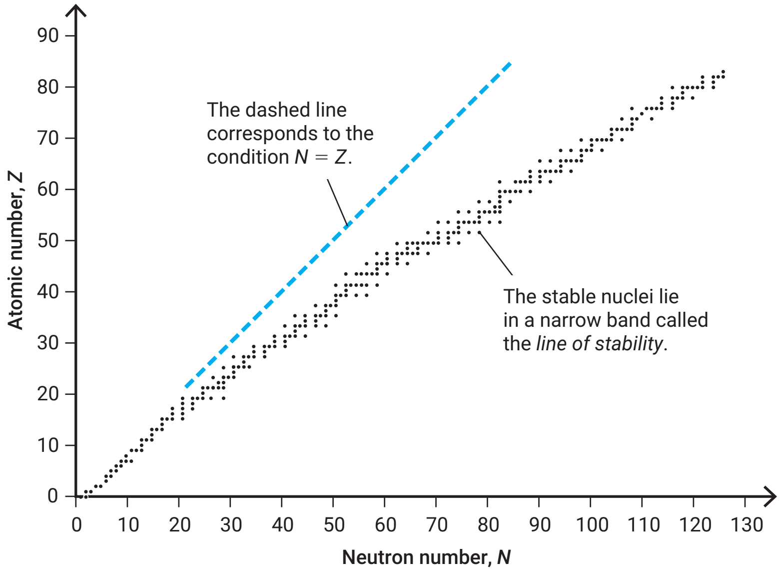
In a helium-4 nucleus, electrostatic forces push the protons apart.



There must be a force between nucleons pulling them together (the strong nuclear force). Gravitational forces are far too small.

Nuclear stability

- As the atom gets bigger (more protons), more neutrons are required to maintain the stability of the nucleus.
- Atoms with an unstable nucleus undergo radioactive decay and emit radiation.



CHAPTER EXAM

MULTIPLE CHOICE

1. The nucleus is composed of:

A neutrons and electrons.
B neutrons and protons.
C protons and electrons.
D nucleons and electrons.

2. Isotopes of elements have similar properties. Which characteristic do all isotopes of the same element share?

A Number of protons
B Number of electrons
C Number of nucleons
D Energy level of the nucleus

3. The element represented by $^{77}_{34}X$ is:

A iridium.
B roentgenium.
C selenium.
D technetium.

4. Two protons are placed very close to each other. The force of electrostatic repulsion is measured to be *F*. Next, the distance between the two protons is quadrupled. What is the new force of electrostatic repulsion acting on the protons?

A $\frac{F}{2}$
B $\frac{F}{4}$
C $\frac{F}{8}$
D $\frac{F}{16}$

5. Each nucleus of the nitrogen-16 isotope contains:

A 7 neutrons.
B 9 neutrons.
C 16 neutrons.
D 23 neutrons.

6. Respectively, the number of protons, neutrons and electrons in the isotope $^{11}_{5}B^{-}$ is:

A 5, 6, 5.
B 5, 6, 6.
C 5, 11, 5.
D 11, 6, 12.

7. Respectively, the number of protons, neutrons and electrons in the isotope $^{212}_{83}Bi^{2+}$ is:

A 81, 131, 83.
B 81, 131, 85.
C 83, 129, 81.
D 83, 129, 85.

8. The fundamental force responsible for holding the nucleus together is:

A electromagnetic.
B gravitational.
C strong nuclear force.
D weak nucleus force.

9. What is the isotope with 22 protons, 26 neutrons and 20 electrons?

A $^{48}\text{Ti}^{2+}$
B $^{48}\text{Ti}^{2-}$
C $^{48}\text{Fe}^{2+}$
D $^{56}\text{Fe}^{2+}$

10. The stability of an isotope depends primarily on the:

A physical state of the element.
B attractive forces between the nucleus.
C relative number of protons and neutrons in the nucleus.
D number of electrons in the shells relative to the number of protons in the nucleus.

SHORT RESPONSE

11. Name the isotope that has 37 protons and 85 nucleons.

12. **Describe** the structure of the atom, listing for each subatomic particle, its:

a location
b relative charge
c relative mass.

13. **Identify** the element represented by X in the following.

a $^{59}_{27}\text{X}$
b $^{230}_{88}\text{X}$
c $^{124}_{53}\text{X}$

DATA ANALYSIS

14. **Analyse data**

Referring to the stability curve shown in Figure 6.4.1, would the isotope with 20 protons and 70 nucleons be stable? Why or why not?

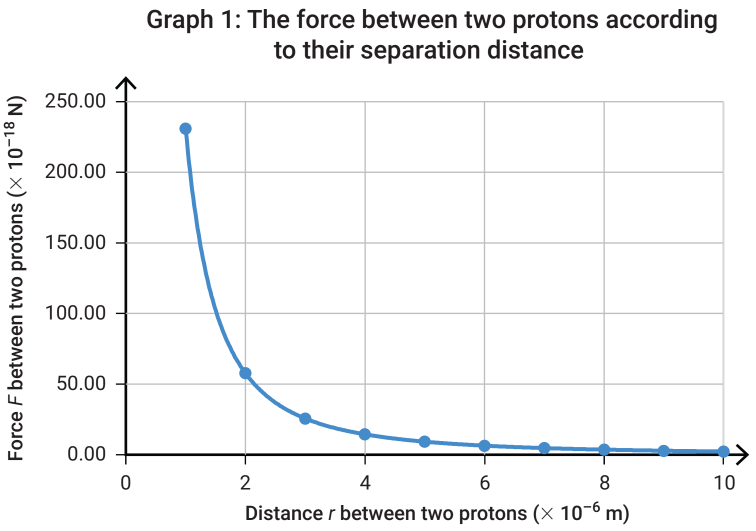
15. Interpret evidence

An experiment was conducted using specialised, highly sensitive equipment to investigate the relationship between the distance separating two protons and the magnitude of the repulsive force between them. Raw data from the experiment is in **Table 1**.

TABLE 1

Distance r between 2 protons ($\times 10^{-6}$ m)	Repulsive force F ($\times 10^{-18}$ N)
1	231.00
2	57.75
3	25.67
4	14.44
5	9.24
6	6.42
7	4.71
8	3.61
9	2.85
10	2.31

Graph 1 was constructed using the raw data from Table 1.

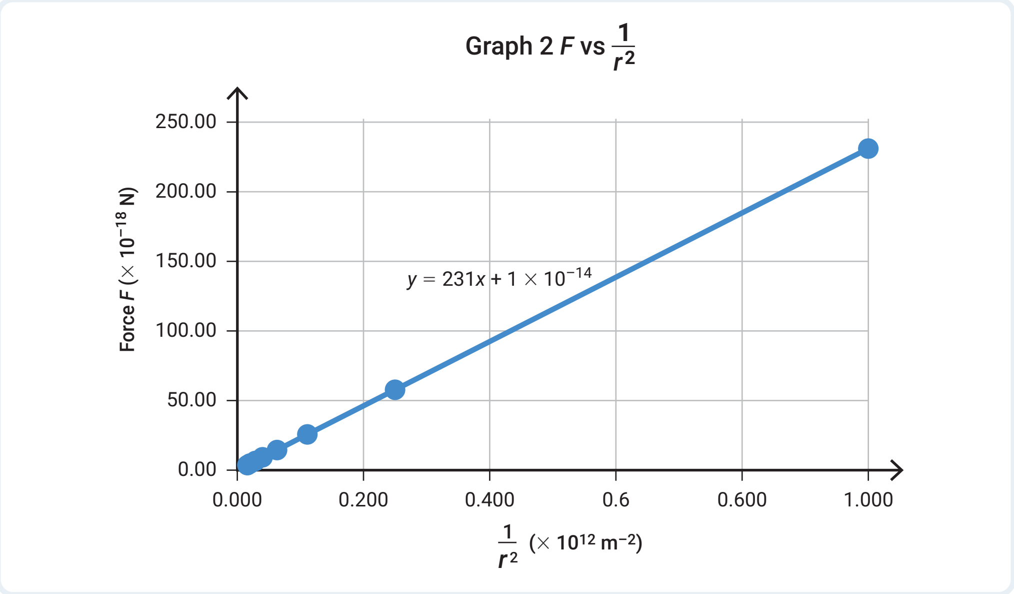


The experimenter then processed the raw data to populate **Table 2**.

TABLE 2

$\frac{1}{r^2}$ (× 10^{12} m^2)	Repulsive force F (× 10^{-18} N)
1.000	231.00
0.250	57.75
0.111	25.67
0.063	14.44
0.040	9.24
0.028	6.42
0.020	4.71
0.016	3.61

Graph 2 was constructed using the processed data in Table 2.



a **Identify** the general relationship or proportionality between the distance separating two protons (r) and the repulsive force (F) between them. **Justify** your answer by referring to Table 1 and/or Graph 1.

b **Infer** why the experimenter processed the data as described.

c **Analyse** the data to draw a conclusion about a more specific mathematical relationship or proportionality between F and r. **Justify** your answer by referring to Table 2 and/or Graph 2.

d **Determine** the expected repulsive force in newtons when two protons are 1.5×10^{-5} m apart by using the experimental evidence provided.

CHAPTER 7

Spontaneous decay and half-life

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SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- 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

- Explore advances in medical treatment and imaging that have come from a deepening understanding of the properties of nuclear radiation.
- Consider how scientific knowledge can be used to predict beneficial and/or harmful or unintended consequences, e.g. choosing appropriate radioisotopes for medical imaging, carefully storing nuclear waste.

SCIENCE INQUIRY

- 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.

Introduction

Radiation that comes from the nucleus of an atom is called radioactivity. Radioactivity is in our everyday lives: it is used in medical diagnosis and treatment; every house is fitted with smoke detectors that use a radioactive source; leaks in pipes are traced using radioactivity, and radioactivity plays an enormous role in nuclear energy production.

Practicals

- Background ionising radiation
- Random decay and half-life: a simulation

Worksheets

- Properties of alpha, beta and gamma radiation
- Decay and half-life

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Isotopes have the same number of protons but different number of neutrons.
- ✓ $^{A}_{Z}X$ nomenclature highlights information about the atom, including the atomic number, mass number and elemental symbol.
- ✓ The atom consists of nucleons and electrons.
- ✓ Different elements are made of different types of atoms, which vary in the number of protons.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain radioactivity and the various modes of radioactive decay
- ✓ define 'radiation'
- ✓ compare non-ionising radiation and ionising radiation
- ✓ identify the types of radiation in the electromagnetic spectrum
- ✓ use notation conventions to express parent nuclides, daughter nuclides, emitted particles and nuclear equations
- ✓ balance nuclear equations
- ✓ predict reactants and products in nuclear equations
- ✓ interpret nuclear equations to categorise decay types
- ✓ describe and explain ionising power and penetrating power
- ✓ predict the paths of alpha, beta and gamma particles in magnetic fields
- ✓ compare the properties of alpha, beta and gamma particles
- ✓ investigate how radioactivity can be detected and measured
- ✓ describe and explain the process of artificial transmutation
- ✓ express transmutations using nuclear equations that denote the parent nuclide, incident particle (bombarding radiation), daughter nuclide and emitted particle
- ✓ describe the production of neutrinos and antineutrinos
- ✓ describe and explain half-life
- ✓ use decay and half-life equations to quantify aspects of a nuclear decay
- ✓ analyse and interpret graphically presented decay data
- ✓ interpret decay chains to predict nuclides
- ✓ use a simulation to examine the phenomena of radioactive decay and half-life
- ✓ describe and explain applications of nuclear physics in nuclear medicine and radioactive dating
- ✓ discuss the positive and negative implications of humanity's application of nuclear physics: future, current and historical.

7.1 Natural radioactive decay

Radiation refers to energy transfer that occurs across space. For example, sunlight is radiation that travels from the Sun to Earth. We experience radiation in a variety of ways, such as light and heat. Radiation can be classified in several ways and distinguished by the effects it has on atoms. Some radiation originates on Earth, and other radiation bombards us from outer space and the upper atmosphere. This radiation is commonly referred to as **radioactivity**.

radiation energy transfer across space; the process by which heat is transferred without the need for a medium; energy from radioactive atoms

radioactivity particles or rays that come from energy rearrangements in a nucleus

Non-ionising and ionising radiation

Radiation is also used to describe the emissions from radioactive atoms. **Gamma rays** are electromagnetic in nature, but alpha and beta radiation are charged particles with mass.

Some forms of radiation can ionise atoms by removing electrons. There are two types of radiation: **non-ionising radiation** and **ionising radiation**. Radiation from radioactive sources is ionising radiation; but electromagnetic radiation can be non-ionising or ionising depending on its energy.

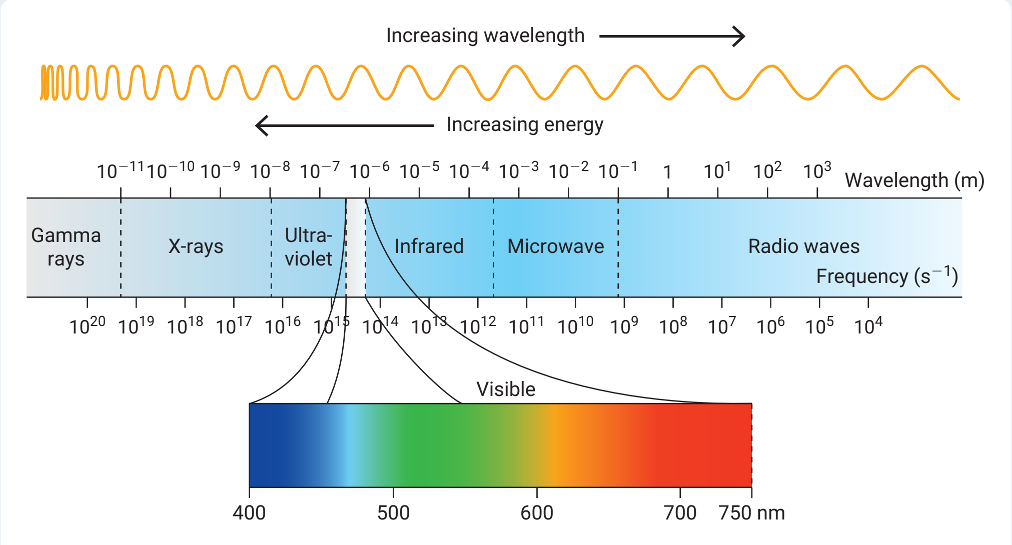
Electromagnetic radiation is pure energy with no mass. It is modelled as continuous waves or massless particles called photons that have an associated wavelength. The **electromagnetic spectrum** is the entire range of wavelengths or frequencies of electromagnetic radiation from high-energy gamma rays to lower-energy radio waves, including visible light (Figure 7.1.1).

gamma ray high-energy electromagnetic radiation

non-ionising radiation electromagnetic radiation that does not ionise nearby atoms and has low energy

ionising radiation electromagnetic radiation that does ionise nearby atoms and has high energy

electromagnetic spectrum the continuous spectrum describing all radiation from high energy to low energy and including visible light



Source: Sapling Learning

FIGURE 7.1.1 The electromagnetic spectrum, classifying radiation from high energy (ionising) to low energy (non-ionising)

Non-ionising radiation

Non-ionising radiation is electromagnetic radiation with low energy. Sources of non-ionising radiation include electric power lines, microwave ovens, televisions and the light from the Sun. These radiations may have good or bad effects on our bodies, but they do not change the electron configuration around the nuclei of atoms.

Ionising radiation

Ionising radiation is high-energy radiation that can affect the electrons surrounding an atom so that a charged ion is formed. Ionising radiation includes alpha particles, beta particles, gamma rays and X-rays. The high-energy nature of these types of radiation can affect us in significant and unwanted ways, including changing the electron configurations, types of atoms, and radioactive materials in our bodies. We are constantly exposed to low-level, background ionising radiation from sources such as metals in Earth's crust and ultraviolet light from the Sun.

Background radiation

There are two types of background radiation: terrestrial radiation and cosmic radiation. Some terrestrial radiation comes from the decay of radioactive elements, such as uranium and thorium, in Earth's crust. The energy from radioactive decay of these materials is one of the factors contributing to the temperature of Earth. Terrestrial radiation can enter our food chain via the naturally occurring radioactive chemicals in soils.

Cosmic radiation comes to us from space. It is comprised mainly of protons (hydrogen nuclei) that interact with Earth's atmosphere to produce cosmic showers of radiation, some of which reach Earth's surface.

The background radiation on Earth varies in different locations. It depends on altitude and proximity to radioactive minerals. Radioactive fallout from nuclear tests and damaged nuclear power stations also adds to background radiation. These doses are usually small unless you are close to the site. The further you are from these additional sources of radiation, the lower the intensity of the background radiation.

PRACTICAL ACTIVITY 7.1.1

BACKGROUND IONISING RADIATION

Research question

How does background radiation vary over time?

Aim

To investigate the random nature of background radiation, and measure the background radiation rate

Materials

- Geiger–Müller tube, or Geiger counter

Procedure

Set up the Geiger–Müller tube to record counts over a period of time, say every 15 seconds. Record the readings in a properly constructed data table.

Analysis of results

1 Produce a frequency table from the data table.
2 Plot a graph of count rate versus time.
3 Calculate and show the mean on the graph.

Interpretation

4 How does the graph of frequency against count rate demonstrate the random nature of background radiation?
5 Provide an estimate of the average background radiation per minute.

LEARNING CHECK 7.1

DESCRIBING

1 List the two main forms of radiation.
2 List the two origins of background radiation.
3 **Explain** why electromagnetic radiation is classified as both ionising and non-ionising.
4 **Propose** why the electromagnetic spectrum categorises different waves based on their energy.

APPLYING

5 Why is it useful to know the background radiation when doing radiation counting experiments? What would have to be done to the data before determining how much radiation is coming from the source?

ANALYSING

6 Terrestrial radiation keeps Earth's surface warm. Research how this happens and **explain** why other planets in our solar system are unable to achieve this.

7 Research two professions that would need to monitor their radiation exposure and **explain** how this exposure is monitored.

7.2 Types of radioactivity

Henry Becquerel (1852–1908) was the first scientist to discover that radiation may be emitted from atoms. In 1896, he identified that uranium salts emit a previously unknown form of radiation. He called this *metal phosphorescence*, because he thought these emanations were an invisible form of light.

Becquerel discovered that this radiation is in fact small particles being emitted from the uranium atoms. Further exploration showed that three different types of particles were emitted. When a radioactive nucleus emits an alpha or beta particle, it breaks into two parts – the lighter, emitted particle and a new nucleus of a different element. The original unstable element (**parent nuclide**) has decayed into a new element (**daughter nuclide**), which is more stable. As you know from Chapter 6, this process is referred to as radioactive decay and occurs naturally until a daughter element is one of the stable nuclides defined on the line of stability.

When a parent nucleus decays to become more stable, it emits radiation. This is in the form of alpha particles, beta particles or gamma radiation. These types of radioactivity are summarised in Table 7.2.1.

parent nuclide the original nuclide before emitting particles from the nucleus

daughter nuclide the nuclide formed after a parent nuclide has emitted particles from its nucleus; the daughter nuclide is more stable than the parent nuclide

TABLE 7.2.1 A summary of the types of radioactivity and their respective symbols

Radioactivity type	Symbol	Description
Alpha particle	α, ${}^{4}_{2}\mathrm{He}^{2+}$	Helium-4 nucleus
Beta particle	β^-, ${}^{0}_{-1}\mathrm{e}$	Electron
	β^+, ${}^{0}_{+1}\mathrm{e}$	Positron
Gamma ray	g, ${}^{0}_{0}\gamma$	Electromagnetic radiation
Neutrino	ν_e, ${}^{0}_{0}\nu_e$	Energy carrier
Antineutrino	$\bar{\nu}_e$, ${}^{0}_{0}\bar{\nu}_e$	Energy carrier

Alpha decay

Weblink
Alpha decay

Alpha radiation is the largest particle that can be emitted from a nucleus. The particle is a positively charged helium nucleus, which contains two protons and two neutrons. It has been stripped of its two electrons, so it carries a 2+ charge. The most common nuclide of uranium, ${}^{238}_{92}\mathrm{U}$, undergoes decay, resulting in 90 protons and 234 nucleons in the daughter nucleus.

KEY FORMULA

Alpha decay can be written as:

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

where:

A = mass number
Z = proton number
X = the element before decay
Y = the element after α decay

The daughter nucleus is ${}^{234}_{90}\text{Th}$, thorium-234, and is a more stable nuclide than the uranium-238 parent nuclide. The nuclear equation for this decay is written as follows:

$${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$$

Alternatively, this can be written as:

$${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}^{2+}$$

In all radioactive decay, energy is released. In this example, the energy is almost all taken away by the alpha particle.

Alpha decay occurs when a nucleus is unstable because it has too many nucleons. By ejecting two protons and two neutrons in the form of a helium nucleus, a daughter nuclide is produced that is more stable.

WORKED EXAMPLE 7.2.1

Neptunium-237 decays by emitting an alpha particle and changes to a different element.

a Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.

b What is the name of the daughter nuclide?

ANSWERS

a 1 **Determine the atomic number of neptunium.**

Locate neptunium on the periodic table; its atomic number is 93.

2 **Write the complete nuclear reaction equation.**

The decay of neptunium is written as: ${}^{237}_{93}\text{Np} \rightarrow {}^{233}_{91}\text{Pa} + {}^{4}_{2}\alpha$

b The daughter nuclide is protactinium-233.

Weblink
Beta decay

Beta decay

Beta radiation is particle radiation from the nucleus, but the particle is much smaller in mass than an alpha particle. There are two forms of beta decay: electron and positron emission. An electron has the opposite charge to a proton, and isn't a nucleon. Its symbol is written as ${}^{0}_{-1}\text{e}$ or ${}^{0}_{-1}\beta$ or simply β^-.

A positron is an anti-electron. It is the same mass as an electron, but has a positive charge of 1.6×10^{-19} C; that is, a positron is a positively charged electron. Its symbol is written as ${}^{0}_{1}\text{e}$ or ${}^{0}_{1}\beta$ or simply β^+.

The mass of both beta particles is very small compared to the mass of nucleons. Beta particles have a mass of 9.11×10^{-31} kg, which is tiny compared to a proton (1.6726×10^{-27} kg) or a neutron (1.6749×10^{-27} kg). These masses are summarised in **Table 7.2.2**.

TABLE 7.2.2 A summary of subatomic and alpha and beta particles, showing their respective masses and net charge

Particle	Mass (kg)	Charge
Proton	1.6726×10^{-27}	Positive
Neutron	1.6749×10^{-27}	Zero
Alpha	6.644×10^{-27}	Positive
Electron	9.1093×10^{-31}	Negative
Positron	9.1093×10^{-31}	Positive

Electron emission

The ejection of an electron from the nucleus, β^- decay, can be modelled by regarding a neutron as capable of emitting an electron and turning into a proton. In this process, another particle known as an **antineutrino**, $\bar{\nu}$, is also emitted. An antineutrino is uncharged and almost undetectable.

antineutrino an elementary particle that accompanies β^- decay

The nuclear equation for β^- decay can be written as ${}_0^1\text{n} \to {}_1^1\text{p} + {}_{-1}^{0}\text{e} + \bar{\nu}$ or ${}_0^1\text{n} \to {}_1^1\text{H} + {}_{-1}^{0}\beta + \bar{\nu}$.

A proton can be written as a hydrogen nucleus in the same way that an alpha particle can be written as a helium nucleus. They have the same atomic and mass numbers.

When thorium-234 undergoes β^- decay, it becomes the nuclide with 91 protons but an unchanged mass number of 234. The new element is protactinium, Pa: ${}_{90}^{234}\text{Th} \to {}_{91}^{234}\text{Pa} + {}_{-1}^{0}\beta + \bar{\nu}$.

Note that the electron is being emitted from the nucleus, not from the surrounding electron shells. Also note that the mass number in beta decay remains unchanged – the number of nucleons has not been altered.

Positron emission

The ejection of a positron from the nucleus, β^+ decay, can be modelled by regarding a proton as capable of emitting a positron and turning into a neutron. In this process, another particle known as a **neutrino**, ν, is emitted. Just like an antineutrino, a neutrino is uncharged and almost undetectable.

neutrino an elementary particle that accompanies β^+ decay

The nuclear equation for β^+ decay can be written as ${}_1^1\text{p} \to {}_0^1\text{n} + {}_1^0\text{e} + \nu$ or ${}_1^1\text{H} \to {}_0^1\text{n} + {}_1^0\beta + \nu$.

When thallium-195 undergoes β^+ decay, it becomes a nuclide with 80 protons but an unchanged mass number of 195. The new element is mercury, Hg: ${}_{81}^{195}\text{Tl} \to {}_{80}^{195}\text{Hg} + {}_1^0\beta + \nu$.

Note that the positron is being emitted from the nucleus, and that the mass number remains unchanged because no nucleons have been emitted.

KEY FORMULA

β^- decay can be represented as ${}_Z^A\text{X} \to {}_{Z+1}^{A}\text{Y} + {}_{-1}^{0}\beta + \bar{\nu}$.

where:
A = mass number
Z = proton number
X = the element before decay
Y = the element after β^- decay
$\bar{\nu}$ = an antineutrino

KEY FORMULA

β^+ decay can be represented as ${}_Z^A\text{X} \to {}_{Z-1}^{A}\text{Y} + {}_{1}^{0}\beta + \nu$.

where:
A = mass number
Z = proton number
X = the element before decay
Y = the element after β^+ decay
ν = a neutrino

Beta emission modelling

Both β^- and β^+ emission models suggest that neutrons are composed of a proton and an electron, and that protons are composed of a neutron and positron. It is more accurate to assume that in an unstable nucleus, the nucleons can *convert* into these two particles and emit beta particles to become stable.

Gamma emission

Gamma radiation is very high-energy radiation. Gamma rays are not particles, but rather contain packets of energy that can be released from a nucleus in order for the nucleus to return to its ground state.

After a nucleus has undergone a **transmutation**, the daughter nuclide is left in an excited state. A very large amount of energy is then given off in the form of gamma rays and the nucleus returns to its ground state; hence it becomes more stable.

transmutation the conversion of one chemical element into another as the result of a nuclear reaction, such as neutron capture, or that occurs in spontaneous radioactive decay, such as alpha decay and beta decay

Gamma radiation does not change the mass number or the atomic number of an atom as it is not a particle. When a nuclide undergoes gamma emission, we write the following, where an asterisk denotes the excited state:

$${}_Z^A\text{X}^* \to {}_Z^A\text{X} + {}_0^0\gamma$$

Often, but not always, the gamma radiation will be simultaneous with alpha or beta radiation.

WORKED EXAMPLE 7.2.2

What daughter nuclide is produced after:

a alpha decay of a polonium-218 nuclide?

b β^- decay of carbon-14?

c positron emission from sodium-20?

d gamma emission from cerium-139?

ANSWERS

a **1 Write the nuclear reaction equation.**

$${}^{218}_{84}\text{Po} \rightarrow {}^{214}_{82}\text{Pb} + {}^{4}_{2}\alpha$$

2 Identify the daughter nuclide.
The daughter nuclide is lead-214.

b **1 Write the nuclear reaction equation.**

$${}^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\beta + \overline{\nu}$$

2 Identify the daughter nuclide.
The daughter nuclide is nitrogen-14.

c **1 Write the nuclear reaction equation.**

$${}^{20}_{11}\text{Na} \rightarrow {}^{20}_{10}\text{Ne} + {}^{0}_{1}\beta + \nu$$

2 Identify the daughter nuclide.
The daughter nuclide is neon-20.

d **1 Write the nuclear reaction equation.**

$${}^{139}_{58}\text{Ce}^{*} \rightarrow {}^{139}_{58}\text{Ce} + {}^{0}_{0}\gamma$$

2 Identify the daughter nuclide.
The daughter nuclide is cerium-139.

LEARNING CHECK 7.2

DESCRIBING

1 When writing nuclear equations, which two numbers must be the same before and after radioactive decay?

2 Write the general equation for alpha, β^-, β^+ and gamma emission.

3 **Compare** nuclear reactions and chemical reactions.

4 Fluorine-21 is a β^- emitter; **identify** the daughter nuclide.

APPLYING

5 Holmium-151 decays by alpha emission. Write a nuclear equation showing this process and name the daughter nuclide.

6 Radon-210 decays into polonium-206. What type of radioactive particle is emitted during this decay? Write the decay equation.

7 Francium-211 decays by emitting an alpha particle and changes to a different element.
  - **a** Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.
  - **b** **Identify** the daughter nuclide.

8 Polonium-213 decays by emitting an alpha particle and changes to a different element.
  - **a** Write a complete nuclear reaction equation that includes the symbol for the daughter nuclide.
  - **b** **Identify** the daughter nuclide.

9 Use the correct symbols to show the decay of terbnium-158 by alpha emission followed by gamma emission.

10 Gold-198 decays to mercury-198. Write the nuclear decay equation and **identify** the radioactive particle emitted during this process.

7.3 Properties of radiation

Alpha, beta and gamma radiation can affect matter. They each have a unique power to ionise and penetrate different materials.

Ionising power

Atoms become ions by losing or gaining electrons. If an atom loses electrons, it becomes a positive ion; if it gains electrons it becomes a negative ion. Negative beta particles are repelled by electrons in atoms. This causes particles to be bounced around, causing collisions that, in turn, bump other electrons out of their atomic shells. These collisions transfer less energy than the interactions between alpha particles and atoms.

Positrons interact with electrons in atoms in a slightly different manner. As positrons attract electrons in the outer shells, it is possible for electrons to be ejected by attraction to a positron as well as a collision from beta-plus decay. Again, this type of collision transfers much less energy than the interactions between alpha particles and atoms. Both types of beta particle have the ability to ionise atoms. As beta particles are the same size as electrons, the collisions are rare.

Gamma radiation can ionise atoms by transferring all its energy to an electron, giving the electron enough energy to eject from the atom. This leaves behind a positive ion. The electron that is ejected may remain free for some time before binding to another atom or molecule.

Alpha particles have far more **ionising power** than beta particles and gamma radiation. As alpha particles are much larger, and have twice the charge, it is easy for an alpha particle to collide with electrons, and to draw electrons away by electrostatic attraction.

In order, the ionising power of radioactive particles is alpha, beta, gamma. This is inversely proportional to the **penetrating power** of these particles. This is to be expected because the particles expend their energy in causing ionisation, and hence do not penetrate as far. Neutrinos and antineutrinos are weakly interacting particles that do not ionise atoms.

Weblink
Ionising and non-ionising radiation

ionising power the ability to ionise nearby atoms; high ionising power means it is likely that nearby atoms will have their electrons stripped

penetrating power the ability to penetrate air, liquids and solids; radiation with high penetrating power can penetrate highly compacted solids

Penetrating power

One of the easiest ways to compare the penetrating power of alpha, beta and gamma radiation **(Figure 7.3.1)** is by looking at what it takes to block them **(Figure 7.3.2)**. It only takes paper to block alpha particles, aluminium to block beta particles and lead to block gamma radiation. It also helps to think about the size of these particles when thinking of their penetrating power as well. It is easier to block something larger **(Figure 7.3.3)**.

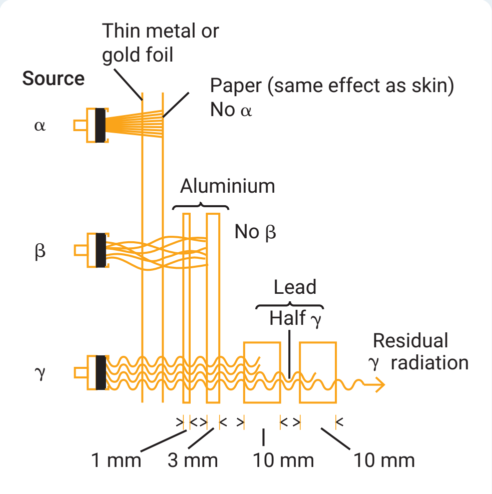


FIGURE 7.3.1 Gamma rays are the most penetrating type of nuclear radiation, followed by beta particles then alpha particles.

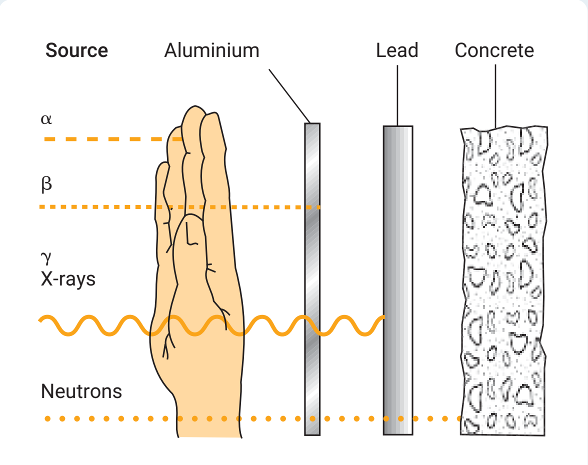


FIGURE 7.3.2 Penetrating power of different radiations. Notice that the alpha particles are easily blocked, and they are also the particle with the most net charge, mass and volume.

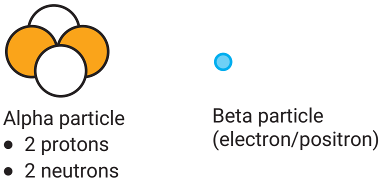


FIGURE 7.3.3 The representative size of alpha particle compared to beta particle. Not to scale. An alpha particle is about 40 000 times more massive than a beta particle.

Neutrons are highly penetrating in air and most other materials because they are uncharged. They are absorbed readily by materials containing a lot of hydrogen. Hence, water and concrete are excellent neutron absorbers and are used to help shield nuclear reactions.

Range in air

As their penetrating power suggests, alpha particles will not travel very far in air; beta particles will travel a range of distances depending on whether they collide with anything, and gamma radiation will travel infinitely far. There are many ions and other charged particles in air, which is what causes the alpha and beta particles to come to a halt. Examples of these are evaporated water, salts and ionisation from nearby thunderstorms, which can also ionise particles in air. Alpha particles come to a stop after a few centimetres in air, whereas beta particles stop after a few metres, depending on how much energy the particles have.

Effects of electric and magnetic fields on radiation

Charged alpha and beta particles moving in straight lines can be deflected in regions subject to electric or magnetic effects. Gamma rays have no mass or charge, which is why they are not deflected in either region. Charged particles are affected by electric and magnetic fields. Electric fields act on all charged particles, and magnetic fields act on moving charged particles. Charged particles emitted from nuclei are generally travelling very fast. Scientists can use electric and magnetic fields to distinguish between the different types of radiation.

Radiation in electric fields

As alpha and beta particles are both charged, they are affected by electric fields. Electric fields always indicate the direction in which a positive charge will move. This means that both α and β^+ particles are accelerated in the direction of the electric field, and β^- particles are accelerated in the opposite direction. The force that acts on each of these particles when it enters the field depends on its charge, and the magnitude of acceleration depends on both the charge and the mass. An alpha particle accelerates more slowly and travels a path with less curvature than the β^+ particle, due to its greater mass. Gamma radiation is not charged and passes through an electric field with no deflection **(Figure 7.3.4)**.

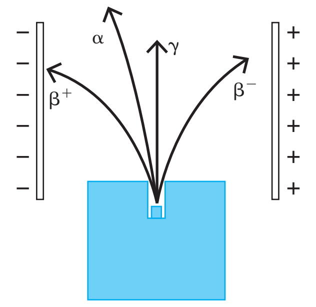
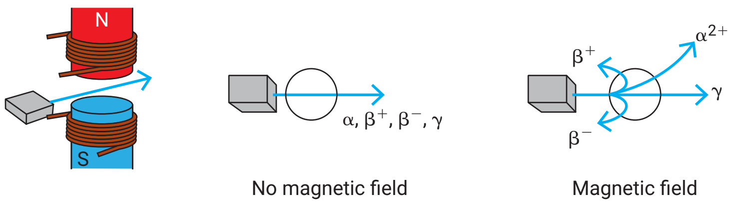


FIGURE 7.3.4 Charges in an electric field. Notice that the radius of deflection of the beta particles is much smaller than that of alpha particles. Gamma radiation is unaffected by an external electric field.

Radiation in magnetic fields

A magnetic field applies a force on any moving charged particle, so that the particle follows a curved path. The magnitude of the force depends on the speed at which the particle is moving and the magnitude of its charge. The direction of the force depends on the sign of the charge. Hence, the force experienced by a β^+ particle is the same size but opposite in direction to that experienced by a β^- particle, if they are moving at the same speed. An alpha particle at the same speed experiences a force in the same direction as a β^+ particle but, again, experiences less deflection **(Figure 7.3.5)**. Gamma radiation does not have a charge, and so it will not be deflected in a magnetic field.



No magnetic field

Magnetic field

FIGURE 7.3.5 Deflections of radiation in a magnetic field. As in an electric field, the beta particles are deflected much more dramatically than the alpha particles, due to their significantly smaller mass.

Weblink
Properties of radiation

Worksheet
Properties of alpha, beta and gamma radiation

The properties of alpha, beta and gamma radiation are summarised in **Table 7.3.1**.

TABLE 7.3.1 Properties of alpha, beta and gamma radiation

	α particles	β particles	γ rays
Nature	A helium nucleus (i.e. two protons and two neutrons)	A fast-moving electron or positron	High-frequency (short wavelength) electromagnetic radiation (i.e. a high-energy photon)
Charge	+2 elementary charges	−1 (electron) +1 (positron) elementary charge	Uncharged
Mass	4 atomic mass units (4 u) or $4 \times 1.66 \times 10^{-27}$ kg	0.0005 u 9.11×10^{-31} kg	No mass
Ionising effect	Strong	Weak	Very weak
Penetration	Few centimetres in air	Few metres in air	Very weakly absorbed in air (most radiation absorbed by a few centimetres of lead)
Effect of electric and magnetic fields	Very small deflection	Large deflection	No deflection
Typical emission velocity	5–7% of speed of light	30–90% of speed of light	Speed of light 3×10^8 m s^{-1}

Detection of radioactivity

Radioactive decay and particle emission is invisible. A number of different devices have been developed to detect the radiation. A charged electroscope can be used easily for this purpose. Solid-state detectors, dosimeters and thermoluminescent dosimeters are also used to detect and measure radiation. Other devices include the cloud chamber, the Geiger–Müller (G-M) tube and the Geiger counter.

To detect radiation today, a Geiger counter is commonly used. A Geiger counter consists of a G-M tube. It is an instrument for measuring radioactive emissions by detecting nearby ionising radiation. The basic design for a G-M tube is seen in **Figure 7.3.6**. Radiation enters the mica window and ionises the argon gas inside the tube. This causes the free electrons to electrically pulse towards the anode, where they are collected by the wire. This collection is then measured

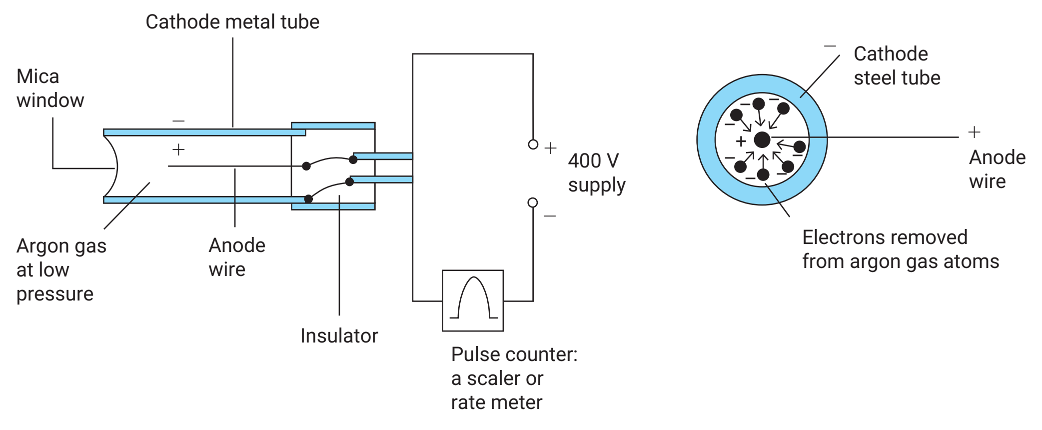


FIGURE 7.3.6 The basic set-up of the inside of a Geiger counter. The counter uses a circuit to detect how many electrons hit the anode and hence determine how many radioactive particles entered the tube.

to determine the number of radioactive particles that originally entered the G-M tube through the mica window by counting the number of pulses.

From this, the *count rate* can be determined by dividing the number of counts (pulses) by the time interval.

$$\text{Count rate} = \frac{\text{number of counts}}{\text{time interval}}$$

The number of counts is the number of electric pulses the G-M tube counts, and the time interval is the period of time for which these counts are collected (in seconds, minutes etc.).

LEARNING CHECK 7.3

DESCRIBING

1 State which type of radiation is most:
  a penetrating
  b ionising
  c likely to cause damage.
2 Which two types of radiation are deflected in the same direction in a magnetic field?
3 Which type of radiation is not deflected at all in either electric or magnetic fields? Why?
4 **Identify** the type of radiation that is least deflected in electric and magnetic fields. **Explain** your answer.

APPLYING

5 A G-M tube detects radiation by using a count rate. What does this mean?
6 If 1600 counts are recorded in a G-M tube in 20 s, what is the count rate?

7.4 Predicting decay

Predicting what type of decay a nuclide may undergo in order to become stable depends on the type of nuclide. Some nuclides have too many protons, some have too many neutrons, and some have too many nucleons altogether within their nucleus. The nuclear make-up determines the type of decay the nuclide undergoes.

If a nuclide has too many neutrons to be stable, it undergoes β^- decay, resulting in one less neutron and one more proton in the nucleus. If a nuclide has too many protons to be stable, it undergoes β^+ decay, resulting in one less proton and one more neutron in the nucleus. If the nuclide has too many nucleons (protons and neutrons) to be stable, it undergoes alpha decay in order to decrease both the number of protons and the number of neutrons in the nucleus.

These emissions can be represented with arrows on the line of stability (**Figure 7.4.1**). In each case, the tail of the arrow stems from the parent nuclide, and the tip of the arrow represents the daughter nuclide. The arrows always point towards the more stable, daughter nuclide.

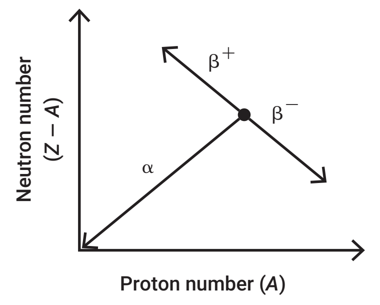


FIGURE 7.4.1 On the line of stability, arrows represent how to show decays.

WORKED EXAMPLE 7.4.1

On the line of stability, use arrows to show the following decays. Write the decay equation for each. (Note: If you do not have a hard copy of the line of stability, draw a simple grid to represent the radioactive decay.)

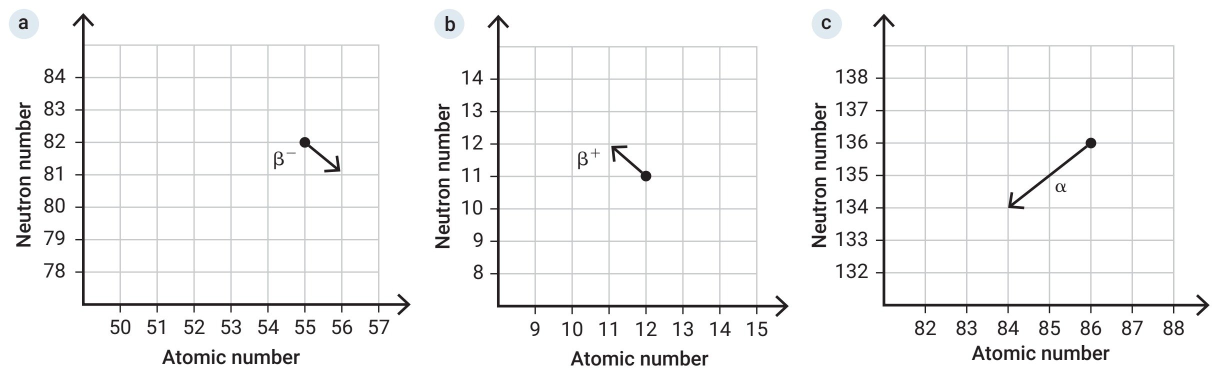
a The β^- decay of caesium-137 **b** The β^+ decay of magnesium-23 **c** The α decay of radon-222

ANSWERS

1 Write the nuclear reaction equation.

a $^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\beta$ **b** $^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{11}\mathrm{Na} + {}^{0}_{1}\beta$ **c** $^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$

2 Use an arrow to demonstrate the decay.



Artificial transmutation

Rutherford was the first to use radioactivity to produce new nuclides to make one element into another. He bombarded nitrogen-14 with alpha particles and analysed the result. Oxygen and hydrogen were formed. The reaction proceeds as follows: nitrogen nuclei absorb helium nuclei and form a composite, unstable nuclide, denoted by an asterisk:

$$^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{18}_{9}\mathrm{F}^{*}$$

The composite nuclide decays to a more stable state (**Figure 7.4.2**):

$$^{18}_{9}\mathrm{F} \rightarrow {}^{17}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p}$$

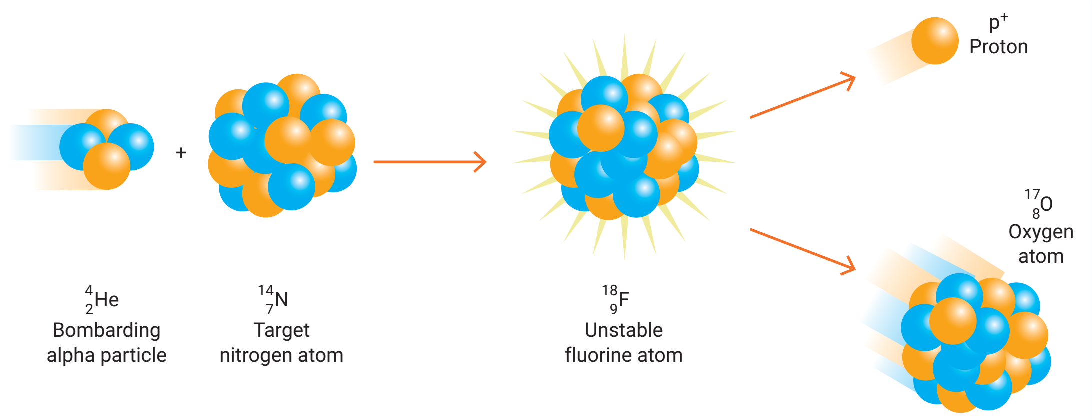


FIGURE 7.4.2 The alpha bombardment of nitrogen

The discovery of the neutron enabled scientists to explore the behaviour of larger atomic nuclei. Because it is neutral, the neutron is not repelled by the nucleus. It can be absorbed into the nucleus of the target atom. This makes it very useful as a form of **bombarding radiation**. It is used in many experiments to transmute a number of nuclides artificially. When a nucleus takes in a neutron, it becomes less stable. Frequently, the nuclide becomes a beta-emitter. Bombarding uranium nuclei with neutrons delivered unexpected results. Capture of a neutron by a uranium nuclide can lead to two results: the nuclide can form a transuranic element (an element beyond uranium) or split into two nuclei of intermediate mass. Both of these results release a large amount of energy.

bombarding radiation radiation composed of particles, such as alpha particles or neutrons, that are bombarded at the nucleus to force transmutation and radioactive decay

Transuranic elements

Each element beyond uranium (atomic number 92) is a **transuranic element**. They do not exist naturally. All are produced artificially and all are radioactive. There are no known stable isotopes of any transuranic element. Some, such as plutonium and neptunium, have very long half-lives (more than 4 million years). Others, such as americium, berkelium and californium, are reasonably long-lived (800–34 000 years). Elements 109–118 have half-lives from minutes to milliseconds or less. Half-lives will be discussed later in the chapter.

transuranic element an element with an atomic number of over 92 that can only be produced synthetically, and does not exist naturally in the universe

LEARNING CHECK 7.4

DESCRIBING

1 **Define** ‘transuranic element’.

2 **Describe** how the first two transuranic elements were produced.

APPLYING

3 Draw uranium-238 undergoing alpha decay on the line of stability and identify the daughter nuclide.

4 Draw protactinium-233 undergoing β^- decay on the line of stability and identify the daughter nuclide.

ANALYSING

5 Bombardment is used to create elements artificially. Research the positive and negative effects of artificially creating elements.

7.5 Balancing nuclear equations

When writing nuclear equations, it is important to balance the mass numbers and atomic numbers. Uranium-238 decays via alpha particle emission as follows:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}^{2+}$$

If the notation is used in which an alpha particle is written as a helium nucleus, as in this instance, it is unnecessary to write the 2+ in the right superscript. That is, the alpha decay of uranium-238 can be written in the following ways:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\mathrm{He}^{2+} \text{ or } {}^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$$

After a nuclide has decayed, the daughter nuclide is left in an excited state before it emits gamma radiation. This gamma emission happens almost instantly (but not always) after radioactive decay. For uranium-238, the complete decay equation is written as follows:

$$^{238}_{92}\mathrm{U} \rightarrow {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha + {}^{0}_{0}\gamma$$

Note that, in most cases, gamma radiation accompanies both alpha and beta particle emission, and hence it is not necessary to include it in the decay equation.

Neutrinos and antineutrinos

An antineutrino and a neutrino accompany β⁻ and β⁺ decay respectively. The decay of thorium-234 is represented as follows:

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta + \bar{\nu} \text{ or } {}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\text{e} + \bar{\nu}$$

and has an antineutrino accompanying the beta emission.

The decay of thallium-195 can be written as:

$$^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\beta + \nu \text{ or } {}^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\text{e} + \nu$$

and has a neutrino accompanying the beta emission.

Neutrino and antineutrino particles are always emitted with beta emission, and can be omitted when writing the nuclear decay equations for the purpose of determining the daughter nuclides. This means the decay of thorium-234 can be written simply as:

$$^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$$

and the decay of thallium-195 can be written as:

$$^{195}_{81}\text{Tl} \rightarrow {}^{195}_{80}\text{Hg} + {}^{0}_{1}\beta$$

LEARNING CHECK 7.5

DESCRIBING

1 List the possible notations that can be used for alpha decay.

2 List the possible notations that can be used for the two types of beta decay.

APPLYING

3 The following elements undergo β⁻ decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.

- a Magnesium-23
- b Krypton-81
- c Caesium-137

4 The following elements undergo β⁺ decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.

- a Carbon-11
- b Iodine-121
- c Oxygen-15

5 The following elements undergo alpha decay. Use the periodic table to find the daughter nuclide and write a balanced nuclear equation for each.

- a Uranium-233
- b Plutonium-240
- c Radon-222

7.6 Using decay equations

So far, we have considered a parent nuclide decaying into a daughter nuclide through radioactive decay. This has only considered one atom. Typically, many atoms of a given element occur together, such as in an ore. Therefore, it needs to be considered that at any given point, any of those nuclides will decay into the daughter nuclide.

Although all unstable elements will decay to be stable, the point at which alpha or beta particles are emitted from the nucleus is entirely random. Spontaneous radioactive decay occurs naturally, and although it cannot be known exactly when a nuclide will decay, we can predict how long it will take for a percentage of the substance to decay.

This can be modelled as an exponential decay function:

$$N = N_0 e^{-\lambda t}$$

where:
N = a unit of parent nuclides after time t
N_0 = the initial unit of parent nuclides at $t = 0$ s
e = is a constant called Euler's number and is equal to 2.718 28
t = time elapsed (s)
λ = the decay constant, unique to each nuclide (s^{-1})

KEY FORMULA

Exponential decay function

$$N = N_0 e^{-\lambda t}$$

where:
N = a unit of parent nuclides after time t
N_0 = the initial unit of parent nuclides at $t = 0$ s
e = is a constant called Euler's number and is equal to 2.718 28
t = time elapsed (s)
λ = the decay constant, unique to each nuclide (s^{-1})

Determining activity over time

Over time, as a radioactive substance decays, its **activity** decreases. This is simply because there are fewer unstable nuclides present. In fact, the activity of a radioactive sample (measured in becquerels, Bq, which is simply 'per second') is directly proportional to the amount of the sample remaining: $A \propto N$. The proportionality constant to equate these two variables is the decay constant λ, unique to each isotope.

activity a measure of the magnitude of radioactive emissions; the number of emissions per second, measured in the SI unit Bq

$$A = \lambda N$$

where:
A = the activity of a substance (Bq)
λ = the decay constant (s^{-1})
N = the unit of the sample remaining when the activity is measured

KEY FORMULA

$$A = \lambda N$$

where:
A = the activity of a substance (Bq)
λ = the decay constant (s^{-1})
N = the unit of the sample remaining when the activity is measured

As the amount of activity over time is directly proportional to how many parent nuclides remain after time t, it can also be modelled as an exponential decay function:

$$A = A_0 e^{-\lambda t}$$

Graphing the activity after time t for any given nuclide results in the decay curve shown in Figure 7.6.1.

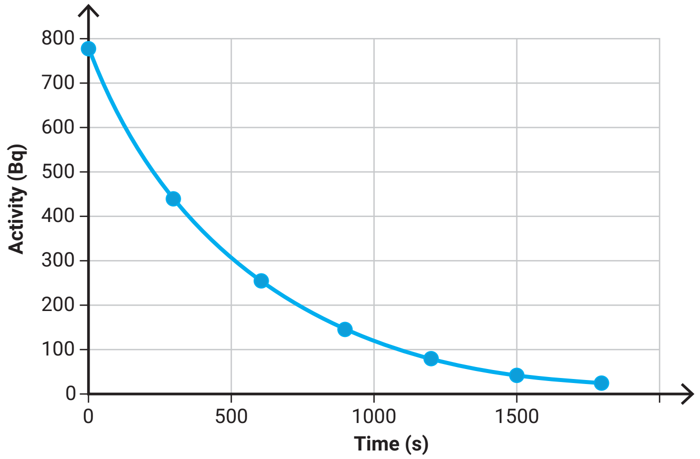


FIGURE 7.6.1 A graphical model of exponential decay. Note that the substance begins with a large activity, and it very quickly tends to zero. The time the substance takes to decay is unique to each nuclide.

WORKED EXAMPLE 7.6.1

Protactinium-234 has a decay constant of 9.9×10^{-3} Bq. Answer the following questions about the decay of protactinium.

a How much of a 2 kg sample of protactinium would remain after 300 s?

b If 700 g of a protactinium sample remains after 2 h, how heavy was the original sample?

c Determine how long it would take for a sample of protactinium to decay by half its original amount.

d Plot the decay of a 100 g sample of protactinium over 10 min. Use at least five data points.

ANSWERS

a **1** **State the equation for exponential decay.**

$N = N_0 e^{-\lambda t}$

2 **Substitute the known values.**

$N = 2e^{-9.9\times 10^{-3}\times 300}$

3 **Calculate the answer.**

$N = 0.102$ kg remaining

b **1** **Convert the time elapsed to seconds.**

$$2\,\text{h} \times \frac{60\,\text{min}}{\text{h}} \times \frac{60\,\text{s}}{\text{min}} = 7200\,\text{s}$$

2 **State the equation.**

$N = N_0 e^{-\lambda t}$

3 **Rearrange to make N_0 the subject.**

$$N_0 = \frac{N}{e^{-\lambda t}}$$

4 **Substitute the known values.**

$$N_0 = \frac{700}{e^{-9.9\times 10^{-3}\times 7200}}$$

5 **Calculate the answer.**

$N_0 = 6.33 \times 10^{33}$ g

$N_0 = 6.33 \times 10^{30}$ kg in the original sample

c **1** **Determine the relationship.**

When half of a sample remains, the ratio $\frac{N}{N_0} = 0.5$.

2 **Write the equation.**

$N = N_0 e^{-\lambda t}$

3 **Rearrange to make $e^{-\lambda t}$ the subject.**

$$\frac{N}{N_0} = e^{-\lambda t}$$

$0.5 = e^{-\lambda t}$

4 **Rearrange for time.**

$\ln(0.5) = -\lambda t$

$$t = -\frac{\ln(0.5)}{\lambda}$$

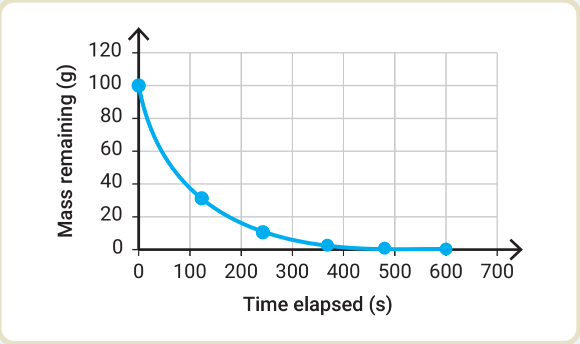
5 **Calculate the answer.**

$$t = -\frac{\ln(0.5)}{9.9\times 10^{-3}}$$

$t = 70$ s

d Drawing a table of values will aid drawing a graph. Five data points are required to demonstrate the decay of protactinium over 10 min. Convert each data point to seconds, as the decay constant is given in Bq. The mass remaining is calculated after each time interval, using the same method as in part **a**.

Time elapsed (min)	0	2	4	6	8	10
Time elapsed (s)	0	120	240	360	480	600
Mass remaining (g)	100	30.4	9.2	2.8	0.9	0.3



Plot these with mass remaining (g) on the *y*-axis, and *t* on the *x*-axis, and draw a trend line.

LEARNING CHECK 7.6

DESCRIBING

1 Write the equation for exponential decay.

2 **Define** 'activity'.

APPLYING

3 Thallium-201 has a decay constant of 2×10^{-6} Bq. After 260 s, how much of a 1 kg sample remains?

4 After 27 years, a sample of plutonium-238 weighs 300 g. Plutonium-238 has a decay constant of 7.9×10^{-3} per year. How much of the sample was there to begin with?

5 After 1257 years, the activity of a sample of radium has reduced to 58% of what it was originally. What is the decay constant?

6 Every 2 s, a sample of protactinium-225 decays by half. Originally, there were 1.6×10^{26} particles in the sample. Plot a graph of the decay of the protactinium sample over the first 12 s.

7.7 Stable nuclides

Nuclides **spontaneously** decay to become more stable. In the case of very large nuclides, it will take more than one type of radioactive decay for this to happen. Consider uranium-238; it decays by alpha emission to become thorium-234, but thorium-234 is not a stable nuclide. Therefore, thorium-234 also decays, most likely by β^- decay to protactinium-234. This process continues until a stable nuclide is formed.

The starting nuclide determines the decay process that the element is likely to undergo to become stable. This decay process is represented as a decay series or decay chain. Decay series are graphical representations of the possible emissions daughter nuclides undergo to become stable, and a decay chain is a flow chart showing this process.

spontaneous happens without any external action; all radioactive materials decay spontaneously, in a random and unpredictable way, and it is impossible to predict when one atom will decay, if at all, in a given period

Decay series and decay chains

Many products of radioactive decay are also radioactive. Eventually, a stable end product is reached. A number of these naturally occurring decay series have been identified. Three examples are the:

1. radium or uranium series from uranium-238 to lead-206 (Figure 7.7.1)
2. actinium series from uranium-235 to lead-207
3. thorium series from thorium-232 to lead-208.

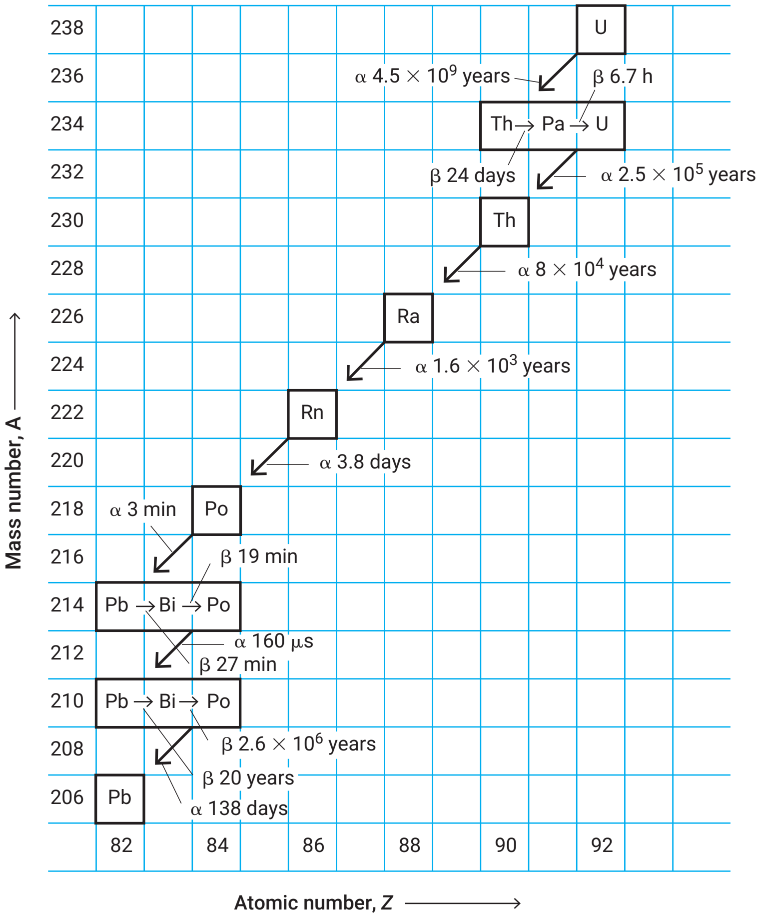


FIGURE 7.7.1 A graphical representation of the radium decay series. The half-life of each nuclide is stated, and gamma radiation is associated with many of these decays.

The end product in each of these series is lead with $Z = 82$. A fourth series, a neptunium series, starts at neptunium-237 and finishes at the stable nuclide thallium-205. Neptunium can only be produced artificially, and only two of its decay chain daughters occur naturally.

The nuclides in the radium series can be represented with the decay chain shown in Figure 7.7.2. Arrows are used to show the daughter nuclide that will result from the previous parent, until a stable nuclide is reached.

Parent $^{238}_{92}\text{U}$

$$\downarrow$$

Daughters $^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} \rightarrow {}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} \rightarrow {}^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} \rightarrow {}^{214}_{84}\text{Po} \rightarrow {}^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} \rightarrow {}^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb}$

FIGURE 7.7.2 The nuclides in the radium series. This decay chain for uranium-238 showing the daughter nuclides is a much more simplistic representation than a decay series, as the half-lives and types of decay are not represented.

WORKED EXAMPLE 7.7.1

The neptunium series begins with an alpha decay of Np-237, followed by a β^- decay.

a Show the first two decays in the series in correct symbol form.

b Write in words the names of the two daughter nuclides.

ANSWER

a $^{237}_{93}\text{Np} \rightarrow {}^{233}_{91}\text{Pa} + {}^{4}_{2}\text{He}$

$^{233}_{91}\text{Pa} \rightarrow {}^{233}_{92}\text{U} + {}^{0}_{-1}\beta$

b Daughter nuclides are protactinium-233 and uranium-233.

The different decay series are summarised in **Table 7.7.1**. There are four decay series but only three arise naturally.

TABLE 7.7.1 Decay series: cascade of decays from a radioactive nuclide until a stable nuclide is reached

Name	Start nuclide	End nuclide
Radium	$^{238}_{92}\text{U}$	$^{206}_{82}\text{Pb}$
Actinium	$^{238}_{92}\text{U}$	$^{207}_{82}\text{Pb}$
Thorium	$^{232}_{90}\text{Th}$	$^{208}_{82}\text{Pb}$
Neptunium	$^{237}_{93}\text{Np}$	$^{205}_{81}\text{Tl}$

LEARNING CHECK 7.7

DESCRIBING

1 List all the types of naturally occurring decay series.

2 **Identify** the atomic number of the stable nuclide that each decay series ends with.

3 **Identify** the decay series that arises from artificial transmutation.

4 Suggest why there are no decay series named for starting nuclides with atomic number less than 82.

APPLYING

5 Write the decay equations for every transmutation in the radium series. Use Figure 7.7.1 to aid you.

6 The thorium series begins with an alpha decay, followed by a β^- decay.
  - **a** Show the first two decays in the series in correct symbol form.
  - **b** Write in words the names of the two daughter nuclides.

7 The uranium series begins with an alpha decay, followed by a β^- decay.
  - **a** Show the first two decays in the series in correct symbol form.
  - **b** Write in words the names of the two daughter nuclides.

7.8 Radioactive half-life

Because radioactive decay is a random event, it is impossible to predict exactly when a certain isotope will decay, or even if it will decay at all in a given time period.

half-life the time it takes for half of a radioactive substance to decay

Worksheet
Decay and half-life

If there is a large enough sample of radioactive nuclei, then it can be said that some fraction of them will decay in a given time. The **half-life** of a radioactive substance is how long it takes for half the substance to decay.

In a 1 g sample of uranium, there are approximately 10^{20} unstable nuclei. In one half-life, half of these will decay. In the second half-life, half of the remaining nuclei decay. This means that after two half-lives, only 25% of the original sample remains.

In general, for a sample of N_0 particles, the number N remaining after n half-lives is given by the equation:

$$N = N_0\left(\tfrac{1}{2}\right)^n$$

where:
N = a unit of parent nuclides after time t
N_0 = initial unit of parent nuclides at $t = 0$ s
n = number of half-lives that have elapsed

The half-life of a substance is given the symbol $t_{1/2}$. Each radioactive isotope has a unique half-life.

The decay constant is directly related to the half-life of an isotope:

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

where:
$t_{1/2}$ = half-life of the isotope (s)
λ = decay constant (s^{-1})
Note that if the decay constant is in Bq, the half-life will be in seconds.

KEY FORMULA

$$N = N_0\left(\frac{1}{2}\right)^n$$

where:
N = a unit of parent nuclides after time t
N_0 = initial unit of parent nuclides at $t = 0$ s
n = number of half-lives that have elapsed

KEY FORMULA

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

where:
$t_{1/2}$ = half-life of the isotope (s)
λ = decay constant (s^{-1})
Note that if the decay constant is in Bq, the half-life will be in seconds.

WORKED EXAMPLE 7.8.1

Krypton-89 has a half-life of approximately 4 minutes.

a How long will it take for a 74 g sample of krypton-89 to only have 12 g of the original isotope remaining?

b What is the decay constant for krypton-89?

ANSWERS

a 1 Determine how many half-lives this would take.

Rearrange $N = N_0\left(\frac{1}{2}\right)^n$ for n.

$$N = N_0\left(\frac{1}{2}\right)^n$$

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$$

$$n = \log_{1/2}\frac{N}{N_0}$$

2 Substitute in values.

$$n = \log_{1/2}\frac{12}{74} = \frac{\log_{12/74}}{\log_{1/2}}$$

$n = 2.62$ half-lives

Each half-life is 4 min long, and $4 \times 2.62 = 10.5$ minutes.

Therefore, it will take 10.5 minutes until only 12 g of krypton-89 remains.

b 1 Rearrange for λ.

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

2 Calculate the answer.

$$\lambda = \frac{\ln 2}{4}$$

$\lambda = 0.17$ decays min^{-1} or $\lambda = \frac{\ln 2}{240}$

$\lambda = 0.00283$ decays s^{-1}

PRACTICAL ACTIVITY 7.8.1

RANDOM DECAY AND HALF-LIFE: A SIMULATION

Research question

How well can radioactive decay be simulated using the random arrangement of macroscopic objects?

Aim

To simulate random decay and half-life of a radioactive material

Materials

- bag or cup
- 80 small counters or similar with an 'up' side and a 'down' side (such as M&M's®)
- clean surface

Procedure

1 As a class, determine which side of the counter represents decay (up) and which side represents no decay (down).

2 Shake the bag and pour the counters onto a clean surface.

3 Record the number of counters that have *decayed* and move them to one side.

4 Replace the not-decayed counters back in the bag and repeat the process until no counters remain.

Analysis of results

1 Use whole-class data to plot a graph of the number of counters remaining versus the number of trials (half-lives).

2 From the graph, determine the half-life of the counters.

Interpretation

3 For radioactivity, how did this experiment model:

  a the randomness of decay?

  b half-life?

4 A radioactive nuclide is an unstable nucleus that could decay at any moment. The decay occurs because the daughter nuclide is more stable than the parent. Discuss.

Extension

In this experiment, the half-life was one 'throw' of the counters. Try modelling a half-life that is less than one 'throw' by repeating this experiment with a large number of dice. What is the half-life when you remove all dice with a one showing at each throw? What if you remove all those with a one or a two showing?

LEARNING CHECK 7.8

DESCRIBING

1 **Define** 'half-life'.

2 Write the equation that links the number of nuclides and the whole numbers of half-lives.

APPLYING

3 The half-life of polonium-218 is 3.0 minutes. A particular nuclide of polonium-218 has not decayed after 9.0 minutes. What are the chances that it will decay some time before 12 minutes?

4 The half-life of carbon-14 is 5730 years. What is its decay constant?

5 The half-life for thallium-200 is 1×10^4 s. A kilogram of thallium-200 contains close to 3.0×10^{24} atoms. After approximately one half-life, how many atoms in the original sample:

  a have decayed?

  b are still able to decay?

6 How many half-lives would it take for 30% of a sample to decay?

7 The half-life of actinium-225 is 10 days. Plot the decay of actinium-225 over 100 days if the original sample is 500 g.

7.9 The big picture

Radioactivity has many positive and negative side effects. Radiation treatments are used in medicine, energy can be harnessed from transmutations for power, and, unfortunately, this energy can also be used for weapons of mass destruction. Radioactivity is also used to determine the age of fossilised biological material such as plants and animals.

Nuclear medicine

Developing our understanding of nuclear radiation has led to significant advances in medical treatment and imaging. Nuclear medicine uses radiopharmaceuticals for medical diagnosis and treatment. In diagnosis, an external detector records the passage or localisation of a radioactive nuclide. Nuclear medicine treatment destroys cells (e.g. cancerous tumours) and can also promote healing. This must be localised so that healthy tissues are not damaged. The best radiation methods use gamma radiation with particular energies in order to destroy mutated cells before they replicate.

Diagnostic imaging techniques like positron emission tomography (PET) and single-photon emission computed tomography (SPECT) use radioactive tracers to visualise internal bodily structures and detect diseases at early stages. These technologies not only enhance the accuracy and effectiveness of medical diagnoses but also enable personalised treatment plans tailored to individual patients. Furthermore, advancements in nuclear medicine continue to push the boundaries of medical science, offering new avenues for research and innovation.

Science empowers us with knowledge that can predict both beneficial and potentially harmful consequences, guiding responsible decision making in various domains. For medical imaging, physicists and healthcare professionals carefully consider the properties of radioisotopes to ensure accurate diagnosis while minimising radiation exposure to patients. By understanding the decay rates and emission characteristics of different isotopes, they can choose those best suited for specific imaging techniques, maximising diagnostic efficacy and patient safety.

Radioactive dating

In the atmosphere, carbon-14 only occurs in trace amounts. The ratio of carbon-14 to all other isotopes of carbon is $1:10^{12}$. When living organisms die, it is approximated that this is also the ratio of carbon-14 to other isotopes of carbon within their bodies. After the organism has died, no new carbon-14 is taken in, and the carbon-14 in the dead organism undergoes β^- decay and transmutes into nitrogen-14.

The half-life for carbon-14 is approximately 5730 years. If the amount of carbon-14 in a dead organism can be measured, it can be compared to the original ratio to determine the time since the organism died.

WORKED EXAMPLE 7.9.1

A sample of fossilised plant material found in the Kimberley was recently analysed, and it was found that only 45% of the typical ratio of carbon-14 was present. If 100% represents the ratio $1:10^{12}$ of carbon-14 to carbon isotopes originally, how old is the sample?

ANSWER

1 Write the equation.

$$N = N_0\left(\frac{1}{2}\right)^n$$

2 Rearrange the equation and substitute known values.

$$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$$

$$0.45 = \left(\frac{1}{2}\right)^n$$

3 Rearrange for *n* and calculate the answer.

$$n = \log_{\frac{1}{2}} 0.45$$

$$n = 1.15 \text{ half- lives}$$

The half-life of carbon-14 is 5730 years.

$1.15 \times 5730 = 6590$ years

The sample is 6590 years old.

Weblink
Radioactive dating game

Carbon-14 is commonly used for dating organisms that are thousands of years old, but other isotopes can also be used for radioactive dating. As long as we know the half-life of the isotope and its original abundance in living organisms, we can estimate the age. Some isotopes have half-lives of millions or billions of years and are used when approximating the ages of fossils that are millions of years old. This reduces the source of error. Examples of such isotopes are uranium-235 and potassium-40.

LEARNING CHECK 7.9

DESCRIBING

1 What are some uses for radioactive isotopes?

2 **Distinguish** between diagnosis and treatment.

3 Why is half-life important when administering a radioisotope to a patient who needs to have a PET scan?

APPLYING

4 **Explain** why it is important to have a local source for radiopharmaceuticals.

5 **Explain** how carbon-14 is used to determine the approximate age of fossils of plants and animals.

ANALYSING

6 Would carbon-14 be a useful isotope for measuring how old something is if the organism is only hundreds of years old instead of thousands? **Explain** your answer.

CHAPTER SUMMARY

Different types of radioactivity

- Alpha particle radiation is the largest particle that can be emitted from a nucleus.
- α decay can be written as:

$${}^{A}_{Z}\text{X} \rightarrow {}^{A-4}_{Z-2}\text{Y} + {}^{4}_{2}\alpha$$

where: A = mass number
Z = proton number
X = the element before decay (parent)
Y = the element after α decay (daughter)

- Beta particle radiation is released from the nucleus, and is significantly smaller than alpha particles.
- There are two types of beta decay:
  - electron (β^-)
  - positron (β^+)
- β^- decay can be represented as:

$${}^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + {}^{0}_{-1}\beta + \overline{\text{v}}$$

where: A = mass number
Z = proton number
X = the element before decay (parent)
Y = the element after β^- decay (daughter)
$\overline{\text{v}}$ = an antineutrino

- β^+ decay can be represented as:

$${}^{A}_{Z}\text{X} \rightarrow {}_{Z-1}^{A}\text{Y} + {}^{0}_{1}\beta + \nu$$

where: A = mass number
Z = proton number
X = the element before decay (parent)
Y = the element after β^+ decay (daughter)
v = neutrino

- Gamma rays can also be released from the nucleus to help the atom return to a stable state.

Properties of radiation

	α particles	β particles	γ rays
Nature	A helium nucleus (i.e. two protons and two neutrons)	A fast-moving electron or positron	High-frequency (short wavelength) electromagnetic radiation (i.e. a high-energy photon)
Charge	+2 elementary charges	−1 (electron) +1 (positron) elementary charge	Uncharged
Mass	4 atomic mass units (4 u) or $4 \times 1.66 \times 10^{-27}$ kg	0.0005 u 9.1093×10^{-31} kg	No mass
Ionising effect	Strong	Weak	Very weak

	α particles	β particles	γ rays
Penetration	Few centimetres in air	Few metres in air	Very weakly absorbed in air (most radiation absorbed by a few centimetres of lead)
Effect of electric and magnetic fields	Very small deflection	Large deflection	No deflection
Typical emission velocity	5–7% of speed of light	30–90% of speed of light	Speed of light 3×10^8 m s^{-1}

Balancing nuclear equations

- In nuclear equations, balance the mass numbers, atomic numbers and include any emitted radiation.

$$^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\text{He}^{2+} \text{ or } {}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$$

Decay equations

- Alpha particle radiation is the largest particle that can be emitted from a nucleus.
- We can use the exponential decay function to predict how long it may take for a percentage of a substance to decay.
- Exponential decay function:

$$N = N_0 e^{-\lambda t}$$

where: N = a unit of parent nuclides after time t
N_0 = the initial unit of parent nuclides at $t = 0$ s
e = is a constant called Euler's number and is equal to 2.718 28
t = time elapsed (s)
λ = the decay constant, unique to each nuclide (s^{-1})

- The activity of a radioactive sample can be identified by:

$$A = \lambda N$$

where: A = the activity of a substance (Bq)
λ = the decay constant (s^{-1})
N = the unit of the sample remaining when the activity is measured

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

Half-life

- The half-life of a radioactive substance is how long it takes for half of that substance to decay.

where: $t_{1/2}$ = half-life of the isotope (s)
λ = decay constant (s^{-1})

Note that if the decay constant is in Bq, the half-life will be in seconds.

CHAPTER EXAM

MULTIPLE CHOICE

1. An example of ionising radiation is:

A microwaves.
B light from the Sun.
C heat from the Sun.
D UV radiation from the Sun.

2. $^{168}_{77}\text{Ir}$ undergoes alpha decay. The daughter nuclide is:

A $^{164}_{75}\text{Re}$.
B $^{166}_{73}\text{Ta}$.
C $^{168}_{76}\text{Os}$.
D $^{168}_{78}\text{Pt}$.

3. The most common way to detect radioactivity is with which instrument?

A A G-M tube
B An electroscope
C An isotope tracker
D A thermoluminescent chamber

4. A radioactive substance loses 60% of its original radioactive material after 6750 years. What is the half-life of the substance?

A 5114 years
B 5625 years
C 6000 years
D 9122 years

5. In an electric field, the least deflected radiation is:

A an alpha particle (α).
B a positron (β^+).
C an electron (β^-).
D a gamma ray (γ).

6. The isotopes of an element all have the same:

A atomic number.
B half-life.
C mass number.
D number of electrons.

7. The half-life of a radionuclide equals:

A half the time needed for a sample to completely decay.
B half the time a sample can be kept before it starts to decay.
C the time needed for half a sample to decay.
D the time needed for the rest of a sample to decay once half of it has already decayed.

8. During the decay of a radionuclide, its half-life:

A decreases.
B increases.
C does not change.
D any of the above, depending on the nuclide.

9. When the uranium isotope U-234 undergoes alpha decay, what is the resulting nuclide?

A Ra-230
B Ra-232
C Th-230
D U-230

10. When the strontium-87 isotope undergoes gamma decay, what is the resulting nuclide?

A Kr-83
B Rb-87
C Sr-87
D Y-87

SHORT RESPONSE

11. **Identify** the daughter nuclide when cobalt-60 undergoes β^- decay.

12. Complete the following partial nuclear equations for natural radioactive disintegrations:

a ${}^{234}_{\square}\text{U} \rightarrow {}^{230}_{\square}\text{Th} + \_\_\_\_\_\_$

b ${}^{214}_{\square}\text{Pb} \rightarrow {}^{214}_{\square}\text{Bi} + \_\_\_\_\_\_$

c ${}^{216}_{\square}\text{Po} \rightarrow {}^{4}_{2}\text{He} + \_\_\_\_\_\_$

d ${}^{210}_{\square}\text{Pb} \rightarrow {}^{0}_{-1}\text{e} + \_\_\_\_\_\_$

e ${}^{218}_{\square}\text{Po} \rightarrow {}^{4}_{2}\text{He} + \_\_\_\_\_\_$

f ${}^{214}_{\square}\text{Bi} \rightarrow {}^{0}_{-1}\text{e} + \_\_\_\_\_\_$

g ${}^{234}_{\square}\text{Pa} \rightarrow {}^{0}_{-1}\text{e} + \_\_\_\_\_\_$

h ${}^{230}_{\square}\text{Th} \rightarrow {}^{4}_{\square}\text{He} + \_\_\_\_\_\_$

i ${}^{91}_{\square}\text{Tc} \rightarrow {}^{0}_{+1}\text{e} + \_\_\_\_\_\_$

13. Write balanced nuclear equations for the following natural radioactive decay processes.

a β-decay of ${}^{107}\text{Rh}$
b α-decay of ${}^{157}\text{Yb}$
c γ-decay of ${}^{121}\text{Cd}$
d β^+-decay of ${}^{156}\text{Ho}$
e β-decay of ${}^{75}\text{Ga}$
f α-decay of ${}^{179}\text{Au}$
g γ-decay of ${}^{187}\text{Hg}$
h β^+-decay of ${}^{20}\text{Na}$

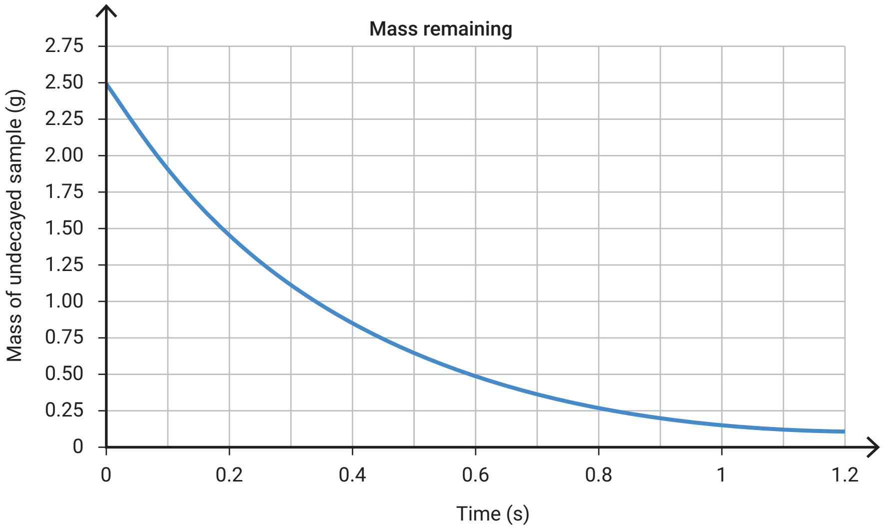
14. The actinium series does not actually start at ${}^{227}\text{Ac}$. Before the production of radioactive ${}^{227}\text{Ac}$, there have been two β^--decays and two α-decays, and subsequent to its appearance there are five more α-particles and three more β^- particles produced.

a What is the starting nucleus of the actinium series?
b What is the stable end product of the actinium series?

DATA ANALYSIS

15. Analyse data

The mass of radioactive material remaining as a function of time is shown in the following graph.

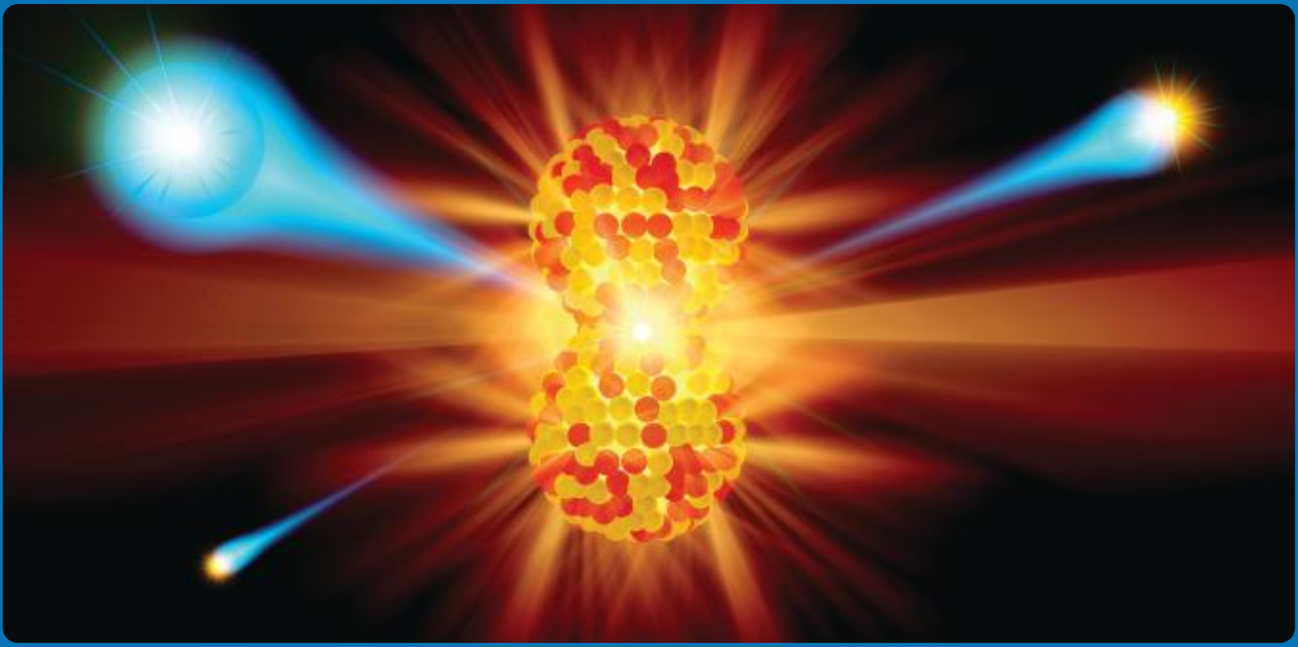


- **a** **Identify** the initial mass (m_0).
- **b** **Determine** the half-life ($t_{1/2}$).
- **c** **Identify** the mass remaining after 0.2 s.
- **d** **Determine** the time needed for the mass remaining to be 1% of m_0.
- **e** If a 4.00 g sample of the same radioactive substance was used, **determine** the time it would take for half of that sample to decay.

CHAPTER

8

Nuclear energy and mass defect



Ian Cuming/Ikon Images/Science Photo Library

SYLLABUS DOT POINTS

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 $\Delta E = mc^2$.
- 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 how an understanding of radioactive decay can enable scientists to make reliable predictions in radiometric dating of materials.
- Appreciate that energy production in stars was attributed to gravity until the knowledge of nuclear reactions led to the understanding that energy production in stars is due to nuclear fusion.

SCIENCE INQUIRY

- Consider whether nuclear fission-based power production could replace fossil fuel-based generation in Australia.
- Investigate nuclear safety, considering the suitability of using the sources of information in terms of their credibility.

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Introduction

The mushroom cloud that accompanies a nuclear explosion illustrates the enormity of the energy released in a nuclear reaction. Harnessing this energy may provide the answer to the world's increasing energy needs.

In this chapter, Einstein's mass–energy equivalence relationship is explained and applied to measure how much energy is released in nuclear reactions.

Worksheets

- Energy from the nucleus
- Nuclear fusion
- Fusion power and the Sun's source of energy

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Nucleons include protons and neutrons in the nucleus of an atom.
- ✓ The SI unit for energy is the joule.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain the processes of nuclear fusion and nuclear fission
- ✓ comprehend how the energy intrinsic to an isotope is linked to the four fundamental forces
- ✓ convert energy values between electron-volts and joules
- ✓ 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
- ✓ interpret data linking mass number and binding energy per nucleon and link it to stability and the potential for energy to be released by fission or fusion
- ✓ compare natural transmutation and artificial transmutation
- ✓ recall examples of neutron-induced nuclear fission equations
- ✓ describe and explain nuclear fission chain reactions and how they can be controlled
- ✓ recall examples of nuclear fusion reactions
- ✓ evaluate and discuss current procedures in nuclear safety and waste disposal.

nucleon a proton or neutron; a particle that makes up the nucleus of an atom

fission the process by which heavy nuclei ($Z > 56$) separate into fragments, with the release of energy; typically, fission fragments have quite different masses

fusion the process by which nucleons join to form a new nucleus. Nucleosynthesis is the set of fusion reactions that lead from nucleons to a variety of nuclides. This occurs for light elements ($Z < 56$) and energy is released

gravitational force the manifestation of Newton's universal law of gravitation; a force of attraction acting between every mass throughout the universe

electromagnetic force the combined electrical and magnetic force acting between charged particles; the force is attractive for unlike charges, and repulsive for like charges

strong nuclear force the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons

weak nuclear force one of the four fundamental forces; acts between subatomic particles (leptons) and is responsible for beta decay

8.1 The energy within the nucleus

Enormous amounts of energy can be produced from atomic nuclei. Radioactive decay products are more energetic than emissions from the atomic-level electron transitions. As such, they can be used to enhance the scope of medical diagnosis and treatment. **Nucleons** (protons and neutrons) are very strongly bound together in the nucleus via the strong nuclear force. Rearrangements of these nucleons by splitting the atom (**fission**) or by adding nucleons together (**fusion**) can release energy. Although each fission or fusion event releases tiny amounts of energy, these amounts are far greater than the energy per atom released in the chemical reactions that take place in traditional methods of obtaining energy, such as the burning of fossil fuels. The difference in energy is typically of the order of 1–10 billion times more energetic. Fission and fusion release enormous amounts of energy due to the significant number of nucleons involved in the reactions multiplied by the energy released per event.

The use of nuclear energy for baseload power remains controversial, due to the negative effects on human health from radioactive waste, as well as when things go wrong, such as the melting of the three Fukushima Daiichi reactors following a tsunami that disabled both the power supply and the cooling at the plant on 11 March 2011, and the explosion of Reactor 4 at Chernobyl on 26 April 1986.

The four fundamental forces

There are four fundamental forces identified by physicists that cannot be reduced to more basic interactions: the **gravitational**, **electromagnetic**, **strong nuclear** and **weak nuclear forces**. The two nuclear forces are described as acting at very short range. The strong nuclear force has the greatest effect on maintaining nucleons within the nucleus, while the weak nuclear force, which acts within nucleons, is responsible for radioactive decay.

TABLE 8.1.1 Comparing the four fundamental forces within a nucleus

	Gravitational force	Weak nuclear force	Electromagnetic force	Strong nuclear force
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Infinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

What holds an atomic nucleus together?

Protons have a positive charge and, because like charges repel, the protons within the nucleus repel each other with an electrostatic force. The electrostatic force becomes relatively large when the protons are close together, as they are within an atom. In the nucleus, protons come within about 2×10^{-15} m (2 femtometres, 2 fm) of each other. The electrostatic force of repulsion acting between a pair of protons is about 60 N when they are at their closest. Protons have mass and, according to the universal law of gravitation, a gravitational force exists that causes them to attract each other. Although one might think that this gravitational force holds the nucleus together, the gravitational force acting between protons is miniscule, even when they are 2 fm apart – it is too small by a factor of 10^{36}. The force that keeps nucleons together is the strong nuclear force **(Figure 8.1.1)**. For example, in a helium-4 nucleus, the protons and neutrons are bound together by the strong nuclear force that overcomes the repulsion due to the electrostatic force.

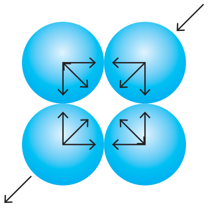


FIGURE 8.1.1 The strong nuclear force acts to bind nucleons together, acting against the force of electrostatic repulsion. Gravitational force, although present, is negligible.

Electron-volt, eV

The energy equivalent of nucleon mass is very small – too small to represent conveniently in joules. As a consequence, a different energy unit is used, making the numbers simpler to work with. This energy unit is the **electron-volt (eV)**. One electron-volt is equivalent to the energy that an electron gains when it moves through a potential difference of 1 volt. Thus, 1 eV is equivalent to 1.60×10^{-19} J. Nuclear energies are often in the range of thousands (×10^3) of eV (keV), millions (×10^6) of eV (MeV) or billions (×10^9) of eV (GeV).

electron-volt, eV a small energy unit, equivalent to 1.60×10^{-19} J

Nuclear binding energy

nuclear binding energy the energy needed to disassemble a nucleus into its component nucleons; a measure of stability of a nuclide

mass defect (Δm) the difference in the mass of an atom and the mass of its constituent parts, as expressed in Einstein's mass–energy equation: $\Delta E = \Delta mc^2$

The binding energy per nucleon governs stability. The higher the binding energy per nucleon, the more stable the nuclide. Nuclei are made up of protons and neutrons. The energy that would be needed to disassemble a nucleus into its component nucleons is known as the **nuclear binding energy**. Each nucleon, on its own, has a rest mass; however, when nucleons are brought together to form a nucleus, the mass of the nucleus is slightly less than the sum of all the individual nucleons. The difference, Δm, between the sum of the individual masses and the mass of the nucleus into which they are combined is called the **mass defect**. The mass defect is a measure of the energy, E, needed to bind all the parts of a nucleus together. Einstein's mass–energy equation is a quantitative statement of this effect:

$$\Delta E = \Delta mc^2$$

where: c = the speed of light in a vacuum, $3.00 \times 10^8 \text{ m s}^{-1}$.

Some of the mass of the individual nucleons appears as the binding energy of the nucleus (Table 8.1.2). In this sense, it is best to consider mass and energy as equivalent and interchangeable; that is, mass ⇔ energy.

It has been observed that in any nuclear event – radioactive decay, nuclear reaction, fusion and fission – there is a loss of mass. This mass defect appears as energy in amounts predicted by Einstein's mass–energy equation.

KEY FORMULA

Einstein's mass–energy equation

$$\Delta E = \Delta mc^2 \text{ (J)}$$

where:
c = the speed of light, $3.00 \times 10^8 \text{ m s}^{-1}$

We can report the mass of nucleons in different ways: in kilograms (kg), in unified mass units (u) and in energy (MeV).

TABLE 8.1.2 Rest masses of nucleons, in kilograms and unified atomic mass units

Nucleon	Mass (kg)	Mass (u)
Proton	1.67208×10^{-27}	1.007 28
Neutron	1.67438×10^{-27}	1.008 66
Electron	9.11×10^{-31}	0.000 55

The unified atomic mass unit, u, has a value of 1.66×10^{-27} kg and energy equivalent of 931.5 MeV.

WORKED EXAMPLE 8.1.1

For an alpha particle, calculate the:

a mass defect
b nuclear binding energy
c binding energy per nucleon.

(An alpha particle, α, is a ${}^{4}_{2}$He nucleus; it has 2 protons and 2 neutrons and no electrons.)

Use the following mass values:

Unified atomic mass unit, u = 1.66×10^{-27} kg
Rest mass of proton, m_p = 1.007 28 u or 1.67208×10^{-27} kg
Rest mass of neutron, m_n = 1.008 66 u or 1.67438×10^{-27} kg
Rest mass of alpha particle, m_α = 4.001 53 u or 6.64254×10^{-27} kg

ANSWERS

a 1 Determine the combined mass of the individual components that make up the nucleus.

Mass of combined components:

$2 \times$ mass of proton $\quad 2 \times 1.672\,08 \times 10^{-27}\,\text{kg}$

$+\,2 \times$ mass of neutron $\quad 2 \times 1.674\,38 \times 10^{-27}\,\text{kg}$

$= 6.692\,92 \times 10^{-27}\,\text{kg}$

2 Subtract the rest mass of the complete particle

Rest mass of alpha particle $\quad 6.642\,54 \times 10^{-27}\,\text{kg}$

Mass defect, Δm $\quad 6.692\,92 \times 10^{-27}\,\text{kg} - 6.642\,54 \times 10^{-27}\,\text{kg}$

$\Delta m = 0.050\,38 \times 10^{-27}\,\text{kg}$

$\Delta m = 0.030\,35\,\text{u}$

b 1 Use Einstein's mass–energy equation.

$\Delta E = \Delta mc^2$, where $c =$ the speed of light, $3.00 \times 10^8\,\text{m s}^{-1}$.

$E = \Delta mc^2 = 0.050\,38 \times 10^{-27}\,\text{kg} \times (3.00 \times 10^8\,\text{m s}^{-1})^2$

$= 4.5342 \times 10^{-12}\,\text{J}$

2 Calculate the nuclear binding energy.

$E = 28.339\,\text{MeV}$ (where $1\,\text{eV} = 1.60 \times 10^{-19}\,\text{J}$, hence $1\,\text{MeV} = 1.60 \times 10^{-13}\,\text{J}$)

c 1 Divide the nuclear binding energy by the number of nucleons (protons and neutrons).

$$E = \frac{4.5342 \times 10^{-12}}{4}$$

$= 1.1336 \times 10^{-12}$ joules per nucleon, or

$$= \frac{28.339\text{ MeV}}{4}$$

$= 7.084\,\text{MeV}$ per nucleon

The binding energy per nucleon is shown graphically in **Figure 8.1.2** for nuclides up to uranium, the heaviest naturally occurring element. The binding energy per nucleon is a significant quantity when determining the stability of nuclides. The greater the binding energy per nucleon, the harder it is to pull the nucleus apart and the more stable the nuclide. Iron-56 is at the top of

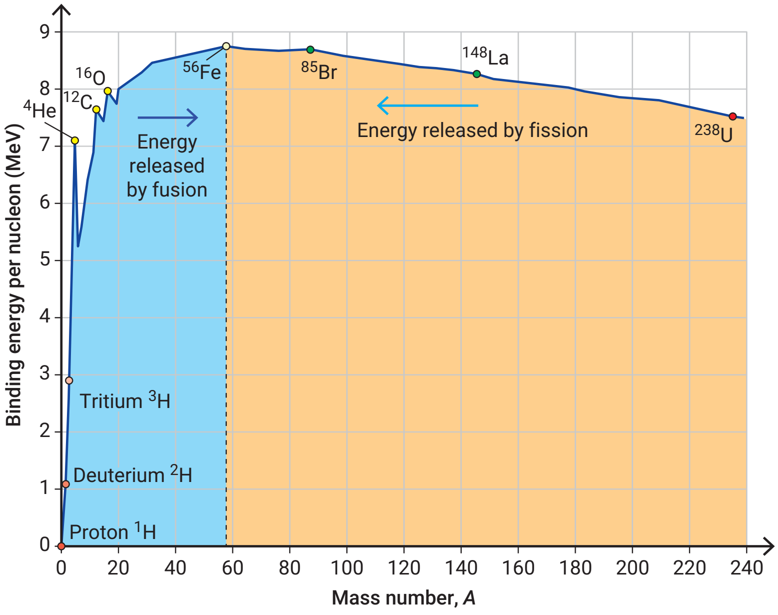


FIGURE 8.1.2 A graph of the binding energy per nucleon as a function of mass number, *A*

the curve and is the most stable of the nuclides. Unstable elements with greater mass than iron release energy when they undergo fission (break apart); elements with a lesser mass than iron release energy when undergoing fusion (being fused or forced together). The binding energy per nucleon governs stability. The higher the binding energy per nucleon, the more stable the nuclide. Fusion is favoured for light nuclides ($Z < 56$). Fission is favoured for heavy nuclides ($Z > 56$).

Table 8.1.3 shows the total binding energy for nuclides as well as the binding energy per nucleon. Consider He-4, which has a total binding energy of 28.29 MeV. It has 4 nucleons, so its binding energy per nucleon is 7.07 MeV per nucleon.

TABLE 8.1.3 Nuclear binding energy and binding energy per nucleon for some nuclides

Element	Binding energy (MeV)	Binding energy per nucleon (MeV)
Deuterium (hydrogen-2)	2.23	1.12
Helium-4	28.29	7.07
Lithium-7	40.15	5.74
Beryllium-9	58.13	6.46
Iron-56	492.24	8.79
Silver-107	915.23	8.55
Iodine-127	1072.53	8.45
Lead-206	1622.27	7.88
Polonium-210	1645.16	7.83
Uranium-235	1783.80	7.59
Uranium-238	1801.63	7.57

LEARNING CHECK 8.1

DESCRIBING

1 **Define** each of the terms in the equation $\Delta E = \Delta mc^2$.

2 **Define:**

  a electromagnetic force
  b strong nuclear force
  c gravitational force
  d weak nuclear force
  e nuclear binding energy.

3 Draw a table to show the relative magnitudes and ranges of the four fundamental forces.

APPLYING

Questions 4 and 5 refer to the following information.

Unified atomic mass unit, u = 1.66×10^{-27} kg

Rest mass of proton, $m_p = 1.00728$ u or 1.67208×10^{-27} kg

Rest mass of neutron, $m_n = 1.00866$ u or 1.67438×10^{-27} kg

Rest mass of electron, $m_e = 9.11 \times 10^{-31}$ kg

Rest mass of ${}^{3}_{2}\text{He} = 3.01603$ u or 5.00661×10^{-27} kg

Rest mass of ${}^{14}_{7}\text{N} = 14.0067$ u or 2.3251×10^{-26} kg

4 For a helium-3 isotope $\left({}^{3}_{2}\text{He}\right)$, **calculate** the following. Include the mass of the two electrons.

  a Mass defect
  b Nuclear binding energy
  c Binding energy per nucleon

5 For a nitrogen-14 isotope, $^{14}_{7}N$, **calculate** the following. Include the mass of the seven electrons.

- **a** Mass defect
- **b** Nuclear binding energy
- **c** Binding energy per nucleon

8.2 Transmutations

Transmutation, the process of transforming one element (or nuclide) into another by radioactive decay or nuclear bombardment, may occur either naturally or artificially. **Natural transmutation** occurs through the continual and spontaneous process of radioactive decay. In contrast, **artificial transmutation** may occur through the bombarding of a nucleus with a neutron or other small nucleus, such as an alpha particle.

The discovery of the neutron enabled scientists to explore the behaviour of larger atomic nuclei. Because they are neutral, neutrons are not repelled by the target nucleus and can be absorbed into the nucleus of the target atom. This makes neutrons very useful as a form of bombarding radiation, and they are used in many experiments to transmute a number of nuclides artificially.

natural transmutation the conversion of one chemical element or isotope into another through natural radioactive decay

artificial transmutation the conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

slow (thermal) neutron neutron with kinetic energy of about 0.1–20 keV

Artificial transmutation

Artificial transmutation may occur in several ways. Adding a proton (as occurs in a cyclotron) and adding larger nuclei (such as alpha particles) are two ways. Artificial transmutation also include the target nucleus being bombarded with an incoming **slow (thermal) neutron**. The nucleus of the atom effectively 'captures' the neutron, becoming unstable and subsequently emitting radioactive decay. Recall that Rutherford was the first to use radioactivity to produce new nuclides. He bombarded nitrogen-14 with alpha particles, analysed the result and found that oxygen and hydrogen were formed. The reaction proceeded as follows.

Nitrogen nuclei absorb helium nuclei and form a composite, unstable nuclide (denoted by an asterisk):

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{18}_{9}\mathrm{F}^{*}$$

The composite nuclide decays to a more stable state:

$$^{18}_{9}\mathrm{F} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

LEARNING CHECK 8.2

DESCRIBING

1 **Identify** the term to match each definition.

- **a** The conversion of one chemical element or isotope into another through natural radioactive decay
- **b** The conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

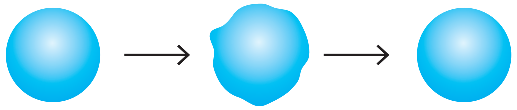
APPLYING

2 Insert the correct values for *A* and *Z* in the transmutation equation for fluorine:

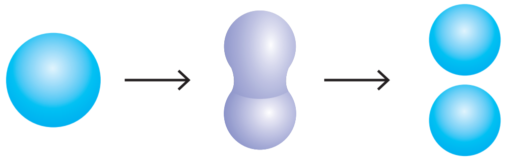
$$^{14}_{\square}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{\square}_{\square}\mathrm{F}^{*}$$

8.3 Nuclear fission

Nuclear fission is the process by which a nucleus splits into two or more fragments. In 1938, while trying to explain others' findings, Lise Meitner (1878–1968) and Otto Frisch (1904–79) determined that a uranium nucleus had split in two. This was an unexpected result at the time. (In general, the fragments are rarely the same size, so it is incorrect to say that the atom 'splits in half'.) In the process, neutrons are released and energy, initially stored as nuclear binding energy, is released. Nuclear fission occurs naturally in rare instances, leading to radioactive decay, or may be induced through an artificial transmutation, triggered by the absorption of a neutron. When a nucleus absorbs a slow neutron, it becomes less stable. Bombarding uranium nuclei with neutrons leads to the formation of a transuranic element, or the splitting of the unstable uranium into two nuclei of intermediate mass **(Figure 8.3.1)**. Adding enough neutrons means the uranium nucleus is neutron rich. One of these neutrons will decay into a proton, which stays in the nucleus, and an electron, which is released as beta radiation. The extra proton means the nucleus is now atomic number 93, which is a transuranic element (neptunium).



After a slight distortion, the drop returns to a spherical shape.



A large distortion may cause the drop to split in two.

FIGURE 8.3.1 The liquid-drop model of fission. A nucleus that absorbs an additional neutron undergoes large distortions and splits into two (or more) smaller fragments.

Weblink
Nuclear fission

Irène Joliot-Curie (1897–1956), daughter of Marie Curie (1867–1934), was the first to identify the products of nuclear fission. Enrico Fermi (1901–1954) was the first to control nuclear fission. On 2 December 1942, in a squash court under the stadium at the University of Chicago, the first self-sustaining nuclear reactor began operation. Five days later, the Japanese entered World War II by attacking Pearl Harbor, and their involvement eventually led to the atomic bomb being dropped on Hiroshima and Nagasaki in 1945. Thus began the Nuclear Age.

Some common nuclear fission reactions can be expressed in equation form, as below. Note that the sums of the nucleon numbers (A) and atomic numbers (Z) on either side of the equation are equal. Further, each equation liberates (frees) additional neutrons – each of which may go on to induce another nuclear fission reaction.

Examples of neutron-induced nuclear fission equations

Fission occurs when neutron absorption in the nuclei of elements such as uranium and plutonium causes splitting into two, usually unequal, fragments. Neutrons are released and can be controlled (to sustain) or deliberately uncontrolled (to magnify) the release of energy.

$$ {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy} $$

$$ {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + 3\,{}^{1}_{0}\text{n} + \text{energy} $$

$$ {}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{144}_{55}\text{Cs} + {}^{90}_{37}\text{Rb} + 2\,{}^{1}_{0}\text{n} + \text{energy} $$

Fission fragments

Nuclides that can undergo nuclear fission after absorbing a neutron are fissionable. There are two types of fissionable nuclides:

- Fissionable nuclides that can support a fission chain reaction are called **fissile** (e.g. U-233, U-235, Pu-239)
- Fissionable nuclides that can't support a fission chain reaction (only single fission reactions from externally produced thermal neutrons) are called fertile (e.g. U-238, Th-232, Pu-240).

Fissile nuclides are very uncommon. Uranium-235 and plutonium-239 are readily fissile and undergo nuclear fission with low-energy 'slow' neutrons (in the range 0.02 eV to several keV). Thorium-232 can absorb a neutron and undergo beta decay to become uranium-233, which is also fissile.

fissile capable of being split or divided (e.g. by undergoing fission) (e.g. U-235, U-238, U-233, Pu-239)

A uranium-235 nucleus may split in many different ways. More than 40 different pairs of fission fragments of uranium-235 have been found. In the nuclear fission equation below, krypton-92 and barium-141 are known as the **fission fragments** (or fission products).

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

fission fragment a nucleus produced as a result of fission; fission product

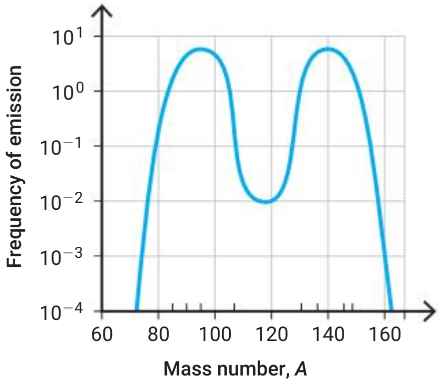


FIGURE 8.3.2 The most likely fission fragments from U-235 have atomic mass numbers around 95 and 140. The vertical scale is logarithmic – equal distances along the axis represent equal ratios (in this case × 10).

Radiochemical analysis shows that most fission fragments have an atomic mass number between 72 and 158 and an atomic number between 30 and 63. The splitting of a fissile nucleus into two equal parts is rare – about 0.01% of fission reactions. Other common fission fragment pairs produced in the fission of uranium-235 are xenon-140 and strontium-94, and tin-132 and molybdenum-101. Many fission fragments are radioactive; hence, spent nuclear fuel is considered radioactive waste that needs to be treated with care and expertise.

Worksheet
Energy from the nucleus

WORKED EXAMPLE 8.3.1

A thermal neutron, mass 1.01 u, causes fission of U-235 (235.04 u). The fission fragments and their masses, in unified mass units, are Rb-93 (92.92 u) and Cs-141(140.92 u).

a How many fast neutrons are released in this fission event?

b Write the nuclear fission reaction using the correct nuclide and nucleon symbols.

c Calculate the mass defect in this event, giving the answer in:

  i unified mass units

  ii kilograms.

d How much energy is released? Give your answer in joules.

ANSWERS

a 1 **Nucleon number is conserved.**

Total nucleons before $= 1 + 235 = 236$

Total nucleons after $= 93 + 141 + x$

2 **Determine the number of neutrons released.**

$$x + 234 = 236$$
$$x = 2$$

Two neutrons were released.

b ${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{93}_{37}\text{Rb} + {}^{141}_{55}\text{Cs} + 2\,{}^{1}_{0}\text{n}$

c i **Calculate the mass defect in unified mass units.**

$$\text{Mass defect} = (1.01 + 235.04) - (92.92 + 140.92 + 2 \times 1.01)\,\text{u}$$
$$= 0.19\,\text{u}$$

ii **Give the answer in kilograms**

$$\text{Mass defect} = 0.19\,\text{u} \times 1.66 \times 10^{-27}\,\text{kg}\,\text{u}^{-1}$$
$$= 3.15 \times 10^{-28}\,\text{kg}$$

d 1 **Use the mass-energy equation.**

$$\Delta E = \Delta m c^2$$

2 **Substitute the known values to calculate the energy released.**

$$\Delta E = 3.15 \times 10^{-28}\,\text{kg} \times (3.00 \times 10^{8}\,\text{m}\,\text{s}^{-1})^2$$
$$= 2.84 \times 10^{-11}\,\text{J}$$

LEARNING CHECK 8.3

DESCRIBING

1 Write the symbol for the element uranium, including the notation for mass number and atomic number.

2 **Define:**

- a fission
- b fission fragment.

APPLYING

3 Complete the missing mass and atomic numbers and element symbol in the nuclear fission.

$${}^{235}_{\square}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{\square}_{36}\text{Kr} + {}^{141}_{56}\square + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

4 In a nuclear reaction that starts with uranium, a thermal neutron, mass 1.01 u, causes fission of U-233 (233.044 u). The fission fragments and their masses, in unified mass units, are Mo-104 (103.91 u), Sn-126 (125.91 u) and four neutrons.

- a Write the nuclear fission reaction using the correct nuclide and nucleon symbols.
- b **Identify** the mass defect in this event in:
  - i unified mass units
  - ii kilograms.
- c How much energy is released? Give your answer in joules.

5 In a fast breeder reactor, a fast neutron, mass 1.01 u, causes fission of Pu-239 (239.05 u). One of the two fission fragments is Tc-104 (103.91 u); three neutrons are also released. The mass defect in this event is 0.19 u.

- a What is the nuclide symbol for the second fission fragment?
- b Write the nuclear fission reaction using correct nuclide and nucleon symbols.
- c **Determine** the mass defect for the reaction, giving the answer in kilograms.
- d How much energy is released? Give your answer in joules.

8.4 Fission chain reactions

Uranium-235 can absorb a thermal (or slow) neutron that has about 5–10 keV of energy. The neutron is absorbed in the uranium nucleus and forms a composite, unstable nucleus that then splits into smaller fragments, each with lower atomic mass than the uranium-235. On average, between two and three neutrons are also released. The neutrons released from the fission of uranium-235 are 'fast' neutrons and do not usually get absorbed by uranium-235 nuclei unless they are slowed down by a moderator. This is a natural process that rarely amounts to anything substantial. However, if conditions are right, the process can be used to harness the energy of the mass defect, which is about 200 MeV per fission event.

A chain reaction occurs when more than one of the neutrons released from the initial fission event causes new events to occur. In **Figure 8.4.1**, each fission event produces two or three neutrons, some of which go on to cause new fission events. Under the right conditions, an uncontrolled fission chain reaction can create a runaway explosion.

Controlled fission is used in nuclear power stations. Thermal nuclear power stations use slow (thermal) neutrons to release energy. The purpose of a nuclear power reactor is to release nuclear energy at a controllable rate. The reactor does not generate electricity directly; rather, the heat generated produces steam that powers the turbines and generators of the electricity production plant.

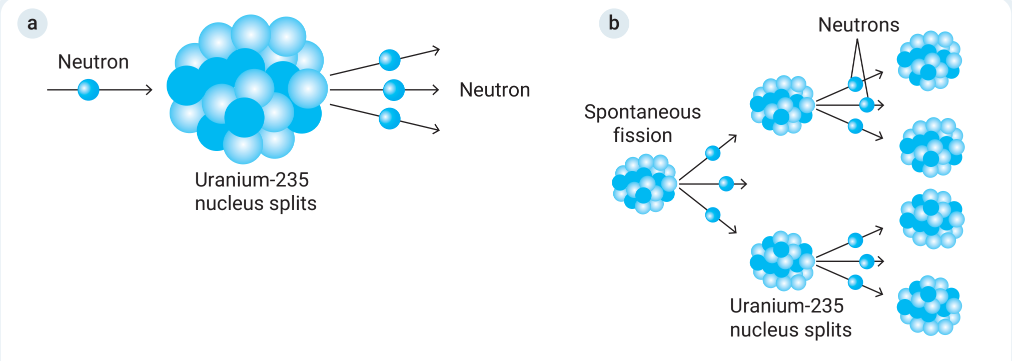


FIGURE 8.4.1 A nuclear fission chain reaction. (**a**) A slow neutron causes a uranium-235 nucleus to become unstable and split, releasing three fast neutrons in addition to energy. (**b**) A chain reaction occurs if, for example, two of the three released neutrons induce nuclear fissions in other uranium nuclei. Consequently, vast amounts of energy are released.

Controlled chain reaction

The chain reaction can be controlled for nuclear power generation. One neutron produces one fission neutron in a **controlled chain reaction**. If more than one neutron is produced on average, then a runaway reaction occurs. If the average number of neutrons produced is less than one, then the reaction dies away. It is quite difficult to establish and maintain a chain reaction, but this is achieved with the use of control rods to absorb excess neutrons. Control rods made of substances that readily absorb neutrons, such as cadmium or boron steel, are inserted into the reactor to reduce the number of neutrons produced by each reaction to one only. Such substances that readily absorb neutrons are often termed 'neutron poisons'.

controlled chain reaction
a chain of nuclear reactions that are controlled to limit the rate at which they occur. In steady state (reaction rate held constant), an average of one neutron from each reaction goes on to cause another reaction. This is the case for a nuclear power reactor running at constant power output

Enrichment

For fission to occur in uranium-235, the initial neutron must be a thermal neutron. The neutrons produced in fission events are 'fast' neutrons. The probability of these neutrons causing new fission events in uranium-235 is very small. It is more likely that they will be captured by uranium-238 or another neutron poison that was produced by an earlier fission event. These neutron poisons hold onto the neutrons and emit α, β or γ radiation.

In order to ensure sustained fission, the proportion of uranium-235 must be increased. This **enrichment** process is achieved by using centrifuges to remove uranium-238 from the mix of uranium isotopes in the ore. This increases, or enriches, the proportion of uranium-235 in the quantity. It is a complex and expensive process.

enrichment a process of separating out U-235 from a sample and adding it to another sample, increasing the proportion of U-235 in natural uranium

Moderator

In order to reduce the energy of the neutrons produced by fission events, a moderator is used. The **moderator** is a material that has nuclides with slightly larger masses than the neutron; for example, hydrogen $\left({}_{1}^{1}\text{H}\right)$, deuterium $\left({}_{1}^{2}\text{H}\right)$ and tritium $\left({}_{1}^{3}\text{H}\right)$. Neutrons share their energy with these nuclides through multiple collisions. The neutrons rapidly lose energy, which increases the probability of them entering a uranium-235 nucleus and causing fission.

moderator light atoms in a nuclear reactor that slow down fast neutrons to thermal speeds, in order to increase the likelihood of further fission events; often heavy water is used

Reactor vessel

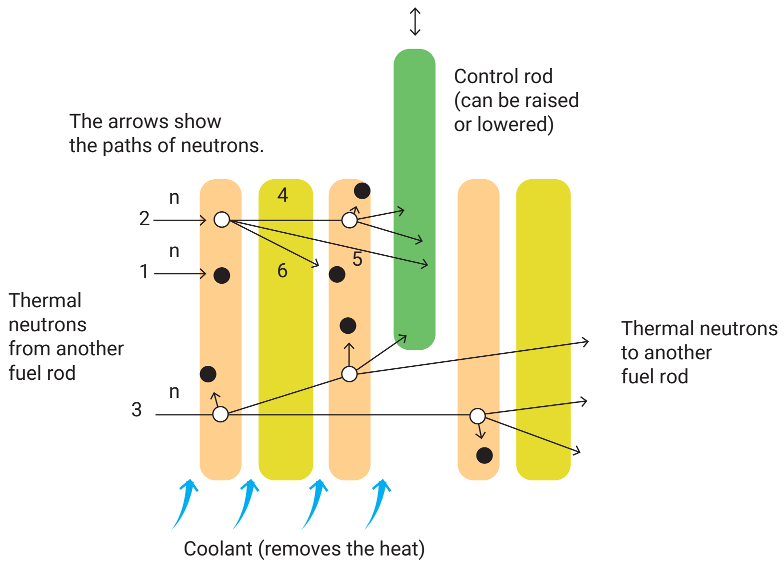
In a reactor, a controlled chain reaction will not proceed unless most of the neutrons available can be used. Apart from absorption in neutron poisons, some neutrons will escape from the fuel. This is because the absorption of a neutron and subsequent fission occurs only when there is a head-on collision between a nucleus and a neutron. Therefore, the reactor vessel is designed to have the right surface area-to-volume ratio so that the neutrons are reflected back into the sample.

Coolant

As a large amount of energy is produced in each fission reaction, and this is carried as kinetic energy by the particles of the fission products, the temperature of the reactor would increase unless a coolant was used. The coolant material is used to absorb and then transfer this heat so that it can be used for energy purposes outside of the reactor itself.

Control rods

On average, the number of neutrons produced by fission events must be equal to the number of fission-producing neutrons in order to sustain a nuclear reaction. Sometimes the reaction threatens to run away, so control rods containing neutron poisons, such as boron-10, are moved into the fuel to lower the number of neutrons in the sample. The control rods are removed when the chain reaction starts to produce too few neutrons.



Key

🟧 Fuel rod

🟨 Moderator, water or graphite (slows down the neutrons)

🟩 Control rod, boron steel or cadmium (absorbs the neutrons)

	Isotope	Natural	Enriched	Neutron capture →
○	^{235}U	0.7%	2.3%	fission
●	^{238}U	99.3%	97.7%	absorption

FIGURE 8.4.2 Controlling a chain reaction in a nuclear reactor. Some neutrons are numbered to explain the process. Neutron 1 is captured by a fuel rod, neutrons 2 and 3 cause nuclear fission, releasing more neutrons, neutron 4 causes further fission, neutron 5 is absorbed by a control rod and neutron 6 is absorbed by a fuel rod.

LEARNING CHECK 8.4

DESCRIBING

1 Construct a table to summarise the role of the moderator, control rods, reactor vessel and coolant components of a nuclear power reactor.

2 **Define** ‘slow (thermal) neutron’.

APPLYING

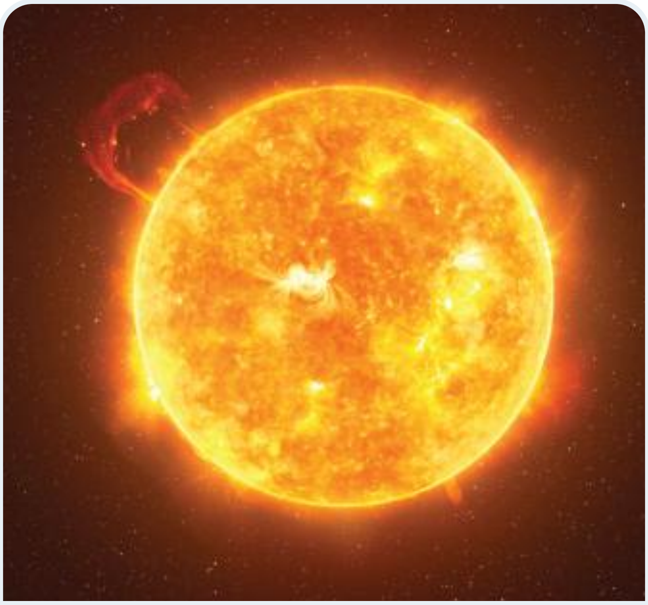
3 **Explain** how the control rods can be used to regulate the rate of reactions within a reactor.

4 **Explain** why a nuclear chain reaction can become explosive very quickly. Use a diagram and mathematical model to assist your explanation.

5 Identify three different criteria that may be used to consider the pros and cons of nuclear power generation in Australia.

8.5 Nuclear fusion

Initially, the energy production in stars was attributed to gravitational contraction, as proposed by early astronomers. However, advancements in nuclear physics revealed that the tremendous energy emitted by stars is actually the result of nuclear fusion reactions occurring in their cores (**Figure 8.5.1**). The fact that stars derive their energy from nuclear fusion fundamentally altered our understanding of stellar processes and the universe's energy dynamics.



Łukasz Szczepanski/Alamy Stock Photo

FIGURE 8.5.1 Solar flares emitted from the sun are a product of nuclear fusion.

Fusion is the joining together of two smaller nuclides to form a new nucleus with a greater atomic number. The new composite nucleus is more stable because its binding energy per nucleon is greater. This is more likely to occur for nuclides that have an atomic number $Z < 56$. Fusion is difficult to achieve because a lot of work is required to fuse nuclei; however, when they do fuse, a lot of additional energy is released. Nuclear fusion reactions occur within the core of the Sun, which fuses 620 million tonnes of hydrogen each second.

Some common nuclear fusion reactions can be expressed in equation form, as below. Note that the sums of the nucleon numbers (A) and atomic numbers (Z) on either side of the equation are equal. Further, each equation releases energy as a result of Einstein's mass–energy equivalence relationship.

Examples of nuclear fusion equations

The fusion of two hydrogen isotopes forms helium, with an excess neutron and the accompanying release of energy.

$$^{2}_{1}\text{H} + ^{2}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

$$^{2}_{1}\text{H} + ^{3}_{1}\text{H} \rightarrow ^{4}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

Weblink
Nuclear fusion animation

Worksheets
Nuclear fusion

Fusion power and the Sun's source of energy

LEARNING CHECK 8.5

DESCRIBING

1 **Define** 'nuclear fusion'.

2 What type of nuclear reaction occurs within the Sun – fusion or fission?

APPLYING

3 Complete the missing values in the nuclear fusion reaction:

$$^{\square}_{1}\text{H} + ^{2}_{\square}\text{H} \rightarrow ^{3}_{2}\text{He} + ^{1}_{0}\text{n} + \text{energy}$$

4 **Contrast** nuclear fusion with nuclear fission.

8.6 Nuclear safety

Nuclear fission for energy production occurs safely in 440 nuclear power reactors worldwide. Specialist scientific and engineering expertise is required to ensure safe operation of the reactor and manage the resultant radioactive waste. As substantial radioactive and fissile materials are stored at nuclear power reactors, sufficient security is also needed to deter potential threats.

Nuclear waste

Nuclear energy production by fission reactors produces radioactive waste. The disposal of radioactive waste is one of the major problems faced by the nuclear power industry. **Table 8.6.1** compares the waste produced by nuclear reactors and coal-fired power stations.

TABLE 8.6.1 Comparative waste produced by nuclear and coal-fired electrical power plants

Type of power	Capacity (MW)	Waste
Nuclear power station	1000	25 tonnes of radioactive material
Coal-fired power station	1000	Millions of tonnes of carbon dioxide and sulfur dioxide

The waste from a nuclear fission reactor has to be stockpiled, shielded and cooled for thousands of years until it would be safe, yet, when used correctly, nuclear power stations are more efficient and less polluting than coal-fired power stations.

Radioactive waste products are classified into three categories: high, intermediate and low level. High-level wastes are radioactive and continue to release significant amounts of energy during the decay process. This energy is in the form of radioactivity and heat, and systems must be in place to reduce harmful effects. **Table 8.6.2** shows a classification of radioactive waste.

TABLE 8.6.2 Classification of radioactive waste

Waste category	Description	Storage
High level	Used fuel rods, highly radioactive. Consists of transuranic isotopes and fission products, some with very long half-lives. No high-level radioactive waste is produced in Australia.	Must be stored in shielded containers to prevent radiation and cooled to stop overheating
Intermediate level	Other reactor components in the reactor core, such as fuel containers, gauges, pipes	Requires shielding, but not cooling
Low level	Used protective clothing; water from showers and water from cleaning protective gear	Must be contained and managed until it decays to background levels of radioactivity or below

LEARNING CHECK 8.6

DESCRIBING

1 **Identify** an example from each of the three nuclear waste categories: high level, intermediate level and low level.

2 **Describe** the mechanism for the storage of spent nuclear fuel.

8.7 Solving problems using Einstein's mass–energy equivalence relationship

Recall Einstein's mass–energy equivalence relationship, equating mass defect with energy via the formula $\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\ \mathrm{m\,s^{-1}}$. This relationship may be used to determine the energy released from both nuclear fission and nuclear fusion reactions.

In nuclear fission reactions, the total mass before fission is greater than the total mass after the fission event. The mass difference is the mass that has been converted into energy. This energy is transferred via the fission products. The large daughter nuclei carry most of this energy as kinetic energy. The released neutrons also have kinetic energy. For example, when uranium-235 undergoes fission to produce krypton-92 and barium-141, three neutrons are released:

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \xrightarrow[\text{yields}]{} {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n}$$

There are 236 nucleons before and after this fission event, yet the mass of the products is less than the sum of the mass of the original neutron and uranium-235 nuclide. This difference is the mass defect.

WORKED EXAMPLE 8.7.1

Calculate the mass defect and the energy released in the nuclear fission reaction:

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{92}_{36}\mathrm{Kr} + {}^{141}_{56}\mathrm{Ba} + 3\,{}^{1}_{0}\mathrm{n} + \text{energy}$$

Use the following mass values:

Unified atomic mass unit, u = 1.66×10^{-27} kg

Rest mass of neutron, m_n = 1.008 66 u or $1.674\,38 \times 10^{-27}$ kg

Rest mass U-235 = 235.1727 u or 3.9039×10^{-25} kg

Rest mass Kr-92 = 91.9262 u or 1.5260×10^{-25} kg

Rest mass Ba-141 = 140.9144 u or 2.3392×10^{-25} kg

ANSWER

1 **Determine the combined mass of the reactants.**

Mass of combined reactants:

mass U-235	3.9039×10^{-25} kg
+ mass of neutron	$1.674\,38 \times 10^{-27}$ kg
	$= 3.920\,64 \times 10^{-25}$ kg

2 Subtract the combined mass of the products.

Mass of combined products:

mass Kr-92 $1.5260 \times 10^{-25}\,\text{kg}$
mass of Ba-141 $2.3392 \times 10^{-25}\,\text{kg}$
$+\,3 \times$ mass of neutron $5.02314 \times 10^{-27}\,\text{kg}$
$= 3.91543 \times 10^{-25}\,\text{kg}$

Mass defect, $\Delta m = 3.92064 \times 10^{-25}\,\text{kg} - 3.91543 \times 10^{-25}\,\text{kg}$
$= 0.00521 \times 10^{-25}\,\text{kg}$
$= 0.31386\,\text{u}$

3 Use Einstein's mass–energy equation.

$\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\,\text{m}\,\text{s}^{-1}$.

4 Substitute known values to calculate energy.

$E = \Delta mc^2 = 0.00521 \times 10^{-25}\,\text{kg} \times (3.00 \times 10^8\,\text{m}\,\text{s}^{-1})^2$
$= 4.6890 \times 10^{-11}\,\text{J}$
$= 293.06\,\text{MeV}$ (where $1\,\text{eV} = 1.60 \times 10^{-19}\,\text{J}$, hence $1\,\text{MeV} = 1.60 \times 10^{-13}\,\text{J}$)

As in nuclear fission reactions, in nuclear fusion reactions the total mass before fusion is greater than the total mass after the fusion event. The mass difference has again been converted into energy. Although it takes a lot of work to force the nuclei together, a lot of energy is released when they do fuse. For example, when two isotopes of hydrogen fuse to form helium, energy is released:

$$^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$$

There are five nucleons before and after this fusion event, yet the mass of the products is less than the mass of the original hydrogen isotopes. This difference is the mass defect.

WORKED EXAMPLE 8.7.2

Calculate the mass defect and the energy released in the nuclear fusion reaction:

$$^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$$

Use the following mass values:

Unified atomic mass unit, $\text{u} = 1.66 \times 10^{-27}\,\text{kg}$
Rest mass of neutron, $m_n = 1.00866\,\text{u}$ or $1.67438 \times 10^{-27}\,\text{kg}$
Rest mass H-2 $= 2.01355\,\text{u}$ or $3.34249 \times 10^{-27}\,\text{kg}$
Rest mass He-3 $= 3.01603\,\text{u}$ or $5.00661 \times 10^{-27}\,\text{kg}$

ANSWER

1 Determine the combined mass of the reactants.

Mass of combined reactants:

mass H-2 $3.34249 \times 10^{-27}\,\text{kg}$
$+$ mass H-2 $3.34249 \times 10^{-27}\,\text{kg}$
$= 6.68500 \times 10^{-27}\,\text{kg}$

2 Subtract the combined mass of the products.

Mass of combined products:

mass He-3 $5.00661 \times 10^{-27}\,\text{kg}$
$+$ mass neutron $1.67438 \times 10^{-27}\,\text{kg}$
$= 6.68099 \times 10^{-27}\,\text{kg}$

Mass defect:

$\Delta m = 6.68500 \times 10^{-27}\,\text{kg} - 6.68099 \times 10^{-27}\,\text{kg}$
$= 0.00401 \times 10^{-27}\,\text{kg}$
$= 0.00242\,\text{u}$

3 **Use Einstein's mass–energy equation.**

$\Delta E = \Delta mc^2$, where c = the speed of light, $3.00 \times 10^8\,\text{m s}^{-1}$.

4 **Substitute the known values to calculate energy.**

$$E = \Delta mc^2 = 0.00401 \times 10^{-27}\,\text{kg} \times (3.00 \times 10^8\,\text{m s}^{-1})^2$$
$$= 3.6090 \times 10^{-13}\,\text{J}$$
$$= 2.2556\,\text{MeV (where } 1\,\text{eV} = 1.60 \times 10^{-19}\,\text{J, hence } 1\,\text{MeV} = 1.60 \times 10^{-13}\,\text{J)}$$

Nuclear fusion versus nuclear fission

Weblink
What is the difference between nuclear fission and fusion?

Fusion reactions release much more energy than fission reactions per kilogram of reactant. We have seen that fusion is favoured for elements up to Fe-56. For lighter elements, the curve of the binding energy per nucleon graph (**Figure 8.1.2**) is quite steep, which means that any fusion reaction will release a relatively large amount of energy when the new nuclide is formed.

For example, Figure 8.1.2 shows that, for tritium, $^{3}_{1}\text{H}$, an isotope of hydrogen, the binding energy per nucleon is approximately 2.9 MeV. This is higher than the binding energy per nucleon for the proton (0 MeV) and deuterium (1.1 MeV). Fusion of a proton with deuterium to produce tritium releases about 1.8 MeV of energy per nucleon. This amounts to the release of approximately 62% of the original binding energy per nucleon.

At the other end of the graph, where fission is favoured over fusion for elements heavier than Fe-56, energy is also released, but comparatively less. The binding energy per nucleon of uranium-235 is approximately 7.6 MeV. For the two most common fission fragments, the binding energy per nucleon is about 8.6 MeV. Taking account of both fission fragments, the difference is approximately 2.0 MeV. For fission, the release of energy per nucleon is about 26% of the original binding energy per nucleon.

Therefore, fusion reactions release a greater proportion of the mass–energy available than do fission reactions.

LEARNING CHECK 8.7

DESCRIBING

1 State the speed of light in a vacuum.

2 **Recall** Einstein's mass–energy equivalence relationship. Define each term in the equation.

APPLYING

3 Use the graph of binding energy per nucleon to **determine** the average binding energy of:

- a iron
- b bromine
- c oxygen
- d uranium
- e helium.

4 **Explain** what mass defect is and how it relates to the energy released in a nuclear reaction.

5 **Calculate** the mass defect and energy released in the following nuclear fission reaction:

$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{90}_{38}\text{Sr} + {}^{143}_{54}\text{Xe} + 3\,{}^{1}_{0}\text{n} + \text{energy}$$

Use the following mass values:

unified atomic mass unit, u = 1.66 × 10^{-27} kg
rest mass of neutron, m_n = 1.008 66 u or 1.674 38 × 10^{-27} kg
rest mass U-235 = 235.1727 u or 3.9039 × 10^{-25} kg
rest mass Sr-90 = 87.6200 u or 1.4545 × 10^{-25} kg
rest mass Xe-143 = 142.9351 u or 2.3727 × 10^{-25} kg

6 **Calculate** the mass defect and energy released in the following nuclear fission reaction:

$${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{144}_{55}\text{Cs} + {}^{90}_{37}\text{Rb} + 2\,{}^{1}_{0}\text{n} + \text{energy}$$

Use the following mass values:

unified atomic mass unit, u = 1.66 × 10^{-27} kg
rest mass U-235 = 235.1727 u or 3.9039 × 10^{-25} kg
rest mass Cs-144 = 143.9321 u or 2.3893 × 10^{-25} kg
rest mass Rb-90 = 89.9148 u or 1.4926 × 10^{-25} kg

7 **Calculate** the mass defect and the energy released in the following nuclear fusion reaction:

$${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + {}^{1}_{1}\text{H} + \text{energy}$$

Use the following mass values:

unified atomic mass unit, u = 1.66 × 10^{-27} kg
rest mass H-1 = 1.007 83 u or 1.673 00 × 10^{-27} kg
rest mass H-2 = 2.013 55 u or 3.342 49 × 10^{-27} kg
rest mass H-3 = 3.016 05 u or 5.006 64 × 10^{-27} kg

8 **Calculate** the mass defect and the energy released in the following nuclear fusion reaction:

$${}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$$

Use the following mass values:

unified atomic mass unit, u = 1.66 × 10^{-27} kg
rest mass of neutron, m_n = 1.008 66 u or 1.674 38 × 10^{-27} kg
rest mass H-2 = 2.013 55 u or 3.342 49 × 10^{-27} kg
rest mass H-3 = 3.016 05 u or 5.006 64 × 10^{-27} kg
rest mass He-4 = 4.026 43 u or 6.683 87 × 10^{-27} kg

CHAPTER SUMMARY

Nuclear forces

- There are four fundamental forces holding the nucleus together.

	Gravitational force	Weak nuclear force	Electromagnetic force	Strong nuclear force
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Infinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

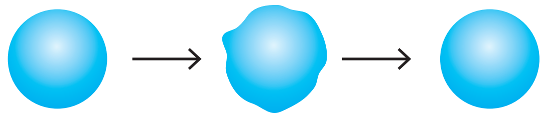
- The electron-volt (eV) is the amount of energy that an electron gains when it moves through 1 volt.
- The mass defect is the energy required, in joules, to bind all parts of a nucleus together. This is expressed as:
  $\Delta E = mc^2$

Transmutations

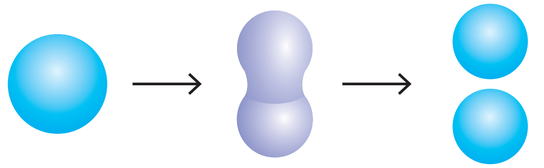
- Transmutation is the process of changing an element from one type to another.
- Natural transmutation occurs through radioactive decay.
- Elements can be made by bombarding a nucleus with a neutron or small alpha particles. This is called artificial transmutation, e.g.:
  ${}^{14}_{7}\mathrm{N} + {}^{4}_{2}\mathrm{He}^{2+} \rightarrow {}^{18}_{9}\mathrm{F}$

Nuclear fission

- Nuclear fission occurs when a nucleus splits into two or more fragments, typically $Z > 56$.
- During this process, neutrons and energy are released.

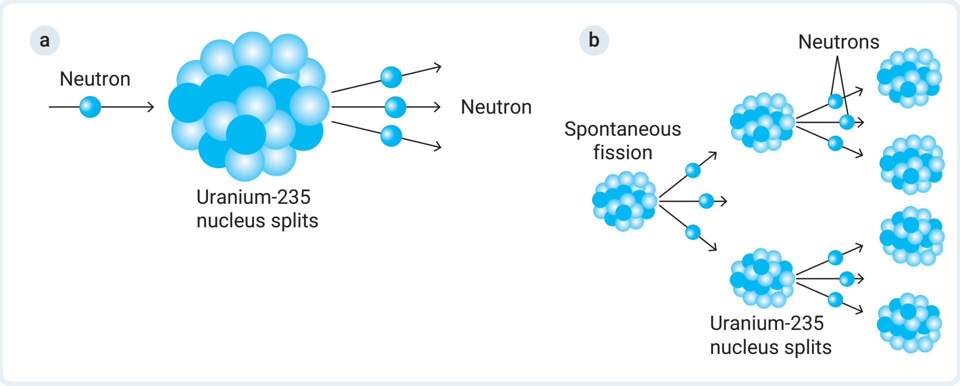


After a slight distortion, the drop returns to a spherical shape.



A large distortion may cause the drop to split in two.

- A chain reaction can occur if more than one of the neutrons released causes new events to occur.



Nuclear fusion

- Nuclear fusion occurs when two smaller nuclides join to form a new nucleus, typically $Z > 56$.
- The new nucleus is more stable.

$${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{H} + {}^{1}_{0}\text{n} + \text{energy}$$

- Fusion reactions release a greater proportion of the mass–energy available than fission reactions.

CHAPTER EXAM

MULTIPLE CHOICE

1. In a nuclear fission reaction, the nucleus:

A splits in half.
B absorbs energy.
C explodes uncontrollably.
D splits into two or more fission fragments.

2. In a thermal nuclear fission reactor, 2 kg of mass is converted into energy. Assuming 100% efficiency, determine the amount of energy generated.

A 6.0×10^{1} J
B 9.0×10^{11} J
C 1.8×10^{17} J
D 3.6×10^{17} J

3. For the equation for the nuclear fusion reaction below, determine the values of x and y.

$$^{2}_{1}\text{H} + {}^{x}_{1}\text{H} \rightarrow {}^{3}_{1}\text{H} + {}^{1}_{y}\text{H} + \text{energy}$$

A $x = 1, y = 1$
B $x = 1, y = 2$
C $x = 2, y = 2$
D $x = 2, y = 1$

4. Determine the equivalent energy value of 1.50×10^{-28} kg, in joules and megaelectron-volts, MeV.

A 4.50×10^{-20} J, 2.813×10^{-7} MeV
B 2.023×10^{-13} J, 1.265 MeV
C 1.35×10^{-11} J, 84.375 MeV
D 1.35×10^{-11} J, 8.4375×10^{7} MeV

5. The energy that heats the Sun has its origins in:

A radioactivity.
B nuclear fission.
C the production of helium from hydrogen.
D the production of hydrogen from helium.

6. An electron-volt (eV) is:

A a unit of electric potential.
B the number of volts in one electron.
C a large unit of energy used in nuclear physics.
D the energy required to move an electron through a potential difference of 1 V.

7. The number of electron-volts in 3×10^{-4} J is:

A 5.4×10^{-165} eV.
B 1.602×10^{-19} eV.
C 1.87×10^{-15} eV.
D 3×10^{-4} eV.

8. The number of MeV in 1×10^{-10} J is:

A 1.6×10^{-35} MeV.
B 6.24×10^{2} MeV.
C 6.24×10^{8} MeV.
D 6.24×10^{14} MeV.

9. The number of joules in 5×10^5 MeV is:

A 8.01×10^{-8} J.

B 8.01×10^{-14} J.

C 3×10^{24} J.

D 3×10^{30} J.

10. The sum of the masses of 10 protons and 10 neutrons is 0.172 u more than the mass of a Ne-20 nucleus. The binding energy per nucleon in this nucleus is:

A 8.6×10^{-3} eV.

B 8.0 MeV.

C 16.0 MeV.

D 7.7×10^{14} eV.

SHORT RESPONSE

11. A slow neutron of mass 1.0086 u causes fission of U-235 (235.044 u). The fission fragments and their masses, in unified atomic mass units, are I-131 (130.906 u) and Y-103 (102.945 u).

a How many neutrons are released in this fission event?

b **Calculate** the mass defect of this event in unified atomic mass units and in kilograms.

c How much energy is released? Give your answer in joules.

12. The binding energy of ${}^{42}_{20}\text{Ca}$ is 361.7 MeV. **Determine** its atomic mass.

13. When ${}^{235}_{92}\text{U}$ undergoes fission, about 0.1% of the original mass is released as energy.

a **Calculate** the amount of energy released by an atomic bomb that contains 10 kg of uranium-235.

b When 1 tonne of TNT is exploded, about 4×10^9 J of energy is released. **Determine** how many tonnes of TNT are equivalent to the destructive power of the atomic bomb from part **a**.

14. **Determine** whether xenon-140 is more likely to undergo fission or fusion. Justify your answer.

CROSS-CHAPTER QUESTION

15. Water is used as a coolant in nuclear reactors to maintain a safe temperature of the radioactive rods. During this process, the water is heated an additional 40°C. **Calculate** the mass of water needed per gram of uranium undergoing fission for the reaction:

$${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{92}_{36}\text{Kr} + {}^{141}_{56}\text{Ba} + 3\,{}^{1}_{0}\text{n}$$

Mass of uranium-235: 235.043 9299 u

Mass of krypton-92: 91.926 173 u

Mass of barium-141: 140.914 403 u

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Explore advances in medical treatment and imaging that have come from a deepening understanding of the properties of nuclear radiation.

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Nuclear medicine imaging: a window into the body

Advances in medical treatment and imaging have emerged from our growing understanding of nuclear radiation properties, and these breakthroughs have revolutionised health care, enabling precise diagnostics and targeted therapies.

Radioisotopes and their role

Radioisotopes, variants of chemical elements with different numbers of neutrons, play a pivotal role in nuclear medicine. These isotopes emit radiation, allowing us to visualise biological processes within the body through a range of applications.

- Diagnostic imaging: Technetium-99m is used in single-photon emission computed tomography (SPECT) and fluorine-18 is used in positron emission tomography (PET). These techniques provide detailed images of organs, tissues and metabolic activity. For example, PET scans using fluorine-18 can detect cancer, brain disorders and cardiovascular diseases.
- Thyroid imaging: Iodine-123 is commonly employed to diagnose thyroid disorders. It helps visualise thyroid function and identify abnormalities such as hyperthyroidism or thyroid cancer.
- Bone scans: Technetium-99m-labelled compounds accumulate in bone tissue, aiding in the detection of fractures, infections and bone tumours.

Therapeutic applications

Beyond imaging, nuclear radiation also has therapeutic benefits.

- Radioactive iodine therapy: In cases of thyroid cancer, patients typically have their thyroid removed and then receive radioactive iodine (iodine-131) to destroy any remaining thyroid tissue. I-131 does not distinguish between cancerous and healthy thyroid cells.
- Radiopharmaceutical therapy: This approach uses pharmaceuticals containing radioisotopes to treat cancer. For example, lutetium-177 is used for neuroendocrine tumours and samarium-153 is used to treat the pain of bone cancer.
- Brachytherapy: Radioactive seeds or sources are implanted directly into tumours. Prostate cancer patients benefit from permanent seed implants (iodine-125 or palladium-103), while temporary brachytherapy treats cervical and breast cancers.

Precision and safety

Advancements in understanding nuclear medicine have led to increased precision and safety.

- Theranostics: A pair of chemically similar radioactive agents, one to deliver therapy to treat metastatic prostate cancer and the other chemically similar agent to identify or diagnose the prostate cancer.
- 3D gamma-ray vision: Recent developments allow us to visualise nuclear radiation in three dimensions. By fusing scene data with radiation data, we can detect and map radioactive materials. This technology aids emergency responses and enhances public communication about radiation.
- Time-of-flight PET: Time-of-flight PET scanners improve image resolution, enabling early cancer detection and accurate staging.
- Radiomics: Analysing large data sets from medical images helps predict treatment outcomes and personalise therapies.

ANSTO

FIGURE 1 Lutetium-177 at ANSTO's OPAL multipurpose reactor

Challenges and future directions

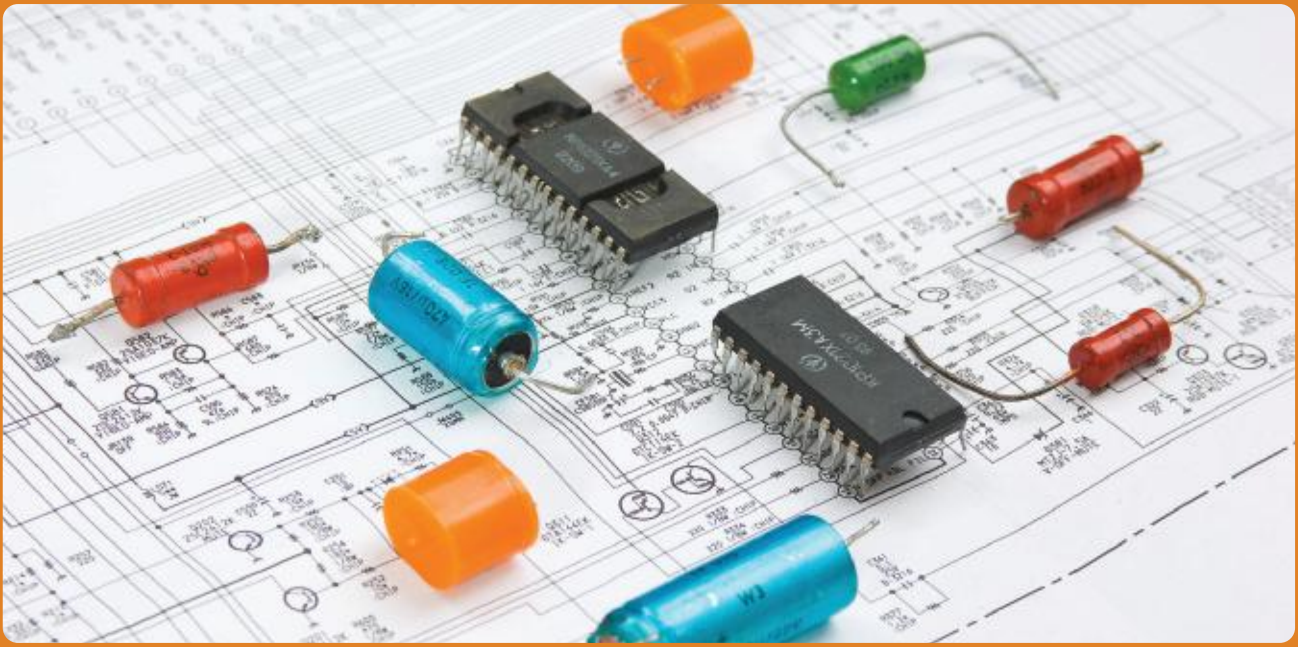
While nuclear medicine continues to evolve, challenges remain.

- Supply chain: Ensuring a stable supply of radioisotopes is critical. Research reactors produce most medical isotopes, but efforts are ongoing to diversify production methods.
- Safety and regulations: Rigorous safety protocols are essential to protect patients, healthcare workers and the environment.
- Short half-lives: Nuclear medicines must have short half-lives to minimise radiation doses to patients. This means the manufacture, packaging and delivery of nuclear medicines to hospitals must happen on time before the radioactivity of the medicine decays.
- Reactor efficiency and reliability: ANSTO's OPAL reactor is one of only a handful of reactors around the world that manufactures technetium-99m for diagnostic scans. OPAL is a very reliable reactor, ensuring the supply of technetium-99m when patients need it.
- Safety and regulations: Producing and transporting nuclear medicine requires expert skills, scientific knowledge and safety, making nuclear medicine production an expensive industry.

Behind every radiation application lies rigorous science, safety and a commitment to enhanced health outcomes for society.

CHAPTER 9

Current, potential difference and energy flow



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SYLLABUS DOT POINTS

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 $P = \frac{W}{t}$.

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Introduction

Electricity is a convenient form of energy that is available from both renewable and non-renewable sources. Electricity can be transmitted over great distances and is used domestically, commercially and industrially. Electrical energy can be transformed into other types of energy such as heat, sound, light and mechanical energy.

In this chapter, the laws of conservation of charge and of energy are explained and applied to electrical circuits, and steps to solve and analyse circuits are detailed.

Practical

- Investigating electrostatic charge

Worksheets

- Electricity warm-up
- Power, current and energy

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ An electric current is the flow of electric charge in a circuit.
- ✓ The atom consists of protons, neutrons and electrons in an organised structure.
- ✓ Electric circuits allow for the flow of electric current.
- ✓ Electrons are negatively charged particles that carry electric charge.
- ✓ Materials that allow current to flow are conductors, whereas those that prevent the flow of current are insulators.
- ✓ The potential difference across a circuit is measured in volts, whereas the electric current flowing through a circuit is measured in amperes.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe electric charge as negative or positive
- ✓ describe how electric charge is quantified
- ✓ recall common positive and negative charge carriers
- ✓ describe and explain static charge, its causes and effects
- ✓ describe the laws of repulsion and attraction of electric charge
- ✓ describe the law of conservation of electric charge
- ✓ define 'electric conductors' and 'electric insulators'
- ✓ define 'electric current'
- ✓ explain that electric charge is conserved at all points in an electric circuit
- ✓ apply Kirchhoff's current law to quantify currents at points in a circuit
- ✓ describe the concepts of electric potential difference, current and power in a circuit
- ✓ solve problems involving electric potential difference, charge, power and current in a circuit
- ✓ compare conventional current and electron flow
- ✓ describe direct current and alternating current
- ✓ explain how electric charge separation produces an electrical potential difference
- ✓ calculate energy consumption in kilowatt hours
- ✓ apply Kirchhoff's voltage law to analyse circuits
- ✓ contrast parallel and series circuits
- ✓ recall how humanity's understanding of electrical phenomena has developed over history
- ✓ discuss the impact of high consumption of electrical energy on infrastructure resilience and sustainability.

9.1 Positive and negative charge carriers

Electricity is a very convenient form of energy. It is available from many sources, such as batteries, alternators and solar panels. It can be generated by power stations that use coal, water (hydroelectricity), natural gas, wind or nuclear fuel. Electrical power is transmitted over large distances for domestic, commercial and industrial use.

Electrical energy is easily transformed into other types of energy, such as:

- radiant heat energy in toasters, ovens and heaters
- radiant sound energy in speakers and headphones

- radiant light energy in incandescent, fluorescent and LED lights
- mechanical kinetic energy in refrigerator motors, electric drills and hair dryers.

Energy can also be used in other appliances to operate logic circuits in alarms, computers, robots and controlling devices.

Energy can be transferred from place to place. It can be transformed from one form to another. Energy in an isolated system is conserved. These important concepts will be developed further in this chapter.

Positive and negative charges

The kinetic particle model of matter involves understanding the nuclear model of the atom. For the Rutherford–Bohr model of an atom, a very small central nucleus is surrounded by **electrons**, arranged in different energy levels. The positively charged nucleus consists of both positively charged **protons** and neutral, uncharged **neutrons** (collectively called nucleons). Almost all of the mass of the atom is found within the nucleus. Electrons, which are negatively charged and make up a very small proportion of the mass, circulate in the region of space around the nucleus in discrete energy level shells (Figure 9.1.1).

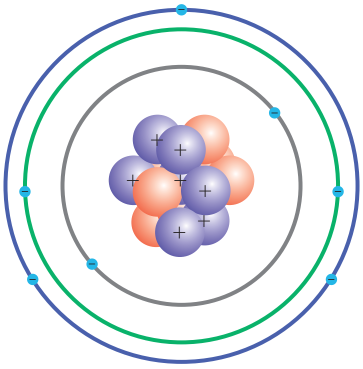


FIGURE 9.1.1 The Rutherford–Bohr model of the atom. Protons and neutrons are located within the nucleus of the atom, while electrons are located in discrete energy level shells outside the nucleus.

electron a negatively charged subatomic particle with mass 9.11×10^{-31} kg

proton a positively charged subatomic particle within the nucleus of an atom

neutron a neutrally charged subatomic particle within the nucleus of an atom; mass of a neutron is approximately the same as that of a proton

TABLE 9.1.1 Relative mass and charge of subatomic particles

	Proton	Neutron	Electron
Relative mass	1	1	1/10 000
Charge	+1	Neutral	–1

Metals such as copper and gold are good conductors of heat and of electricity. The arrangement of atoms within a metal is in the form of a **metallic lattice** (Figure 9.1.2). The lattice structure allows electrons that are delocalised to move freely throughout the metal. As a result, metals allow the conduction of electricity.

metallic lattice a regular arrangement of large numbers of metal atoms that allows free electrons to move readily

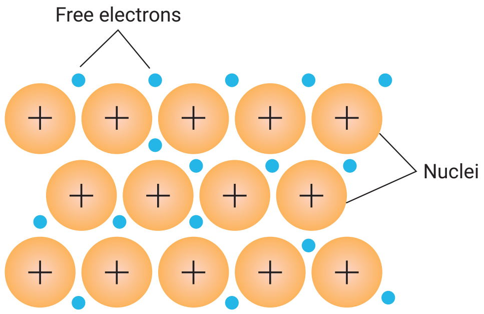


FIGURE 9.1.2 The lattice structure of metals allows delocalised electrons to flow freely throughout the metal; hence, metals conduct electricity.

Charge carriers

static electricity charges at rest, or stationary; typically produced on insulators by friction between two surfaces

Static electricity is the build-up of electric charge on an object. There are many familiar examples of the effects of electrostatic charge: a plastic comb run through hair or a plastic ruler rubbed on woollen material attracts small pieces of tissue paper; sometimes a crackling noise can be heard and flashes of light observed when a person takes off a polyester or nylon top in the dark; when a balloon is rubbed near hair and then held a few centimetres away, this causes the hair to stick to the balloon.

All objects are made of atoms and, consequently, all objects are made of positively charged protons, negatively charged electrons and neutrons with no charge. The overall sum of charges on a neutral object is zero – there is the same number of positive and negative charges. A positively charged object has more positive charges than negative charges. A negatively charged object has more negative charges than positive charges. When an object becomes charged, it is due to the transfer of negatively charged electrons either to the object, making it negatively charged, or away from the object, making it positively charged.

Electric charge can be positive or negative

potential energy energy that is stored in a system because of the configuration and interaction of the bodies within the system

Charge is an intrinsic property of an object. Charge cannot be created or destroyed, but it can move from one object to another. In everyday language, charge is used to mean a form of energy. We say we ‘charge’ our phone, but this is not scientifically accurate. When you charge your phone, you are providing energy to the battery in order to separate charge. The battery separates the charge using chemical reactions. This separated charge is stored as electrical **potential energy** until it is needed. The charge itself is not energy, but the charged object can be given energy or it can store energy.

If two charged objects of the same net charge (both positively charged or both negatively charged) come near each other, they push away from each other; that is, like charges repel. If two charged objects have the opposite net charge (one positively charged, one negatively charged), they come towards each other; that is, opposite charges attract. Charges are known to exist due to this electrostatic force, which is experienced as attraction or repulsion.

Like charges repel, opposite charges attract

A neutral object has the same number of positive charges as negative charges. Neutral objects do not attract or repel other neutral objects. The amount of charge on an object depends on the difference between the number of protons and the number of electrons.

For example, if two balloons are blown up and held near each other, they do not repel or attract each other; they stay still. The balloons are both neutral because they have the same number of protons and electrons. Because they are both neutral, there is no attraction or repulsion **(Figure 9.1.3a)**.

Weblink
Balloons and static electricity

If one of the balloons is rubbed on a person’s hair, electrons move from the hair onto the balloon. The balloon now has more electrons than protons, which means it has an overall negative charge. The person’s hair has lost some of its negative charge, so its overall charge is positive. The positive charge on the hair is attracted to the negative charge on the balloon **(Figure 9.1.3b)**.

If both the balloons are rubbed on a person’s hair, the balloons are both negatively charged; they have more electrons than protons. As like charges repel, the balloons move away from each other **(Figure 9.1.3c)**.

If one of the balloons is recharged on a person’s hair and then held near a neutral scrap of paper, the negatively charged balloon attracts the neutral paper. A charged object attracts neutral objects because the charges in the neutral object rearrange themselves. This rearrangement means that the local area nearest the charged object attracts the charged object to the neutral object **(Figure 9.1.3d)**.

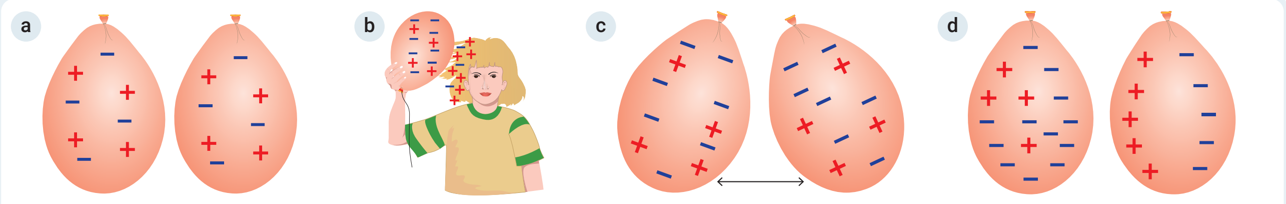


FIGURE 9.1.3 (**a**) Two neutral balloons do not attract or repel. (**b**) Electrons move from your hair to the balloon. There are more electrons than protons, so the balloon has an overall negative charge. (**c**) Both balloons have an overall negative charge, which causes them to repel each other. (**d**) The large negative charge on the balloon causes a local rearrangement of charges on a neutral balloon. The neutral balloon is attracted to the negatively charged balloon.

PRACTICAL ACTIVITY 9.1.1

INVESTIGATING ELECTROSTATIC CHARGE

Research question

How do different materials interact when electrostatically charged?

Aim

To investigate the electrostatic effect of positive and negative charges on a range of objects

Materials

- plastic straws
- paper serviettes
- glass or Perspex rods
- wool or fur (for charging the rods)
- cotton thread
- retort stand
- latex balloon

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
There is a minimal risk of a very small electric shock.	As the magnitudes of the charges are quite small, similar to the size that you might get from discharging a car door, no risk management is required.

Procedure

1. Rub a straw with a paper serviette to charge the objects and place the serviette against different vertical surfaces. Note how the serviette behaves. (Does it behave differently on metal and non-metal surfaces?)
2. Rub a second straw with a serviette to charge it. Bring the two charged straws near each other. Note how the straws behave.
3. Attach a straw to a length of cotton thread (15 cm). Suspend the straw by the thread from a retort stand. Charge both the straw and the glass or Perspex rod on the wool or fur. Hold the charged rod near the suspended straw. Note how the suspended straw behaves.
4. Blow up the balloon and tie it off. Turn on a tap to a very fine but consistent flow. Charge the balloon by rubbing it against the wool or fur. Bring the balloon close to, but not touching, the flow of water. Note how the water behaves.
5. Tear up another serviette into a large number of very small pieces and place them on a desk. Charge the glass or Perspex rod on the wool or fur. Hold the charged rod near the very small pieces of paper. Note how the pieces of paper behave.

Analysis of results

1. Describe your findings for each experiment. Use the terms ‘attract’ and ‘repel’ where possible.

Interpretation

2. Compare your findings to those of others in your class.
3. What conclusions can you draw?

Measuring charge

If an object has the same number of negative electrons as it does positive protons, then it will be neutral. If an object has more negative electrons than positive protons, it will have an overall negative charge. If an object has more positive protons than negative electrons, it will have an overall positive charge.

The quantity of charge is represented by the symbol q. Charge (q) is measured in coulombs, C. Given one electron has a charge of -1.60×10^{-19} C, we can determine the number of electrons in one coulomb of charge by:

Let e equal the number of electrons:

$$\begin{aligned} 1\text{ C} &= e \times 1.60 \times 10^{-19} \\ e &= \frac{1}{1.60 \times 10^{-19}} \\ &= 6.25 \times 10^{18} \end{aligned}$$

Therefore, one coulomb of charge requires 6.25×10^{18} electrons or protons.

If one electron has a charge of -1.60×10^{-19} C, then is it possible for an object to have a charge of 0.8×10^{-19} C? As you cannot have a fraction of an electron, it is impossible to have a charge of 0.8×10^{-19} C. Any amount of charge has to be a multiple of 1.60×10^{-19} C. This discrete unit of charge, $q = 1.60 \times 10^{-19}$ C, was discovered by Robert Millikan (1868–1953) in his famous oil drop experiment of 1910.

insulator a material that inhibits the flow of electrons (e.g. rubber)

conductor a material that allows the flow of electrons (e.g. metals)

Charges on conductors and insulators

If electrons are added to an object, the electrons repel each other and, under the right conditions, can spread out. If that object is an **insulator**, the electrons cannot spread out on that surface and the charge remains 'static', in one place. If the object is a **conductor**, the electrons can spread out on the surface and produce an even distribution of charge.

If electrons are removed from a conductor, then there are more positive charges in one area (it is termed locally positive). Because the protons are bound within the nucleus of atoms, they cannot move; however, they attract the electrons that can move from nearby atoms. As a result, the electrons distribute themselves evenly among the positive charges (**Figure 9.1.4**).

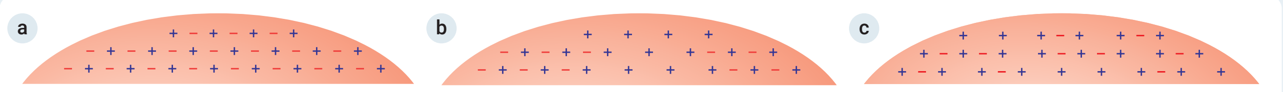


FIGURE 9.1.4 (**a**) A conductor has an even spread of electrons and protons with no net charge. (**b**) Some electrons are removed from the surface of the conductor. There is an excess of protons in one spot. (**c**) The electrons are free to move and are attracted to the positive area. They spread out over the surface to distribute the charge evenly. There is an overall positive charge.

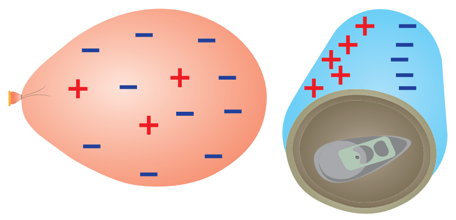


FIGURE 9.1.5 The charges in the soft-drink can rearrange themselves because of the negative charge of the balloon.

If an empty soft-drink can is laid on its side on a desk and a negatively charged balloon is held near the can, the electrons in the metal are repelled and move to the other side of the can. This means that the side of the can closest to the balloon has a positive charge and is attracted to the balloon (**Figure 9.1.5**). Although the can is neutral overall, the side closest to the balloon is locally positive; hence, there is a larger electrostatic attraction.

LEARNING CHECK 9.1

DESCRIBING

1 **Describe** and **explain:**
  - **a** static electricity
  - **b** potential energy
  - **c** insulator
  - **d** conductor.

2 Which of the following amounts of charge is possible? You may select more than one answer.
  - **A** 1.20×10^{-19} C
  - **B** 2.40×10^{-19} C
  - **C** 4.00×10^{-19} C
  - **D** 4.80×10^{-19} C

UNDERSTANDING

3 State the charges on a proton, a neutron and an electron.

4 Draw a table to **compare** the relative mass and the position of the elementary particles (proton, neutron, electron).

APPLYING

5 A positively charged conductor is moved towards a neutral conductor.
  - **a** Use a diagram to show what occurs to the charges on the neutral conductor.
  - **b** **Explain** whether the neutral conductor will be attracted, repelled or neither.
  - **c** Use a diagram to show what happens if the positively charged conductor touches the neutral conductor.

9.2 Conservation of charge

Law of conservation of charge

Like energy, charge is also conserved within an isolated system. The net charge in a system can only be increased by adding charges from outside of the system or decreased by removing charges from the system. This phenomenon is called the **law of conservation of charge**.

This law is applicable to the flow of charge over time; that is, current, as described by Kirchhoff's current law.

law of conservation of charge the net charge within an isolated system is constant

Kirchhoff's current law

There are basic rules that apply to the analysis of electrical circuits that will assist in determining unknown values. Kirchhoff's first law expresses the conservation of electric charge. It is also referred to as **Kirchhoff's current law**.

Kirchhoff's current law (first law) in an electrical circuit, the total current arriving at a junction is equal to the total current leaving the junction

Let us look at the current as it travels around the parallel circuit shown in Figure 9.2.1. The current travels from the positive terminal towards the first junction. Some of the current then travels towards point B, while the rest of the current travels towards point C. At the second junction, all of the current comes back to the one path and passes through point D. At each junction, the total current entering the junction is equal to that exiting the junction.

Charge is conserved. The total number of charges entering a junction is the same as the number of charges leaving the junction. This means that the sum of all of the currents going into a junction is the same as the sum of all the currents out of that junction (**Figure 9.2.2**).

Total current into a junction = total current out of the junction

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}} \text{ or } I_{\text{t}} = I_1 + I_2 + \ldots I_n$$

where: I = current (A)

KEY FORMULA

Total current into a junction = total current out of the junction

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}} \text{ or } I_{\text{t}} = I_1 + I_2 + \ldots I_n$$

where: I = current (A)

Weblink
Simulation of charge conservation

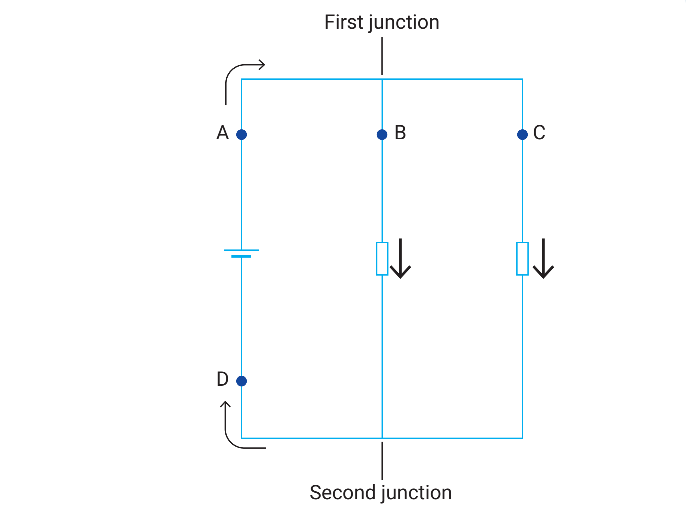


FIGURE 9.2.1 The electric current flowing through a parallel circuit splits at one junction, but then rejoins later. The total current flowing into a junction is the same as the total current leaving the junction.

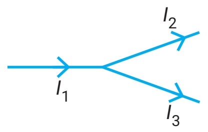
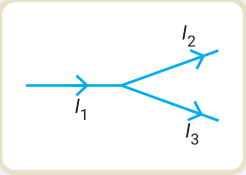


FIGURE 9.2.2 Kirchhoff's current law (first law). The total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction: $I_1 = I_2 + I_3$.

WORKED EXAMPLE 9.2.1

In the diagram, $I_1 = 3$ A and $I_2 = 1$ A. What is the value of I_3?



ANSWER

1 **Use Kirchhoff's current law.**
Total current into a junction = total current out of the junction
$I_1 = I_2 + I_3$

2 **Rearrange the equation to find the unknown.**
$I_3 = I_1 - I_2$

3 **Substitute known values and calculate the answer.**
$I_3 = 3\text{ A} - 1\text{ A}$
$I_3 = 2\text{ A}$

LEARNING CHECK 9.2

DESCRIBING

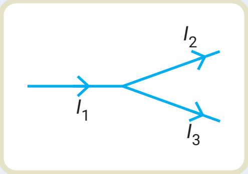
1 Are the following statements true or false?
  a The amount of current changes at different points in a series circuit.
  b The potential energy changes at different points in a series circuit.

2 State the law of conservation of charge.

3 **Explain** Kirchhoff's current law.

APPLYING

4 Use the diagram to answer the following questions.



  a If $I_1 = 100$ mA and $I_2 = 10$ mA, what is the value of I_3?
  b If $I_2 = 0.75$ A and $I_3 = 1.5$ A, what is the value of I_1?

9.3 Simple electrical circuits and batteries

Worksheet
Electricity warm-up

Electrical circuits involve energy and the movement of charge. When charges move around the circuit, they can lose or gain potential energy.

When there is an excess of charge on a conductor, the electrons repel each other and move so that the charge is distributed more evenly. This same concept can be applied to see how a battery provides energy to an **electrical circuit**. An electrical circuit is a complete loop through which charge can flow. If the loop is not complete, then charge cannot flow.

electrical circuit a complete conducting loop through which charge can flow

Figure 9.3.1 shows a light globe, switch and battery connected by conducting wires. This is an example of a simple electrical circuit.

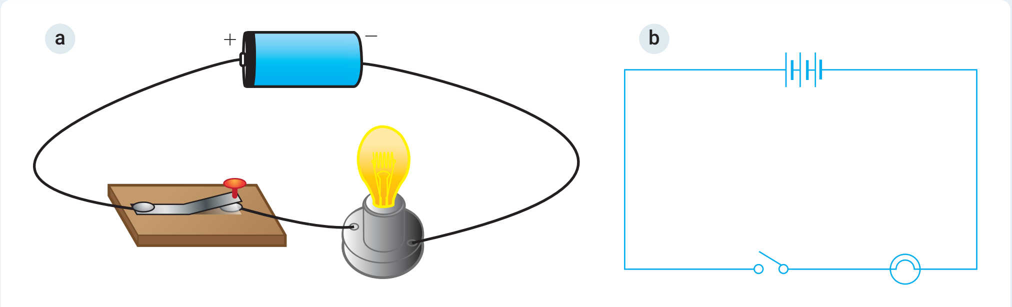


FIGURE 9.3.1 (**a**) A simple electrical circuit comprising a potential rise (battery), switch and a potential drop (light globe). (**b**) A circuit diagram of an equivalent circuit.

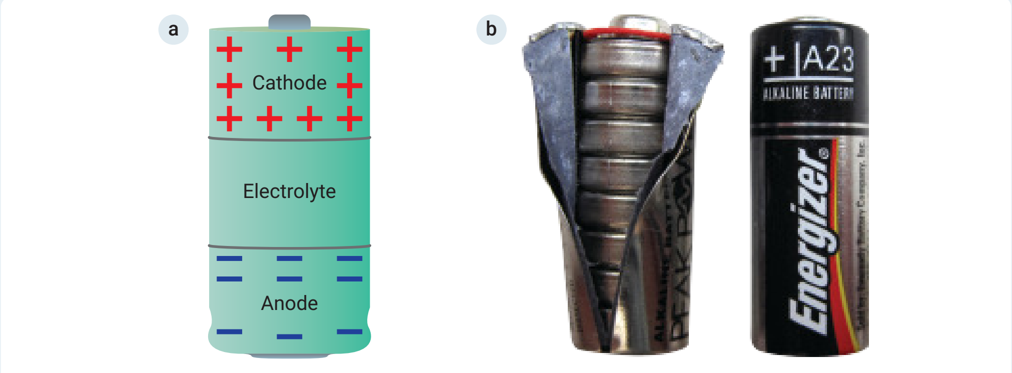
electromotive force (EMF) a source of potential energy per charge (voltage)

Weblink
Electric vocabulary

Batteries

A battery is a source of potential energy per charge, or **electromotive force (EMF)**. In a charged battery, a chemical reaction separates the positive and negative charges. There are many like charges close together in separate parts of the battery, giving the charges a large amount of potential energy. In a circuit, the negative terminal of the battery is connected to the positive terminal by connecting wires. The build-up of electrons in the negative terminal causes the electrons in the wire to move towards the positive terminal.

Figure 9.3.3 shows a simple circuit with a battery and a light globe. Electrons near the negative terminal (e.g. electron *a*) have a high potential energy – they are near other electrons. As the electrons move through the circuit, their potential energy is transformed into radiant light and heat in the light globe. Electrons near the positive terminal (e.g. electron *b*) have a low potential energy – they are near many protons. The same logic can be applied to protons when considering conventional current. Protons near the positive terminal have a high potential energy – they are near other protons. Protons near the negative terminal have a low potential energy because they are near electrons. The light globe is an example of a load or potential drop and transforms the energy provided by the source into other forms.



By Lead holder (Own work) [CC BY-SA 3.0], via Wikimedia Commons

FIGURE 9.3.2 (a) A simplified battery. (b) An AA battery is a collection of smaller cells.

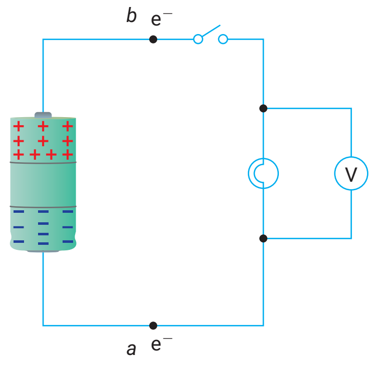


FIGURE 9.3.3 Electron *a* near the negative terminal has a high potential energy. Electron *b* near the positive terminal has a low potential energy. The voltmeter measures the potential energy difference between electron *b* and electron *a*.

Physicists use symbols to represent different components in circuit diagrams. Some examples of common symbols are shown in **Figure 9.3.4**. The most important symbols to focus on for now are the battery, light globe (filament lamp), switch and resistor.

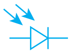
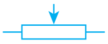
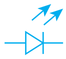
Device	Symbol	Device	Symbol
Wires crossed, not joined		Earth or ground	
Wires joined; junction of conductor		Switch (open)	
Fixed resistor		Switch (closed)	
Variable resistor		Diode	
Light-dependent resistor		Photodiode	
Rheostat or resistor with moving contact		LED	
Thermistor		AC supply	
Filament lamp		DC supply	
Battery of cells		Voltmeter	
Alternative for battery		Galvanometer	
Cell		Ammeter	
		Signal lamp or indicator	

FIGURE 9.3.4 Conventional symbols used in electrical circuit diagrams

Weblink
Circuit symbols

Using the symbols to draw the circuit in Figure 9.3.3 in full circuit diagram convention, it would look like **Figure 9.3.5**.

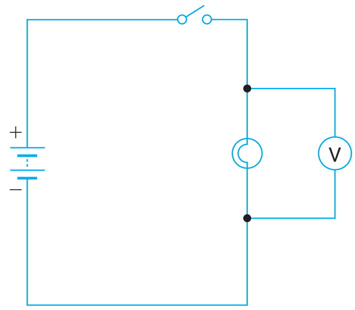


FIGURE 9.3.5 A simple circuit (from Figure 9.3.3) drawn with circuit symbols

LEARNING CHECK 9.3

DESCRIBING

1 **Describe** and **explain** 'electromotive force'.

2 Draw the circuit symbol for:
   - a a variable resistor
   - b a filament lamp
   - c an AC supply
   - d an ammeter
   - e a signal lamp or indicator.

3 **Describe** what is required to make an electrical circuit.

4 **Explain** how the movement of charge allows a battery to store energy.

APPLYING

5 People often 'charge' their phones when their battery is running low. Are they adding more charge to the phone or is another process taking place? **Describe** what is happening.

9.4 Electric current, potential difference and power

Current

When there is an electrical potential difference between two points in a circuit, the negatively charged electrons are attracted towards the positive terminal. This causes the electrons to move along the wire, creating a flow of **current**. This electric current is carried by the discrete charge carrier, the electron, with a charge of $q = 1.60 \times 10^{-19}$ C each. The amount of current, I, depends on the amount of charge, q, that passes a point in a given time, t. The unit of current is the ampere, A. One ampere is equal to one coulomb of charge (or 6.25×10^{18} electrons) passing a given point in one second.

current (I) the rate of flow of charge (i.e. charge per unit time)
unit: ampere (A): $I = \frac{q}{t}$

$$I = \frac{q}{t}$$

where:
I = current, in amperes (A)
q = charge, in coulombs (C)
t = time, in seconds (s)

KEY FORMULA

Current, I, is the rate of flow of charge (i.e. charge per unit time).

$$I = \frac{q}{t}$$

where:
I = current, in amperes (A)
q = charge, in coulombs (C)
t = time, in seconds (s)

KEY FORMULA

1 ampere = 1 coulomb per second
$1 \text{ A} = 1 \text{ C s}^{-1}$

WORKED EXAMPLE 9.4.1

An electron discharge tube produces a beam of electrons with a measured current of 30 mA.

a Determine the amount of charge emitted in 1 min.

b Calculate the number of charges emitted in 1 min.

ANSWERS

a **1** **State the equation.**

$$I = \frac{q}{t}$$

2 **Substitute known values.**

$$30 \times 10^{-3}\ \text{A} = \frac{q}{60\ \text{s}}$$

3 **Rearrange the equation to find the unknown.**

$$q = 30 \times 10^{-3} \times 60\ \text{C}$$

4 **Calculate the answer.**

$$q = 1.8\ \text{C}$$

1.8 coulomb of charge is emitted.

b **1** **Identify the relationship between charge and electrons.**

1.0 C of charge represents 6.25×10^{18} electrons.

2 **Calculate the answer.**

1.8 C $\times$ 6.25×10^{18} electrons per coulomb $= 1.125 \times 10^{19}$ electrons

1.13×10^{19} electrons are emitted.

Measuring current

Current is measured with an ammeter. An ammeter measures the amount of charge passing through a point each second. It is inserted within a circuit in series, as shown in **Figure 9.4.1**.

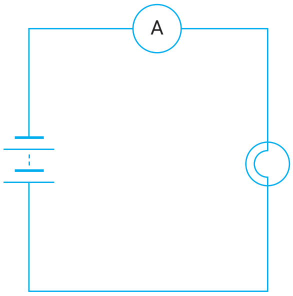


FIGURE 9.4.1 An ammeter is placed in series in the circuit. The amount of charge that passes a point in a given time is $q = It$.

Conventional current

So far, we have talked about current as the flow of electrons because it is the movement of electrons that creates the current in a conducting wire. When scientists were making discoveries about electricity, they were not aware of today's model of the atom nor the mechanism for the movement of charge. As a result, they established the convention of electricity flowing in the direction of a positive charge, from positive terminal to negative terminal **(Figure 9.4.2)**. This

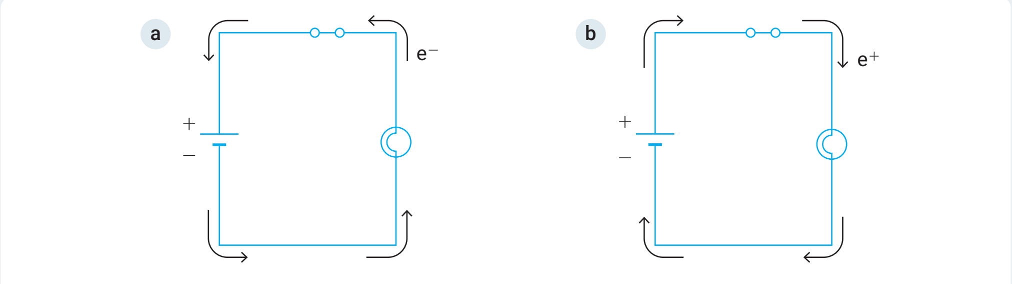


FIGURE 9.4.2 (**a**) Electrons flow from the negative terminal to the positive terminal. (**b**) Conventional current is the flow of positive charge from the positive terminal to the negative terminal.

is known as **conventional current**. Physicists have kept the convention because it makes no difference to the laws and rules applied to electromagnetism.

conventional current the convention to describe electrical current as the flow of positive charge

Direct current and alternating current

direct current (DC) current that is always in one direction

alternating current (AC) current that changes direction periodically, typically 50 oscillations per second (50 Hz)

Electrical energy is supplied by either **direct current (DC)** or **alternating current (AC)** sources. In DC, the net charge flows in one direction, and in AC the charge flow alternates direction periodically.

DC is used in electrical devices such as mobile phones, torches and toys. The most common source of DC is a battery, although many appliances that you use convert AC from your wall sockets into DC, via an adapter (rectifier) **(Figure 9.4.3)**. AC is used in car alternators, motors and air conditioners. The electrical energy supplied by a powerpoint in the wall is AC because it is simpler to produce and transmit and power losses in the wires during transmission are minimised. The standard AC power supply in Australia has a potential difference of 240 V_{rms} (**root mean square voltage**) and a frequency of 50 Hz. Different countries have different standards for electricity supply, voltage and frequency.

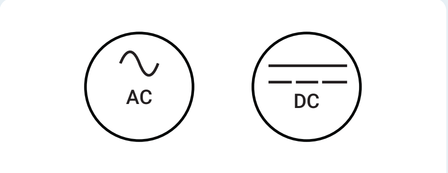


FIGURE 9.4.3 The circuit symbols for alternating current (AC) and direct current (DC) are often seen on power adapters and electrical devices.

root mean square voltage (V_{rms}) AC voltages may be compared to DC voltages by converting the peak voltage to the root mean square voltage, or $V_{rms} = \frac{V_{peak}}{\sqrt{2}}$

Potential difference

Electrical potential describes how much potential energy there is per unit of charge at different locations in a circuit. Potential difference is also commonly known as 'voltage'.

Hence, electrical potential difference is measured in units of joules per coulomb, $J\,C^{-1}$, which is commonly known as the volt, V.

Charge separation

Energy is required to separate opposite charges. If a positive charge and a negative charge are close together, they are attracted strongly. If energy is provided, then the charges can be pulled apart, providing the charges with energy – electrical potential energy – that is ready to be released. Potential energy is energy that is ready to be transferred or transformed, and hence it provides the potential difference required to make a current flow. If 'let go', the positive and negative charges move towards each other, making an electric current. As the electrons move towards each other, they lose potential energy, and it takes work to separate them again. In a similar manner, two like charges (e.g. two electrons) will repel each other more when they are close together than when they are further apart.

The potential energy per unit of charge:

$$V = \frac{W}{q}$$

where: V = voltage, in volts (V)
W = potential energy (or ability to do work), in joules (J)
q = charge, in coulombs (C)

$$1.0\,\text{V} = 1.0\,\text{J}\,\text{C}^{-1}$$

KEY FORMULA

The potential energy per unit of charge

$$V = \frac{W}{q}$$

where: V = voltage, in volts (V)
W = potential energy (or ability to do work), in joules (J)
q = charge, in coulombs (C)

$1.0\text{ V} = 1.0\text{ J C}^{-1}$

The electrical potential is measured relative to a reference point, often the ground or the positive terminal of a battery. Hence, what we generally measure is not potential but **potential difference**, which uses the same value and symbol, V. The potential difference between two points is simply the difference in potential energy per unit charge between those two points. It is sometimes referred to as 'voltage' because it is measured in volts, V.

potential difference (V) a measure of the potential energy per unit of charge; potential difference and voltage are measured in volts (V); also called voltage: $V = \frac{W}{q}$

When a charge q moves between two points, it will lose or gain electrical potential energy. The energy change – loss or gain – is equal to the work done to move the charge, and is written as $W = qV$. Again, V is the voltage, measured in volts, V, W is the work (or energy), measured in joules, J, and q is the charge, measured in coulombs, C.

The potential difference between two points in a circuit is measured with a voltmeter. The voltmeter needs to be connected in parallel to two different parts of the circuit, as shown in Figure 9.4.4.

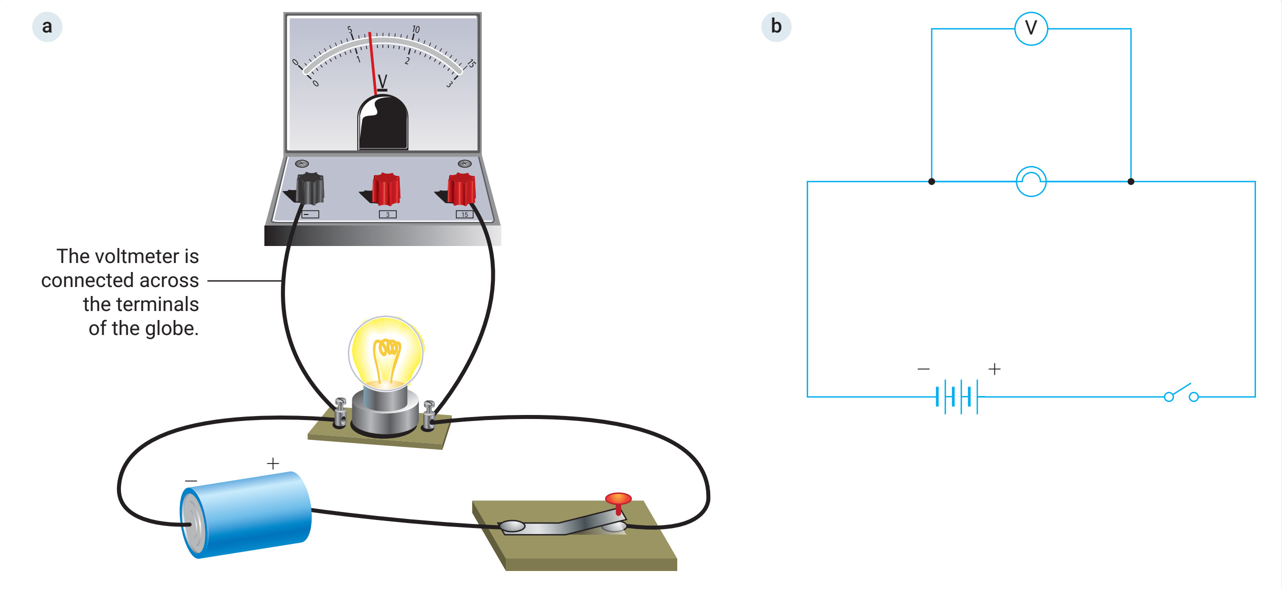


FIGURE 9.4.4 (**a**) The voltmeter measures the potential difference between any two points. It is placed in parallel across an element within the circuit. (**b**) The circuit can be represented as a circuit diagram.

WORKED EXAMPLE 9.4.2

Determine the voltage applied across a resistor if 90 J of work is done by 10 C of charge.

ANSWER

1 **State the equation.**

$$V = \frac{W}{q}$$

2 **Substitute known values.**

$$V = \frac{90\ \text{J}}{10\ \text{C}}$$

3 **Calculate the answer.**

$$V = 9.0\ \text{V}$$

Power

For a light globe to glow, it needs to be provided with an energy source, such as a battery. The light globe transforms the electrical energy into radiant light and heat energy. It is useful to know how quickly this energy is being transformed. **Power (*P*)** is a measure of the rate of energy transformation per unit of time. Power is measured in watts (W), which is equivalent to joules per second, as well as volt-amperes.

power (*P*) a measure of the rate of energy transformation per unit of time

$$P = \frac{W}{t} = V \times I$$

where:
V = voltage, in volts (V)
I = current, in amperes (A)
t = time, in seconds (s)
Energy (or work, W) is measured in joules (J).
Power (P) is then measured in watts (W): 1 watt = 1 W = 1 joule per second = 1 J s^{-1}

For example, a 100 W globe converts 100 J of energy in 1 s. A 50 W globe takes 2 s to convert the same amount of energy. Therefore, the 100 W globe is more powerful because it uses more energy per second than the 50 W globe. It is twice as powerful because it converts energy at twice the rate.

KEY FORMULA

$$P = \frac{W}{t} = V \times I$$

where:
V = voltage, in volts (V)
I = current, in amperes (A)
t = time, in seconds (s)

Energy (or work, W) is measured in joules (J).
Power (P) is then measured in watts (W): 1 watt = 1 W = 1 joule per second = 1 J s^{-1}

Weblink
Basic electrical quantities: current, voltage, power

WORKED EXAMPLE 9.4.3

An electric toaster is measured to use 108 kJ of energy while operating for 1 min. What is the power rating of the toaster?

ANSWER

1 **State the equation.**

$$P = \frac{W}{t}$$

2 **Substitute known values and calculate the answer.**

$$P = \frac{108\,000\text{ J}}{60\text{ s}}$$

$P = 1800$ W

Energy and power

Power delivery within an electrical circuit can also be deduced from voltage and current values:

$$\begin{aligned} P &= \frac{W}{t} \\ P &= \frac{Vq}{t} = V\frac{q}{t} \\ P &= VI \end{aligned}$$

and the amount of energy transferred can be deduced from $P = V \times I$:

$$\begin{aligned} P &= \frac{W}{t} \\ W &= Pt \\ W &= VIt \end{aligned}$$

WORKED EXAMPLE 9.4.4

An air conditioner operates at 240 V and draws a current of 10 A.

a Calculate its power rating.

b Determine how much energy was used (work was done) by the air conditioner in 4 h.

ANSWER

a 1 **State the equation for power.**

$P = V \times I$

2 **Substitute known values and calculate the answer.**

$$\begin{aligned} P &= 240\text{ V} \times 10\text{ A} \\ &= 2400\text{ W} \end{aligned}$$

b 1 **State the equation for work.**

$W = V \times I \times t$

2 **Substitute known values and calculate the answer.**

$W = 240\ \text{V} \times 10\ \text{A} \times (4 \times 60 \times 60)\ \text{s}$

$= 34\,560\,000\ \text{J}$

3 **Give the answer in the appropriate unit.**

$W = 34.56\ \text{MJ}$

Energy units

kilowatt-hour (kWh) a convenient measure of electrical energy equal to the power consumption of 1 kilowatt in 1 hour: $1.0\ \text{kWh} = 3.6 \times 10^6\ \text{J}$

The SI unit for energy, the joule, is often too small to be convenient when measuring the energy use of household appliances. Electricity companies use the larger unit of the **kilowatt-hour (kWh)** for the purpose of charging for electricity consumption.

To derive the conversion of energy values from kilowatt-hours to joules, use the following process.

One kilowatt-hour (1 kWh) is the *energy* used by a 1 kW appliance in 1 h:

$E\,(\text{kWh}) = P\,(\text{kW}) \times t\,(\text{h}) = 10^3\ \text{W} \times (60\ \text{min h}^{-1} \times 60\ \text{s min}^{-1})$

Thus: 1.0 kilowatt-hour = $1.0\ \text{kWh} = 3.6 \times 10^6\ \text{J}$

WORKED EXAMPLE 9.4.5

A refrigerator is left running continuously for one week while the family is away on holiday. It operates at 240 V and draws a current of 4.0 A.

a Determine the power rating of the refrigerator.
b Calculate the amount of energy used, in MJ, over the week.
c Calculate the amount of energy used, in kWh.

ANSWERS

a 1 **State the equation for power.**

$P = V \times I$

2 **Substitute known values and calculate the answer.**

$P = 240\ \text{V} \times 4.0\ \text{A}$

$= 960\ \text{W}$

b 1 **State the equation for energy.**

$W = V \times I \times t$

2 **Substitute known values and calculate the answer.**

$W = 240\ \text{V} \times 4.0\ \text{A} \times (1 \times 7 \times 24 \times 60 \times 60)\ \text{s}$

$= 580\,608\,000\ \text{J}$

$= 5.81 \times 10^2\ \text{MJ}$

c 1 **Identify the relationship between energy in joules and kWh.**

$$W = \frac{\text{J}}{\text{J per kWh}}$$

2 **Substitute known values and calculate the answer.**

$$W = \frac{580\,608\,000\text{J}}{3.6 \times 10^6\ \text{J per kWh}}$$

$= 161.3\ \text{kWh}$

LEARNING CHECK 9.4

DESCRIBING

1 **Describe** and **explain:**

- **a** conventional current
- **b** alternating current
- **c** potential difference
- **d** power.

2 State the conversion between joules and kilowatt-hours.

3 **Explain** why the kilowatt-hour is used for measuring household energy consumption, rather than the joule.

APPLYING

4 An X-ray machine produces a very high potential difference to accelerate electrons and produce a current of 15 A for 0.5 s. **Determine** the amount of charge produced over this period.

5 A voltage drop of 12 V was measured across a light globe as 15 C of charge passed through it. **Determine** how much energy was transformed from electrical to radiant light and heat within the light globe.

6 A washing machine requires 540 kJ of energy to complete a single 40-minute load. It is connected to a typical 240 V household circuit.

- **a** **Calculate** the current drawn by the washing machine.
- **b** **Determine** the power rating of the machine.

7 Household lighting equivalent to 660 W is left on for 8 h a day in a typical household (240 V) circuit. **Determine** the amount of energy used in:

- **a** MJ, on a typical day
- **b** kWh, in one week.

9.5 Solving problems involving current, charge and time, electrical potential and power

Worksheet
Power, current and energy

Solving problems is an art that is best learnt by continued practice and by applying some strategy. To solve problems involving current, charge and time, electrical potential and power, complete the following steps:

1. Read the question carefully and try to understand the scenario.
2. Organise the information, particularly the values and units provided.
3. Sketch a diagram of the scenario.
4. Consider what formula may be applied.
5. Verify the units and perform any conversions required to make them SI units.

Problems involving current, charge and time

WORKED EXAMPLE 9.5.1

A current of 2.0 A flows in a 20 cm section of a conducting wire. How many electrons pass through the end of the section every second?

ANSWER

1 **State the equation.**

$$I = \frac{q}{t}$$

2 **Rearrange equation to find the unknown.**

$q = I \times t$

3 **Substitute known values.**

$q = 2.0\text{ A} \times 1\text{ s}$

4 **Calculate the charge.**

$q = 2.0\text{ C}$

5 **Calculate the number of electrons passing through per second.**

The number of electrons (elementary particles) is thus $q \times 6.25 \times 10^{18}$ electrons C^{-1}.

$$\begin{aligned} e &= 2\text{ C} \times 6.25 \times 10^{18}\text{ electrons C}^{-1} \\ &= 1.25 \times 10^{19}\text{ electrons} \end{aligned}$$

1.25×10^{19} electrons pass through the end of the section every second.

Problems involving electrical potential

WORKED EXAMPLE 9.5.2

A resistor has a potential difference across it of 24 V. Determine the amount of charge required to flow through the resistor to complete 180 J of work.

ANSWER

1 **State the equation.**

$$V = \frac{W}{q}$$

2 **Rearrange the formula to find the unknown.**

$$q = \frac{W}{V}$$

3 **Substitute known values.**

$$q = \frac{180\text{ J}}{24\text{ V}}$$

4 **Calculate the answer.**

$q = 7.5\text{ C}$

Problems involving power

WORKED EXAMPLE 9.5.3

A current of 2.0 A flowing in a heater for 1 h converts 1.7 MJ of electrical energy into heat energy.

a How much charge was transferred through the heater?
b What potential difference exists across the heater?
c Determine the power rating of the heater, in kW.
d How much energy, in kWh, is used if the heater runs for 2 h?

ANSWERS

a **1** **State the equation.**

$I = \frac{q}{t}$

2 **Rearrange equation to find the unknown.**

$q = It$

3 **Substitute known values.**

$q = 2.0 \text{ A} \times (60 \text{ min h}^{-1} \times 60 \text{ s min}^{-1})$

4 **Calculate the answer.**

$q = 7.2 \times 10^3 \text{ C}$

b **1** **State the equation.**

$V = \frac{W}{q}$

2 **Substitute known values.**

$V = \frac{1.7 \times 10^6 \text{ J}}{7.2 \times 10^3 \text{ C}}$

3 **Calculate the answer.**

$V = 236.11$ V or 240 V (rounded to two significant figures)

c **1** **State the equation.**

$P = VI$

2 **Substitute the known values.**

$P = 240 \text{ V} \times 2.0 \text{ A}$

3 **Calculate the answer.**

$P = 480 \text{ W}$

$= 0.48 \text{ kW}$

d **1** **State the equation.**

$W = P \times t$

2 **Substitute unknown values.**

$W = 0.48 \text{ kW} \times 2.0 \text{ h}$

3 **Calculate the answer.**

$W = 0.96 \text{ kWh}$

LEARNING CHECK 9.5

DESCRIBING

1 Outline the steps to solving problems involving current, charge and time, electrical potential and power.

2 State the charge on an electron.

UNDERSTANDING

3 **Determine** the number of protons in +1.0 C of charge.

4 **Explain** how a potential difference creates a flow of electrons.

APPLYING

5 How much charge passes through a load if a current of 4.0 A flows for 5.0 s?

6 A current of 80 mA flows through a circuit. There are 3.0×10^{21} conduction electrons within a 5 cm section. How many electrons pass through the end of this section every second?

7 Given that 3 C of charge flows past a point in a circuit in 30 s, calculate the current flowing.

ANALYSING

8 A heater operates at 240 V and draws a current of 8 A from a household circuit.

  a **Calculate** its power rating.

  b **Determine** how much energy is used (work is done) by the heater if it is used for 6 h.

9 A resistor has a potential difference across it of 12 V. Given that 450 J of energy is converted to heat as the charge travels through the resistor, **determine** the amount of charge that flows through the resistor and the number of electrons that this represents.

10 A voltage drop of 9 V was measured across a light globe as 3.0 C of charge passed through it. **Determine** how much energy was transformed from electrical to radiant light and heat within the light globe.

9.6 Energy input and output in circuits

In any circuit, sources such as batteries and power packs provide potential energy to electrons, and loads, such as resistors and light globes, convert that energy into other forms. In accordance with the law of conservation of charge, the total energy expended throughout a circuit equals the energy provided; that is, the energy input will equal the energy output. Although this is the case for energy, the same cannot be said for current or voltage, as they differ depending on the complexity of the circuit. However, there are systematic ways to analyse electrical circuits, including the use of Kirchhoff's current law, as previously introduced, and **Kirchhoff's voltage law**.

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

Kirchhoff's voltage law

In a series circuit, the application of Kirchhoff's voltage law is relatively straightforward, as the potential difference provided by the energy source is shared between the loads.

For example, consider **Figure 9.6.1** and suppose that the potential difference across the battery is 12 V. Remember that potential difference is potential energy per unit charge.

Weblink
Kirchhoff's circuit law

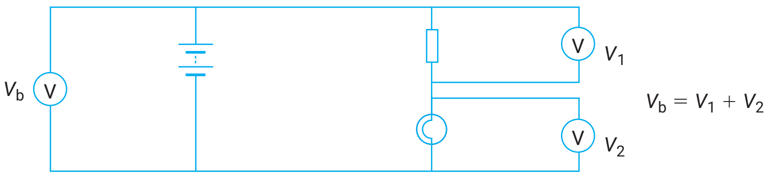


FIGURE 9.6.1 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops. In a series circuit, the voltage rise from the source is shared, not necessarily equally, between the loads in the circuit.

Let's define the zero of potential energy as being at the negative terminal of the battery. A charge q close to the positive terminal of the battery has potential energy $W = 2\,\text{V} \times q$. Think about moving around the circuit now. If you do a complete lap from the positive terminal of the battery back to the same point, you return to a point with the same potential energy again. Hence, whatever potential energy was gained by passing through the battery is lost as you pass through the globe and the resistor. We call components such as light globes and resistors loads or potential drops because potential energy is transformed into other forms ('lost') as a charge passes through these components. The total change in potential around a complete loop in a circuit is zero. That means the total of all positive potential differences equals the total of all negative potential differences.

In Figure 9.6.1 it can be seen that $V_b = V_1 + V_2$. The potential difference provided by the battery is shared between the two loads; that is, the potential rise equals the sum of the potential drops in a series circuit. For example, if the battery provided 12 V and the resistor had a measured voltage of $V_1 = 8\,\text{V}$, then $V_2 = V_b - V_1 = 12\,\text{V} - 8\,\text{V} = 4\,\text{V}$.

Now consider **Figure 9.6.2**. We have the same components, but now each is connected directly across the battery terminals. We call this a parallel circuit. Applying the same idea as above, if a charge moves around one loop of this circuit, returning to its original position, the potential energy of the charge must be the same as when it started. It doesn't matter which loop we follow – this will always be the case. Hence, the magnitude of the potential difference measured on each voltmeter is the same: $V_b = V_1 = V_2$.

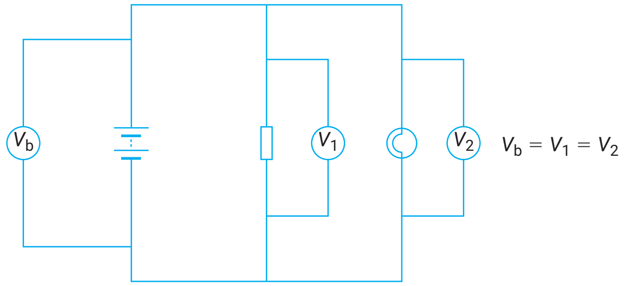


FIGURE 9.6.2 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops in each individual loop. In a parallel circuit the potential difference provided by the source is shared by the load within a single, closed loop.

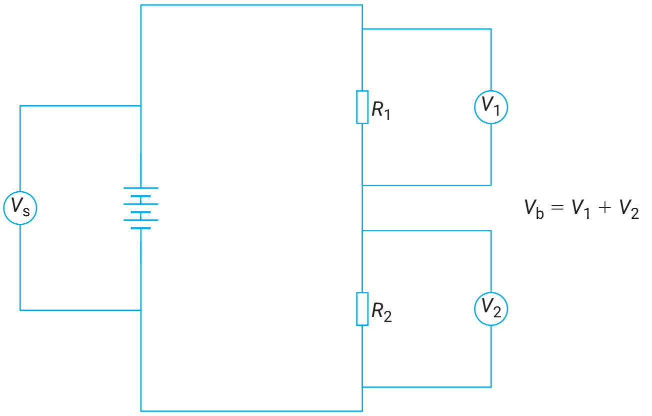


FIGURE 9.6.3 According to Kirchhoff's voltage law, the sum of the potential rise is equivalent to the sum of the potential drops in each individual loop. In a series circuit, the voltage rise from the source is shared, not necessarily equally, between the loads in the circuit.

WORKED EXAMPLE 9.6.1

In Figure 9.6.3, $V_s = 12$ V and $V_1 = 4$ V. Calculate the value of V_2.

ANSWER

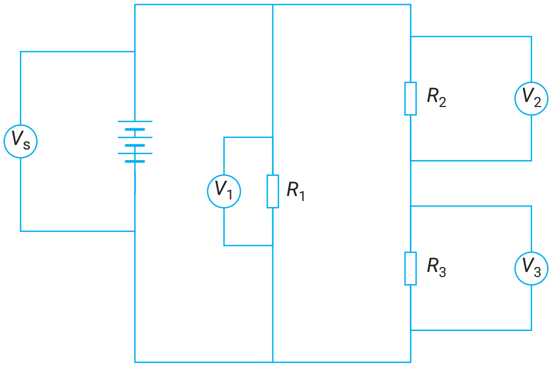
1 **Apply Kirchhoff's voltage law.**
According to Kirchhoff's voltage law, the sum of the potential rise equals the sum of the potential difference.
$V_s = V_1 + V_2$

2 **Substitute known values.**
$12\text{ V} = 4\text{ V} + V_2$

3 **Calculate the answer.**
$V_2 = 12\text{ V} - 4\text{ V}$
$= 8\text{ V}$

WORKED EXAMPLE 9.6.2

In the following circuit, $V_s = 24$ V and $V_2 = 6$ V. Calculate the value of V_1 and V_3.



ANSWER

According to Kirchhoff's voltage law, the sum of the potential rise equals the sum of the potential difference in each closed loop. In this case, the voltage supply and R_1 are in one closed loop, while the voltage supply, R_2 and R_3 are in a second closed loop.

1 **For the first closed loop:**

$V_s = V_1$

$24\text{ V} = V_1$

$V_1 = 24\text{ V}$

2 **For the second closed loop:**

$V_s = V_2 + V_3$

$24\text{ V} = 6\text{ V} + V_3$

$V_3 = 24\text{ V} - 6\text{ V}$

$V_3 = 18\text{ V}$

LEARNING CHECK 9.6

DESCRIBING

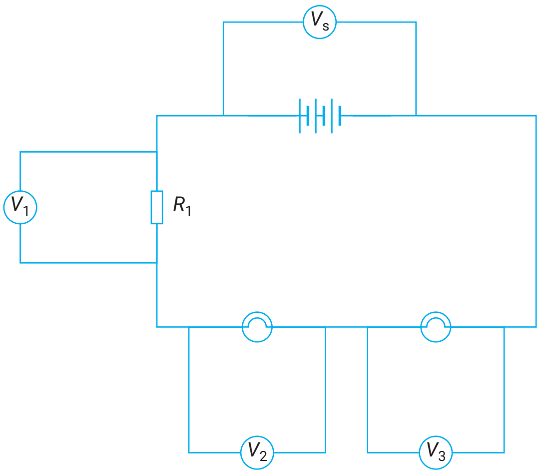
1 State Kirchhoff's voltage law.

2 State the law of conservation of electric charge.

3 Draw a combination circuit with some elements in series and others in parallel. Label the series components and the parallel components.

APPLYING

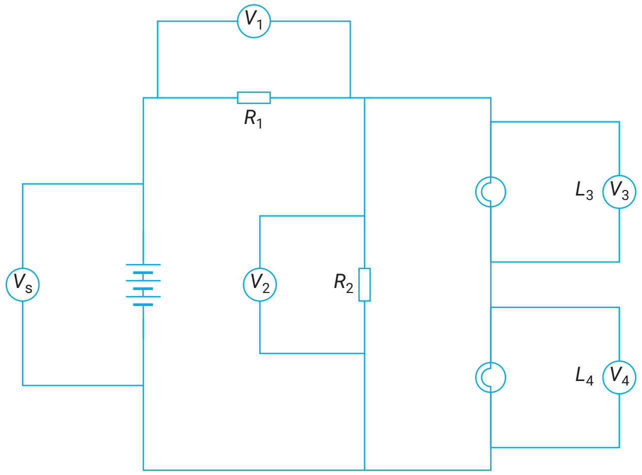
Questions 4 and 5 refer to the following diagram.



4 Let $V_s = 14$ V and $V_1 = 8$ V. The light globes are identical. **Determine** the voltage drops V_2 and V_3.

5 Let $V_1 = 2$ V and $V_2 = V_3 = 6$ V. **Determine** the supply voltage, V_s.

6 In the folowing diagram, let $V_s = 18$ V and $V_1 = 4$ V. The light globes are identical. **Determine** the voltage drops across V_2, V_3 and V_4.



CHAPTER SUMMARY

Charged carriers

- Subatomic particles have different charges.
- Like charges repel, opposite charges attract.
- Charge is measured in coulombs (C), where one coulomb of charge requires 6.25×10^{18} elementary particles.

Conservation of charge

- Total current into a junction = total current out of the junction
  $\Sigma I_{\text{in}} = \Sigma I_{\text{out}}$ or $I_t = I_1 + I_2 + \ldots I_n$ (i.e. charge per unit time).

$$I = \frac{q}{t}$$

where: I = current (A)
q = charge (C)
t = time (s)

Current, potential difference and power

- Current is the measure of the rate of flow of charge per unit of time. This can be expressed as:

$$I = \frac{q}{t}$$

where: I = current (A)
q = charge (C)
t = time (s)

- 1 ampere = 1 coulomb per second
  $1\ \text{A} = 1\ \text{C s}^{-1}$
- The potential difference measures the potential energy at different locations. This can be expressed as:

$$V = \frac{W}{q}$$

where: V = voltage (V)
W = potential energy (J)
q = charge (C)

- $1\ \text{V} = 1.0\ \text{J C}^{-1}$
- Power measures the rate of energy transformation per unit of time. This can be expressed as:

$$P = \frac{W}{t}$$

where: P = power (W)
W = work (J) (can also be energy)
t = time (s)

- Power can also be expressed as:

$$P = VI$$

where: P = power (W)
V = voltage (V)
I = current (A)

- Power is measured in watts (W): 1 watt = 1 W = 1 joule per second = $1\ \text{J s}^{-1}$

CHAPTER EXAM

MULTIPLE CHOICE

1. The amount of electric charge on an object is determined with reference to the number of:
   - **A** protons in the object.
   - **B** electrons in the object.
   - **C** neutrons in the object.
   - **D** protons and electrons in the object.

2. Electrons are removed from an area of a neutral conductor. Which of the following is most likely to happen?
   - **A** There is no movement of charge.
   - **B** The conductor now becomes an insulator.
   - **C** Protons within the conductor move towards the area.
   - **D** Electrons within the conductor move towards the area.

3. For any closed loop in an electrical circuit, the sum of the potential differences must be zero. This is otherwise known as:
   - **A** Coulomb's law.
   - **B** Kirchhoff's current law.
   - **C** Kirchhoff's voltage law.
   - **D** the law of conservation of charge.

4. Electrons are added to an area of an insulator. What is most likely to happen?
   - **A** There is no movement of charge.
   - **B** The insulator will now attract electrons.
   - **C** Protons in the insulator move towards the area.
   - **D** Electrons in the insulator move away from the area.

5. Which one or more of the following combinations of units is equal to the watt?
   - **A** $J\,s^{-1}$
   - **B** $A^2\,W^{-1}$
   - **C** $V^2\,A^{-1}$
   - **D** $V^2\,W^{-1}$

6. What is the power of a 120 V light bulb that draws a current of 1.25 A?
   - **A** 9.8 W
   - **B** 77 W
   - **C** 96 W
   - **D** 150 W

7. What is the power rating of a 120 V appliance that draws a current of 20 A?
   - **A** 0.72 kW
   - **B** 2.4 kW
   - **C** 6 W
   - **D** 48 kW

8. A 150 W light bulb is connected to a 120 V power line. What is the current that flows in it?
   - **A** 0.313 A
   - **B** 0.625 A
   - **C** 1.25 A
   - **D** 1.88 A

9. A conductor is a material that:

A allows all charge to flow through.

B allows no charge to flow through.

C is easy for a charge to flow through.

D is difficult for a charge to flow through.

10. A 2 A current is allowed to flow for 10 s. How many electrons will pass in that time?

A 3.20×10^{-18}

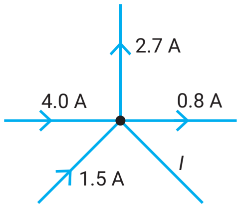
B 20

C 1.25×10^{19}

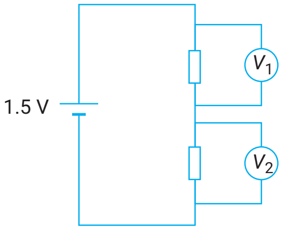
D 1.25×10^{20}

SHORT RESPONSE

11. **Determine** the magnitude and direction of the current *I* in the following circuit.



12. In the following circuit, V_2 has a reading of 750 mV. What is the reading of V_1?



13. Towards which terminal (positive or negative) do electrons move when there is a potential difference applied across a wire?

14. Does conventional current describe the direction of flow of positive charge or negative charge?

15. A current of 2.0 A flows in a battery when a light globe is connected across the terminals. The potential drop across the terminals is measured to be 6.0 V.

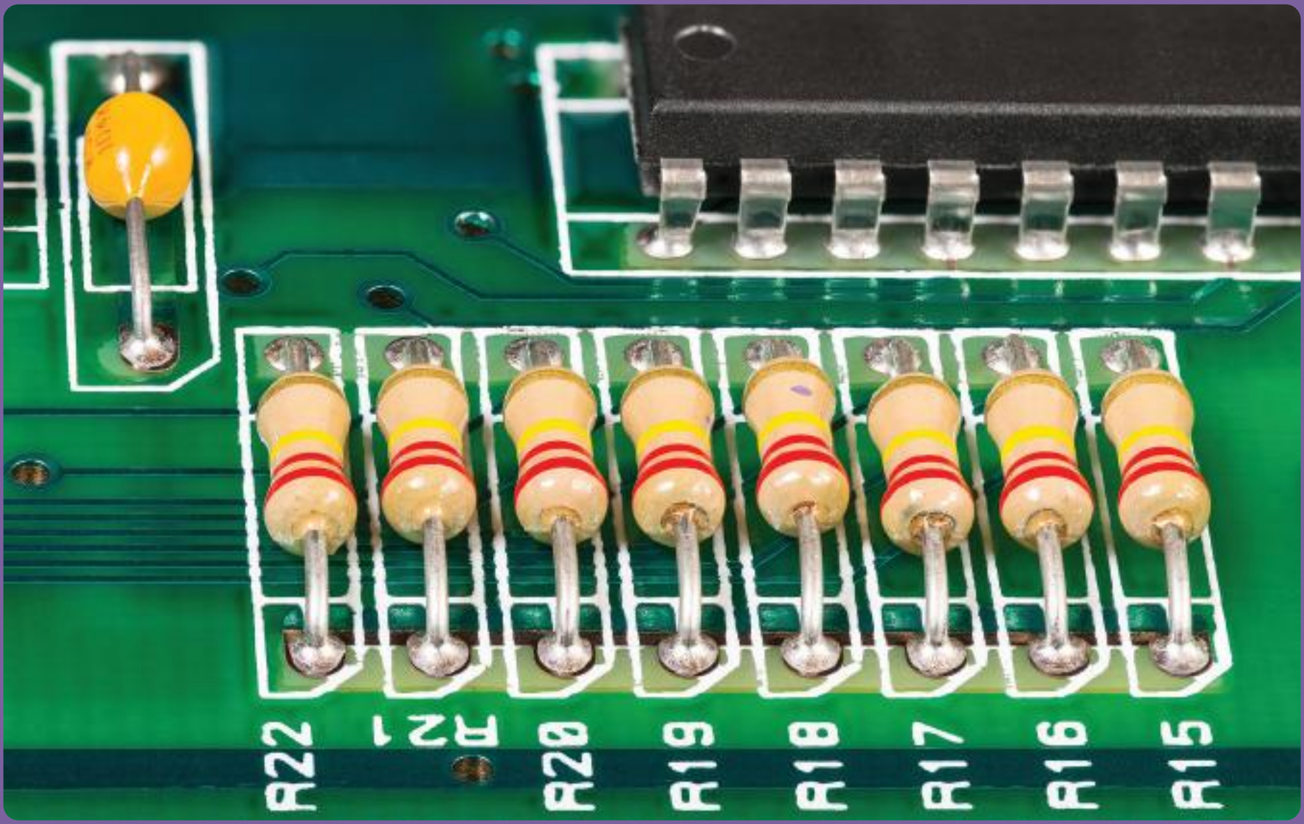
a What quantity of electric charge flows through the globe each second?

b How much energy is given to each coulomb of charge that passes through the battery?

c **Determine** how long it will take the battery to supply 480 J of energy.

CHAPTER 10

Resistance



KPixMining/Adobe Stock Photos

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- 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 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.

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Introduction

Electrons moving within a wire do not travel in a straight line, but zigzag as they collide with the atoms in the wire, losing energy. This opposition to the flow of electric charge is termed ‘resistance’. In the case of older incandescent light bulbs, as the electrical energy passes through the filament of the bulb, it is converted into both useful light and wasted heat.

In this chapter, the laws relating to resistance will be explained and applied to find the resistance within a range of common circuits and scenarios.

Practicals

- Comparing ohmic and non-ohmic resistors
- Determining the resistivity of a wire

Worksheets

- Resistance
- Resistance and graphs

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Conventional current is the theoretical movement of positive charges in a circuit.
- ✓ The particles in a current, the electrons, carry energy.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ explain the concepts of resistance, conductors, semiconductors and insulators
- ✓ compare the resistivity of common materials
- ✓ explain the relationship between the resistance of a wire and its cross-sectional area, length and resistivity
- ✓ calculate the resistivity of a wire
- ✓ describe Ohm's law
- ✓ perform calculations using Ohm's law
- ✓ contrast ohmic and non-ohmic resistors
- ✓ interpret current–voltage graphs to categorise resistors as ohmic or non-ohmic
- ✓ apply data interpretation skills to:
  - identify random and systematic errors
  - generate lines of best fit, trend equations, error bars, maximum and minimum gradients and uncertainty values
  - link the physics of electricity to the design and use of modern appliances and components.

10.1 Resistance

When a potential difference is applied across a wire, the electrons tend to move from the negative terminal towards the positive terminal. This movement is not in a straight line; rather, the electrons zigzag as they collide with the atoms in the wire; that is, the wire resists the flow of charge. This deterrent to the flow of charge is called **resistance**.

A material that allows current to flow through it easily is called a **conductor**. Conductors have a large number of free or conduction electrons. The free electrons move from one area to another when there is a potential difference, making up the electric current. Metals are good examples of conductors because they have many free electrons and offer little resistance to the flow of charge. An **insulator** is a material that does not allow current to flow through it because it does not have free electrons. Plastics and ceramics are examples of good insulators. A **semiconductor** is a material with a very small number of free electrons at room temperature. A current can flow through a semiconductor, but not easily. Whether a material is a conductor, an insulator or a semiconductor depends on what sort of atoms it is made of, and how those atoms are bound to each other (Table 10.1.1).

resistance the opposition to the flow of electrical charge throughout a given material; and the ratio between potential difference and current; unit: ohm (Ω)

conductor a material of low resistance that allows the flow of electrons (e.g. metals)

insulator a material that inhibits the flow of electrons (e.g. rubber)

semiconductor a material that conducts electricity less readily than a conductor but more readily than an insulator

TABLE 10.1.1 Examples of conductors, insulators and semiconductors

Good conductors	Poor conductors	Insulators	Semiconductors
Copper Aluminium Graphite	Water Human body Sugar	Glass Rubber Dry air	Silicon Germanium Gallium

Some materials resist the movement of charge more than others (Table 10.1.2). **Resistivity** (ρ), like resistance, refers to how much a material opposes the flow of charge. When you measure the resistivity of a substance, you need to state the temperature at which it was measured. Temperature affects the conductivity of a material.

Resistivity (ρ) a measure of how much a material opposes the flow of charges; unit: Ω m

TABLE 10.1.2 Resistivity of some materials commonly used in electric circuits

Material	Resistivity at 20°C (Ω m)
Copper	1.7×10^{-8}
Constantan	49×10^{-8}
Nichrome	1.1×10^{-6}
Carbon (graphite)	5.0×10^{-5}
Silicon	0.1–6.0

The resistance of a wire is affected by the cross-sectional area, A. As the thickness of the wire increases, the resistance decreases because there are more conduction electrons in any length of the wire; hence:

$$R \propto \frac{1}{A}$$

As the length of the wire increases, the resistance also increases because the charges have to collide with more atoms as they travel to the other end; hence, $R \propto \ell$. This is summarised by the resistivity formula:

$$R = \rho \frac{\ell}{A}$$

where: R = resistance (Ω)
ρ = resistivity (Ω m)
ℓ = length (m)
A = cross-sectional area (m^2)

To calculate the resistance of a wire, you need to know the resistivity of the material at a given temperature, the cross-sectional area of the wire and the length of the wire (Figure 10.1.1).

Worksheet
Resistance

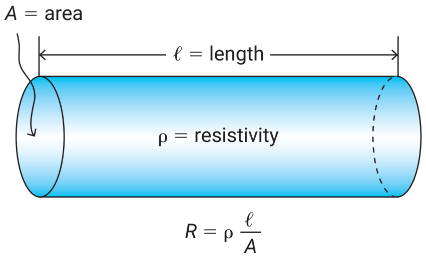


FIGURE 10.1.1 The resistance of a length of wire depends on its resistivity, length and cross-sectional area.

Weblinks
Resistance in a wire

How to read resistor colour codes

WORKED EXAMPLE 10.1.1

A wire has a cross-sectional area of 2.0 mm^2 and is 10.0 m long. If the resistance of the wire at room temperature is $1.1 \times 10^{-6}\ \Omega$, calculate the resistivity of the wire.

ANSWER

1 State the correct formula.

$$R = \rho \frac{\ell}{A}$$

2 Rearrange the formula to find ρ.

$$\rho = \frac{RA}{\ell}$$

3 Substitute the known values.

$R = 1.1 \times 10^{-6}\ \Omega$

$A = 2.0\ \text{mm}^2 = 2.0\ (\times 10^{-3}\ \text{m})^2 = 2.0 \times 10^{-6}\ \text{m}^2$

$\ell = 10.0\ \text{m}$

$$\rho = \frac{1.1 \times 10^{-6}\ \Omega \times 2.0 \times 10^{-6}\ \text{m}^2}{10.0\ \text{m}}$$

4 Calculate the answer.

$\rho = 2.2 \times 10^{-13}\ \Omega\ \text{m}$

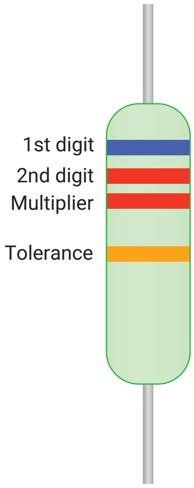


FIGURE 10.1.2 A colour-coded resistor

Resistor colour codes

Carbon resistors typically have four colour-coded bands on their cases. These bands are part of a code that allows you to determine their approximate resistance as well as their tolerance.

The fourth band is the tolerance band, which indicates the accuracy of the resistor. A gold band as the fourth band means a 5% accuracy, a silver band means 10% accuracy and no fourth band means 20% accuracy. The lower the percentage tolerance, the closer to its stated value and the more accurate the resistor is.

To read the three other bands, place the tolerance band on the right and start from the left end. The first two bands form a two-digit number according to their colour (see **Table 10.1.3**). The third band is the multiplier and tells you how many zeros to put after the number, or more precisely, the index of the multiplier, $\times 10^n$.

Andrew Lambert Photography/Science Photo Library

FIGURE 10.1.3 Many types of resistor are available. The resistance of carbon resistors is indicated by the coloured bands on their plastic casing.

Reading a resistor colour code

Look at the resistor in **Figure 10.1.2**.

1. Read the tolerance band.
   This is gold so the resistor has 5% accuracy.
2. Read the colours of the first two bands to determine the digits.
   The first band is blue, so it has a value of 6. The second band is red, so it has a value of 2. The digits are 62.
3. Read the third band to determine the multiplier.
   The third band is also red, so the multiplier is $\times 10^2$. The number is now 6200.
4. Resistor values are always coded in ohms, so the value of this resistor is 6200 ohms or 6.2 kΩ.

Determine the values of the resistors in **Figure 10.1.3**, using the resistor colour codes in Table 10.1.3.

TABLE 10.1.3 Resistor colour codes

Resistor band colour	Digit or multiplier value
Black	0
Brown	1
Red	2
Orange	3
Yellow	4
Green	5
Blue	6
Violet	7
Grey	8
White	9
Gold (tolerance)	± 5%
Silver (tolerance)	± 10%

LEARNING CHECK 10.1

DESCRIBING

1 **Identify** an example of:

- **a** a good conductor
- **b** a poor conductor
- **c** an insulator
- **d** a semiconductor.

2 State the formula for resistivity.

3 **Explain** why the resistance of a conductor depends on its length.

4 **Define** ‘resistance’.

APPLYING

5 A wire has a cross-sectional area of 0.5 mm^2 and is 2.0 m long. If the resistance of the wire is 50 mΩ, what is the resistivity of the wire?

6 A copper wire has a resistivity of $1.8 \times 10^{-8}\ \Omega$ m. It has a length of 50 cm and a cross-sectional area of 1 mm^2. **Calculate** the resistance.

10.2 Ohm's law, ohmic and non-ohmic devices

Ohm's law the physical law that states that the current flowing through a conductor is directly proportional to the voltage across the conductor; i.e. $\frac{V}{I}$ = a constant, where the constant is the resistance of the conductor

potential difference (V) a measure of the potential energy per unit of charge, also called voltage; unit: volt (V)

current (I) the rate of flow of charge; that is, charge per unit time; unit: ampere (A)

ohmic device a component with constant resistance (i.e. a device that exhibits a proportional relationship between current and voltage: $R = \frac{V}{I}$)

non-ohmic device a component that does not provide a constant resistance: $R \neq \frac{V}{I}$

Ohm's law

Resistance affects current and voltage. If a 12 V battery is placed in a circuit with a small resistance, the current will be large. If a 12 V battery is placed in a circuit with a large resistance, the current will be smaller. **Ohm's law** describes the relationship between resistance, current and voltage. The resistance, R, of a circuit component is defined as the ratio of the **potential difference (V)** to the **current (I)**.

Ohmic and non-ohmic devices

A resistor is an electrical component that restricts the flow of current. In an **ohmic device**, the resistance is constant for a wide range of voltages and currents. For ohmic resistors:

$$R = \frac{V}{I} = \text{constant}$$

or:

$$V = IR$$

where:

R = resistance, in ohms (Ω)
V = voltage, in volts (V)
I = current, in amps (A)

$$1.0 \text{ ohm} = \frac{1.0 \text{ V}}{1.0 \text{ A}} = \frac{1 \text{ volt}}{1 \text{ ampere}} = 1 \text{ V A}^{-1}$$

KEY FORMULA

$$R = \frac{V}{I}$$

where:

R = resistance, in ohms (Ω)
V = voltage, in volts (V)
I = current, in amps (A)

$$1.0 \text{ ohm} = \frac{1.0 \text{ V}}{1.0 \text{ A}} = \frac{1 \text{ volt}}{1 \text{ ampere}} = 1 \text{ V A}^{-1}$$

Current through an ohmic device is directly proportional to the potential difference across it. This is known as Ohm's law, and R is the constant resistance.

A characteristic current–voltage graph for an ohmic resistor is shown in Figure 10.2.1. The constant resistance of an ohmic device can be calculated as the inverse of the gradient.

In a **non-ohmic device**, the resistance of the device is not constant; hence, the current–voltage graph for a non-ohmic resistor is non-linear (Figure 10.2.2). It is not a straight line as the resistance is not constant; the current does not vary proportionally with the voltage across the device.

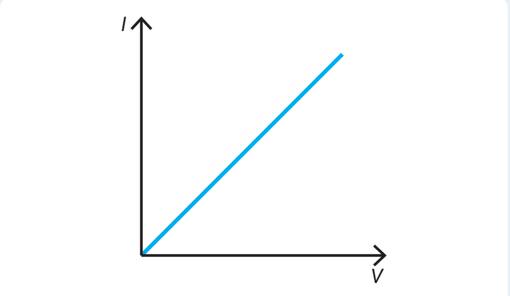


FIGURE 10.2.1 The resistance of an ohmic device is constant because the voltage is proportional to the current. The resistance may be calculated as the inverse of the gradient.

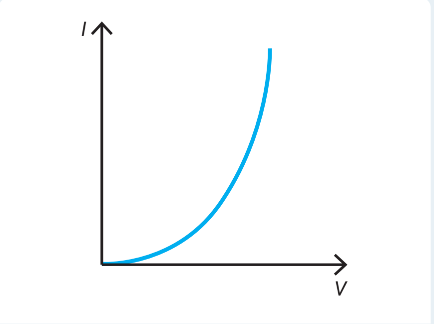


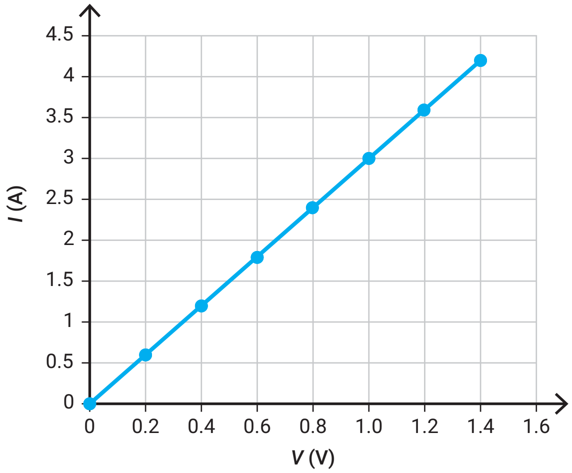
FIGURE 10.2.2 The resistance of a non-ohmic device is not constant. The voltage is not proportional to the current.

A number of devices with non-constant resistance are used in electrical circuits. These include light globes, diodes, light-emitting diodes (LEDs), thermistors and light-dependent resistors (LDRs). The resistance of a non-ohmic device can be found; however, it will only hold true for the precise values for which it is determined. To calculate the resistance for a certain voltage, you can use the equation $R = \frac{V}{I}$ or use a tangent to the curve.

WORKED EXAMPLE 10.2.1

The current–voltage graph for an ohmic resistor is shown.

Calculate the resistance.



ANSWER

1 **State the relationship between the gradient and resistance.**

The gradient, *m*, represents the change in current with voltage.

$$m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$$

2 **Rearrange to make *R* the subject.**

$$\frac{1}{R} = \frac{y_2 - y_1}{x_2 - x_1}$$

3 **Substitute known values.**

$$\frac{1}{R} = \frac{3.0 - 0.0\ \text{A}}{1.0 - 0.0\ \text{V}}$$

4 **Give the answer with the correct unit.**

$R = 0.33\ \Omega$

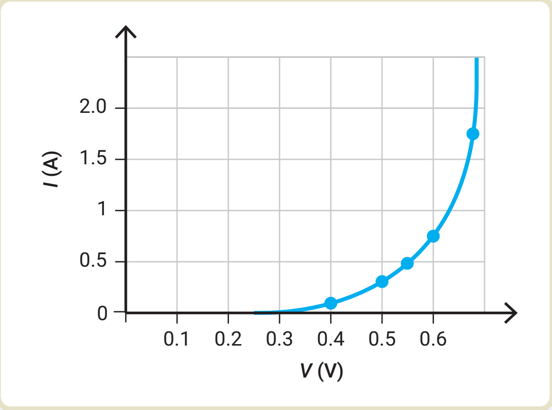
Weblinks
Ohm's law
Ohm's law and resistance

Worksheet
Resistance and graphs

WORKED EXAMPLE 10.2.2

The current–voltage graph for a diode is shown.

Calculate the resistance when there is a potential difference of 0.6 V across the diode.



ANSWER

1 **Read the correct value from the graph.**

At 0.6 V the current is 0.75 A.

2 **State the correct formula, then substitute known values.**

$$R = \frac{V}{I}$$

$$= \frac{0.6\ \text{V}}{0.75\ \text{A}}$$

3 **Give the answer with the correct unit.**

$R = 0.8\ \Omega$

PRACTICAL ACTIVITY 10.2.1

COMPARING OHMIC AND NON-OHMIC RESISTORS

Introduction

Whether a resistor is ohmic or non-ohmic may be illustrated visually by measuring and graphing the current through and voltage across a device. If the relationship is constant, and produces a linear graph, then the resistor is ohmic. If it produces a non-linear curve, then the resistor is non-ohmic.

Research question

What is the relationship between the potential differences and currents of resistors connected in series?

Aim

To examine the relationship between the potential drop across each of three resistors connected in series and the current through them to determine whether they are ohmic or non-ohmic resistors

Materials

- variable DC power supply (0 to 12 V)
- 2 different resistors
- light-emitting diode (LED) (a simple electronics kit provides a range of resistors and LEDs)
- 2 multimeters (to measure voltage across and current through the circuit)

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Electric shock is possible from faulty equipment.	Ensure that the power pack is not damaged and that it is connected correctly to the mains supply.
Resistors may become hot enough to burn.	Turn the power off when the circuit is not in use.

Procedure

1 Connect the circuit as shown in **Figure 10.2.3**. Note that the longer leg of the LED must be connected to the positive terminal of the power pack.

2 With the DC supply set to 2 V, record the potential rise applied to the circuit across the power supply as well as the potential drop across resistor 1, resistor 2 and the LED. The multimeter should be used in parallel to

measure the voltage across each. Copy the results table and record your measured values.

3 Still with the DC supply set to 2 V, record the current through the circuit. The multimeter should be used in series to measure the current. Record the measured values in your results table.

4 Repeat the procedure for DC supply settings of 4, 6, 8, 10 and 12 V. Record the measured values in your results table.

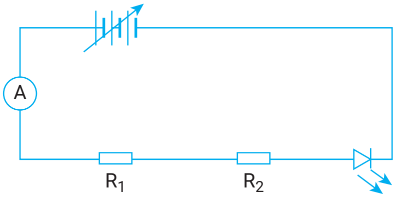


FIGURE 10.2.3 The experimental set-up for comparing ohmic resistors and non-ohmic resistors

Results

Supply voltage (V)	Voltage of resistor 1 (V)	Voltage of resistor 2 (V)	Voltage of LED (V)	Current (A)
2				
4				
6				
8				
10				
12				

Analysis of results

1 On one set of axes, plot a scatter graph of current, I, against voltage, V, for each of the three devices.

2 Add a line of best fit for each. Include the equation of the line and the R^2 correlation coefficient for any straight lines obtained.

3 Use the gradients of the lines and the relationship $m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$ to determine the resistance of the devices that provided a straight line.

Interpretation and evaluation

4 Why were at least five data points measured?

5 Were the measured values for voltage and current precise? (Refer to the correlation coefficient.)

6 List three sources of error in the measurements taken.

7 Which of these three devices is/are ohmic? Which is/are non-ohmic? Explain why.

8 For the ohmic devices, determine their resistance. (Show your calculation.)

9 For the ohmic devices, were their resistance values accurate? (Refer to the value of the resistor, if known.)

PRACTICAL ACTIVITY 10.2.2

DETERMINING THE RESISTIVITY OF A WIRE

Introduction

The resistance of a wire depends on the length (ℓ), cross-sectional area (A) and resistivity (ρ) of the wire. In this experiment, you will determine the resistance of a wire for different lengths and thicknesses to allow you to calculate the resistivity of the wire.

Research question

Can the resistivity of a conducting wire of known length and cross-sectional area be accurately determined by measuring its current and voltage?

Aim

To determine the resistivity of a wire

Materials

- variable DC power supply (0 to 12 V)
- 2 m of nichrome wire
- micrometer screw gauge
- tape measure
- 2 digital multimeters (to measure voltage and current, or resistance)
- 2 retort stands
- 2 G clamps

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The wire can penetrate the skin if it is snapped.	Be careful not to overstretch the wire.
The wire may get hot when a current is passed through it.	Ensure that any current sent through the wire is kept low and that the power is turned off immediately after taking measurements.

Procedure

1 Set up the materials as shown in **Figure 10.2.4**.

2 Tie 1 m of wire between the two retort stands, making sure that the wire is taut and without kinks.

3 Use the micrometer screw gauge to measure the thickness of the wire at three points and calculate an average diameter. Use the diameter measurement to find the radius and then calculate the cross-sectional area of the wire.

4 Measure the resistance for a minimum of five different lengths of the wire. Copy the results table and record your measurements. (An alternative method for determining the resistance of the wire is to place a power pack set at 12 V across the wire and to measure the voltage across and current through five different lengths of the wire.)

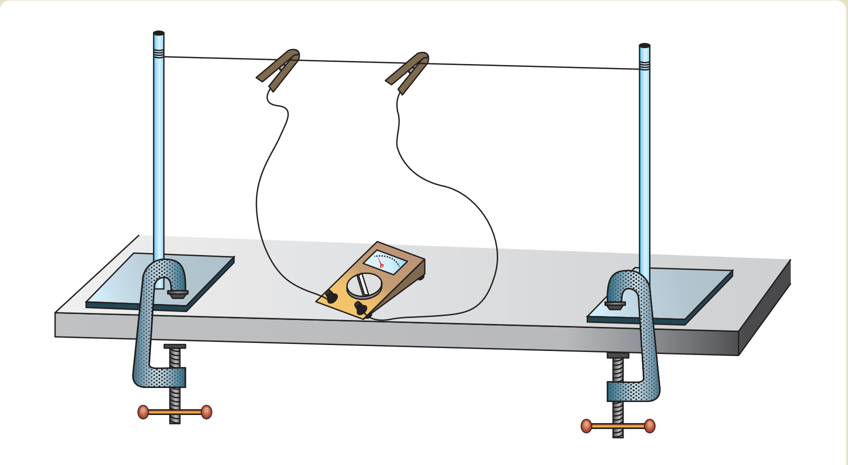


FIGURE 10.2.4 The experimental set-up for determining the resistivity of a wire

Results

Length (m)	Resistance (Ω)	Voltage (V)	Current (A)

Analysis of results

Resistivity is given by the formula:

$$\rho = \frac{RA}{\ell} \quad \text{or} \quad R = \frac{\rho \ell}{A}$$

where: ρ = resistivity, in ohm metres (Ω m)
R = resistance (Ω)
A = cross-sectional area (m^2)
ℓ = length (m)

1 Plot a scatter graph of resistance versus length with uncertainty bars.

2 Add a line of best fit. Include the equation of the line and the R^2 correlation coefficient.

3 Use the gradient of the line and the relationship $m = \frac{\Delta R}{\Delta \ell} = \frac{\rho}{A}$ to determine the resistivity of the nichrome wire. Multiply the gradient by the cross-sectional area to determine the resistivity. Estimate the uncertainty in this value.

Interpretation and evaluation

4 Why were at least five data points measured?

5 Was the measured value for resistivity accurate? (Refer to Table 10.1.2 for values of the resistivity of some materials commonly used in electric circuits.)

6 Was the measured value for resistivity precise?

7 List three sources of error in the measurements taken.

8 Predict how differences in temperature may affect the results.

LEARNING CHECK 10.2

DESCRIBING

1 State the units for the following.
  - **a** Resistance
  - **b** Resistivity
  - **c** Current
  - **d** Voltage

2 **Describe** why a minimum of five data points are used to sketch a scatterplot.

3 State three different sources of error and explain a method to minimise each error.

4 **Explain** how you can test to determine whether a device is ohmic or non-ohmic.

5 State Ohm's law.

6 List an example of an ohmic device and a non-ohmic device.

7 **Describe** the difference between ohmic materials and non-ohmic materials.

APPLYING

8 Helen measured the current through an LED for five different potential differences. Her measurements are in the table.

Potential difference (V)	2.4	2.6	2.8	3	3.2
Current (mA)	0	1	4	12	25

  - **a** Plot the points on an I–V graph.
  - **b** Is this device ohmic or non-ohmic? **Explain** your answer.
  - **c** What is the resistance when there is a potential difference of 3 V across the LED?

10.3 Interpreting graphs

When a current passes through any conductor, a voltage drop occurs because of the resistance of the conductor. For some materials, including metals, the drop in the voltage is proportional to the current. This is Ohm's law, which we know is mathematically expressed as:

$$R = \frac{V}{I}$$

In a table of measured values, it is not necessarily immediately apparent whether this law is supported or not (i.e. whether a device is ohmic or non-ohmic). By graphing the data as a scatterplot and illustrating it visually, we can see the relationship more readily (**Figure 10.3.1**).

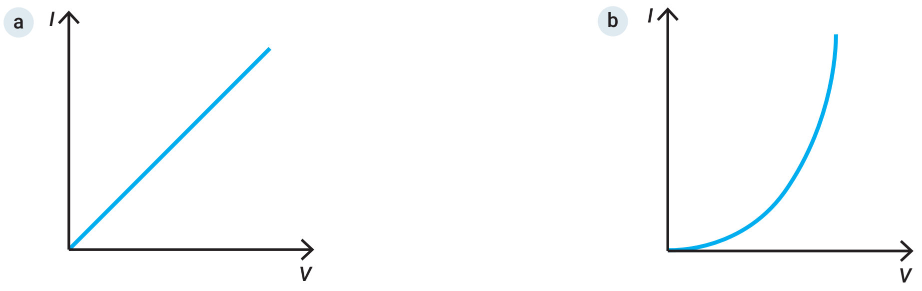


FIGURE 10.3.1 (**a**) In ohmic devices, the voltage is proportional to the current, as evidenced by a linear graph. (**b**) In non-ohmic devices, the voltage is not proportional to the current, as evidenced by a non-linear curve.

When graphing experimental values, it is seldom that all data points line up exactly along a line of best fit. Of course, there is error associated with each measured value; hence, we cannot expect all data to be perfectly precise. How can we tell whether a set of values is precise enough? An experimental error is a difference between a measured value and an expected or theoretical value. Recall that errors can occur in many ways but are generally categorised as random error or systematic error. Common sources of random error include poor use of equipment and changes in the environment or surroundings while completing an experiment. Common sources of systematic error include incorrect calibration of a measurement device or not accounting for a zero error. **Figure 10.3.2** demonstrate these two types of experimental error.

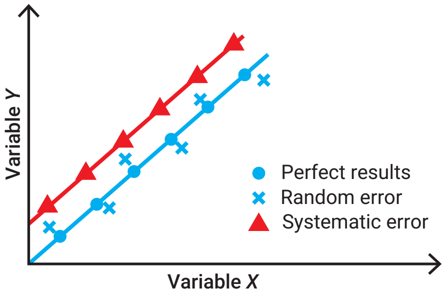


FIGURE 10.3.2 Experimental data is seldom perfect: usually there is one-sided (systematic) error, two-sided (random) error or both present in measured values.

In many instances, the best way to present and analyse data is to sketch a graph. Similarly, one of the most effective ways to represent errors or uncertainties is to use error bars. Error bars represent the uncertainty, by showing the lower and upper boundaries associated with each value. Rather than working out specific values for each point, it is often helpful to simply use the uncertainty of the worst (least precise) value for all points. The graph can be evaluated against the uncertainties of each value. A precise and representative line of best fit lies within the boundaries of each of the error bars **(Figure 10.3.3)**.

Syllabus link
The digital chapter discusses error in detail.

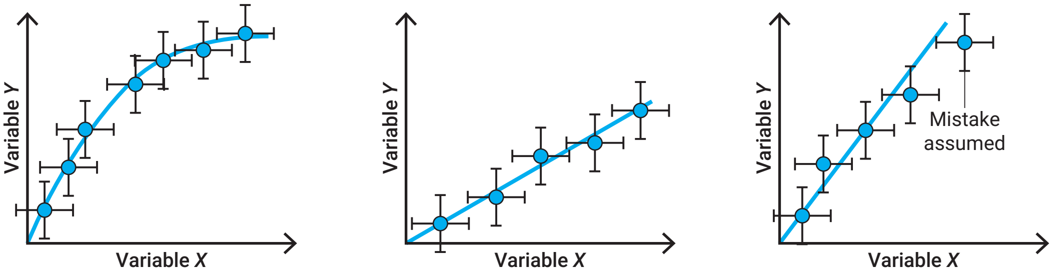


FIGURE 10.3.3 The line of best fit should lie within the boundaries of the error bars if the data is precise.

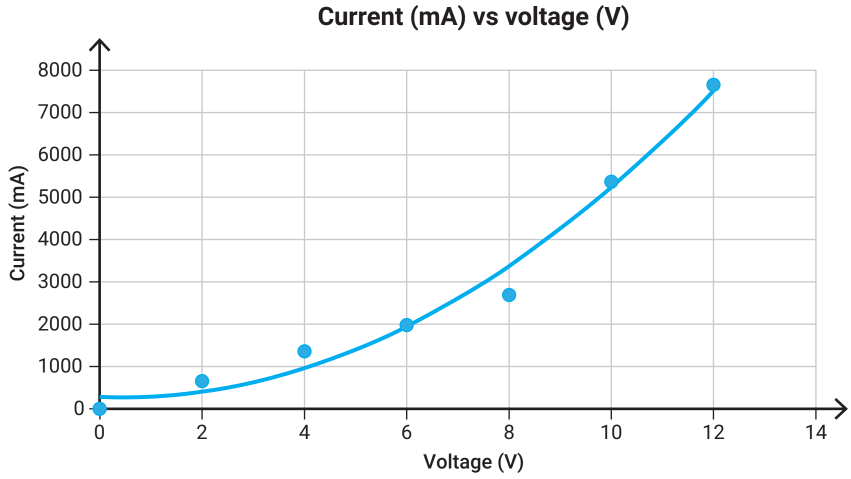
WORKED EXAMPLE 10.3.1

Current and voltage values were measured when investigating the properties of a fuse in an electrical circuit. The values are listed in the following table.

Voltage (V)	0	2	4	6	8	10	12
Current (mA)	0	660	1360	1980	2690	5370	7660

Graph the current and voltage values to determine whether the fuse is ohmic or non-ohmic. Give the graph a title and label the axes correctly. If it is ohmic, determine the resistance.

ANSWER



The current–voltage graph does not appear to be linear; therefore, the fuse is not ohmic over this range of values.

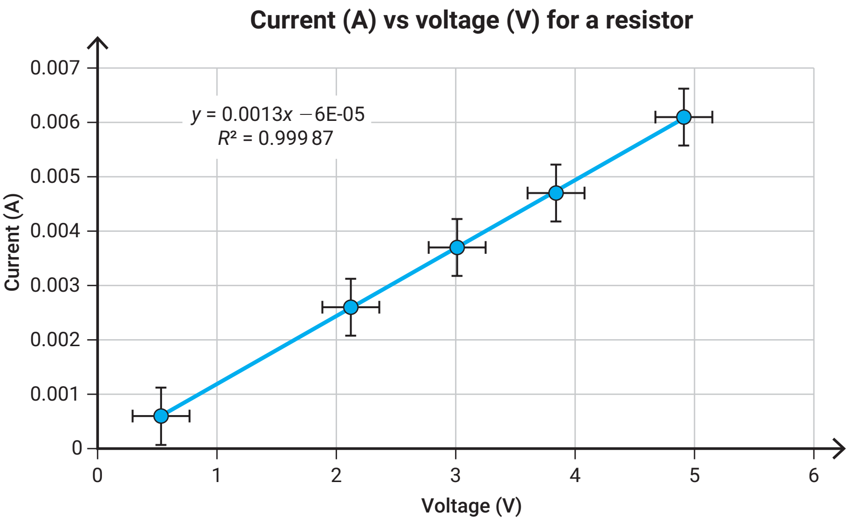
WORKED EXAMPLE 10.3.2

It is claimed a resistor has a resistance of 820 Ω ± 5% (i.e. 820 Ω ± 41 Ω). A student wishing to investigate this claim set up a circuit and measured the voltage across and current through the resistor for five different voltages. The current and voltage values are collated in the table below.

V_{820} (V) (± 0.05 V)	4.91	3.84	3.01	2.12	0.53
I (A) (± 0.0005 A)	0.0061	0.0047	0.0037	0.0026	0.0006

Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly. Note the uncertainty in each value and add the error bars to your graph. If the resistor is ohmic, determine the resistance and whether the experimental value is accurate.

ANSWER



1 State the relationship between the gradient and resistance.

The current–voltage graph appears linear; therefore, the resistor is ohmic. The gradient of the graph represents $m = \frac{\Delta I}{\Delta V} = \frac{1}{R}$; hence, the inverse of the gradient is the resistance.

2 Rearrange to find *R*.

$$m = 0.0013 \text{ A V}^{-1} = \frac{1}{R}$$

$$R = \frac{1}{0.0013}$$

3 Calculate the answer and state the unit.

$R = 769.2\ \Omega$

4 Comment on the accuracy of the data.

The line of best fit lies within the error bars of each value; hence it is precise.

The resistance value of 769.2 Ω lies outside the claimed tolerance of the resistor, as the lower boundary is equivalent to 820 Ω – 41 Ω = 779 Ω; hence, the data is inaccurate.

LEARNING CHECK 10.3

DESCRIBING

1 Give an example of a random error and a systematic error.

2 State the purpose of including error bars on a graph of experimental data.

3 **Explain** the difference between a random error and a systematic error.

ANALYSING

4 It is claimed a resistor has a resistance of 390 Ω ± 5%. A student wishing to investigate this claim measured the voltage across and current through the resistor for five different voltages. The measurements were collated in the table.

V_{390} (V) (± 0.05 V)	4.67	3.66	2.87	2.02	0.51
I (A) (± 0.0005 A)	0.012	0.009	0.007	0.005	0.001

a Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly.

b State whether the device is ohmic or non-ohmic.

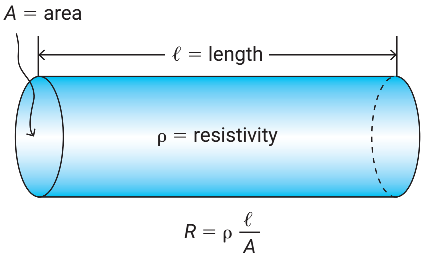
c If the resistor is ohmic, **determine** the resistance and whether the experimental value is accurate.

Resistance

- Resistance is the opposition to flow of charge through a material.
- Conductors have low resistance, whereas insulators are highly resistant to the flow of electrons.
- Resistance can be expressed as:

$$R = \rho\frac{\ell}{A}$$

where: R = resistance (Ω)
ρ = resistivity (Ω m)
ℓ = length (m)
A = cross-sectional area (m^2)



Ohm's law

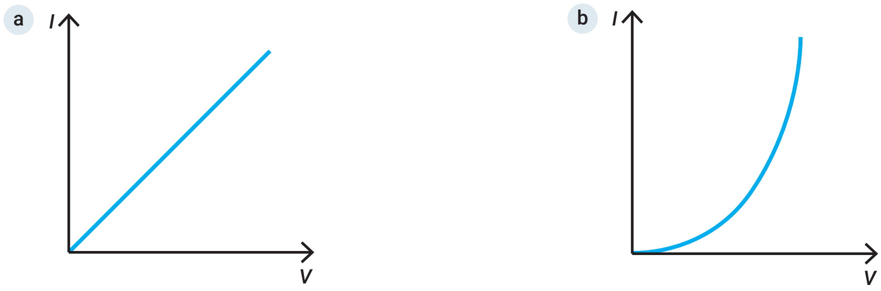
- Ohm's law describes the relationship between the resistance, current and voltage as shown:

$$R = \frac{V}{I}$$

where: R = resistance (Ω)
V = voltage (V)
I = current (A)

$$1.0\text{ ohm} = \frac{1.0\text{ V}}{1.0\text{ A}} = \frac{1\text{ volt}}{1\text{ ampere}} = 1\text{V}\text{A}^{-1}$$

- In an ohmic device **(a)**, the resistance is constant, whereas in a non-ohmic device **(b)**, the resistance is not constant.



CHAPTER EXAM

MULTIPLE CHOICE

1. Resistance is best defined as:
   - **A** a value measured in Ω m.
   - **B** the current through a conductor divided by voltage across it.
   - **C** a measure of the amount of charge that can flow through a circuit in a given time.
   - **D** a quantity representing the opposition to the flow of electrical charge through a given material.
2. What is the voltage across a 150 Ω resistor when 20 mA of current passes through it?
   - **A** 3 C
   - **B** 3 V
   - **C** 30 V
   - **D** 7500 V
3. Which will have the most resistance?
   - **A** A long, thin wire
   - **B** A long, thick wire
   - **C** A short, thick wire
   - **D** A short, thin wire
4. What is the resistance of a 12 V bulb with 40 mA flowing through it?
   - **A** 0.3 Ω
   - **B** 0.48 Ω
   - **C** 300 Ω
   - **D** 480 Ω
5. What is the current flowing through a 50 kΩ resistor when its potential difference is 6 V?
   - **A** 1.2×10^{-7} mA
   - **B** 0.12 mA
   - **C** 120 mA
   - **D** 300 mA
6. If a conductor is ohmic, the relationship between:
   - **A** voltage and current is constant.
   - **B** voltage and current varies depending on the voltage of the conductor.
   - **C** voltage and current varies depending on current flowing through the conductor.
   - **D** resistance and voltage varies depending on current flowing through the conductor.
7. According to Ohm's law, the:
   - **A** power of a device is a product of the voltage and current.
   - **B** voltage and current of a device are inversely proportional.
   - **C** current and resistance of a device are inversely proportional.
   - **D** product of the current and resistance of a device is equal to the resistivity.
8. Resistance is the:
   - **A** allowance of electrical charge to flow through a given material.
   - **B** opposition to flow of electrical charge through a given material.
   - **C** magnitude of the flow of electrical charge through a given material.
   - **D** magnitude of the potential energy lost as charges flow through a given material.

9. What is the resistance of a device with 200 mA flowing and a potential difference of 18 V?

A 0.09 Ω

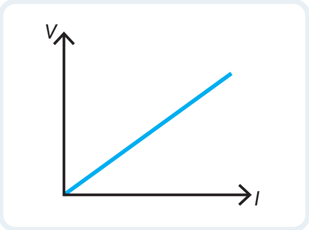
B 3.6 Ω

C 90 Ω

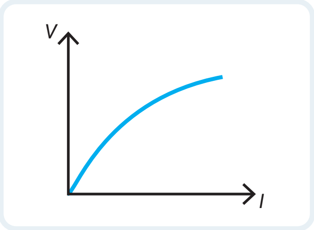
D 360 Ω

10. Which of these represents an ohmic resistor?

A



B



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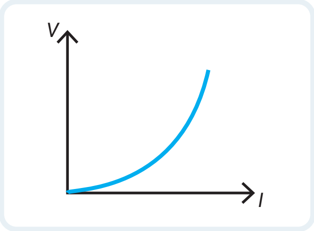

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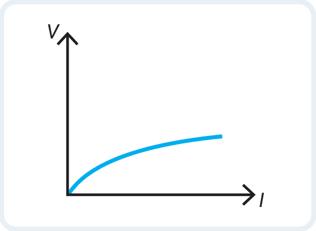
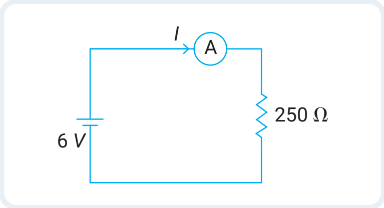


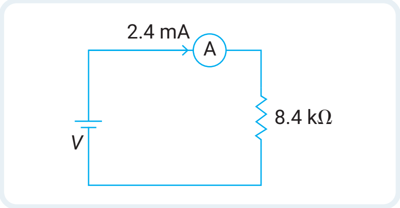
SHORT RESPONSE

11. Determine the unknown value (V, I or R) in each of the following cases.

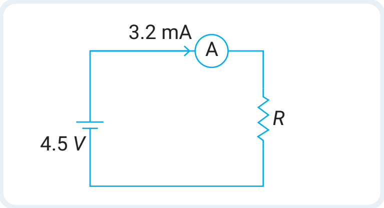
a



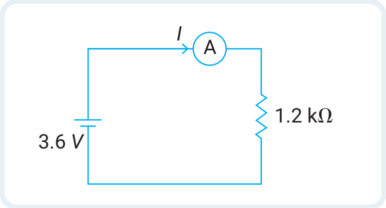
b



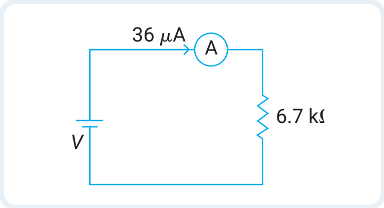
c



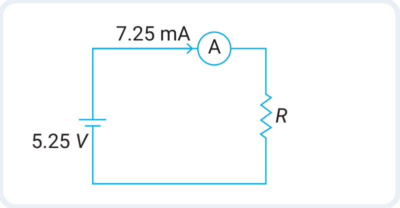
d



e



f



DATA ANALYSIS

12. Interpret evidence

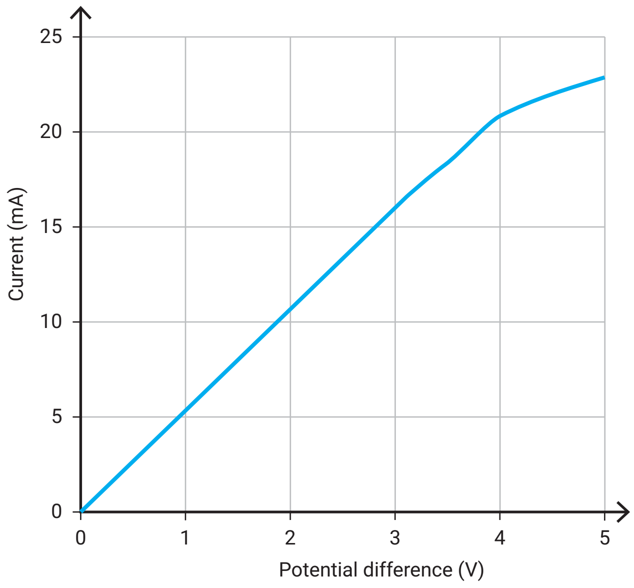
It is claimed a resistor has a resistance of 390 Ω ± 5% (i.e. 390 Ω ± 5% of 390 Ω). A student wishing to investigate this claim set up a circuit and measured the voltage across and current through the resistor for five different voltages. The measurements were collated in the table below.

V_{390} (V) (± 0.5 V)	2.37	1.87	1.43	1.02	0.26
I (A) (± 0.0005 A)	0.0061	0.0047	0.0037	0.0026	0.0006

Graph the current and voltage values to determine whether the resistor is ohmic or non-ohmic. Give the graph a title and label the axes correctly. Note the uncertainty in each value and add error bars to your graph. If the resistor is ohmic, **determine** the resistance and whether the experimental value is accurate.

13. Analyse data

The graph of how the current through a component varies with the potential difference applied across it is shown below.

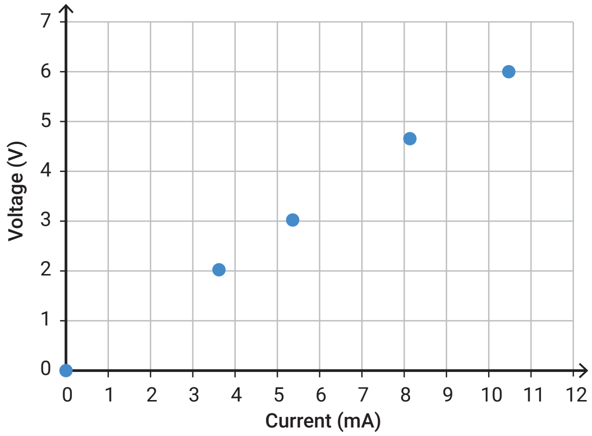


a **Identify** the current at which the component stops behaving as an ohmic conductor.

b **Determine** the resistance of the component at 2.5 V.

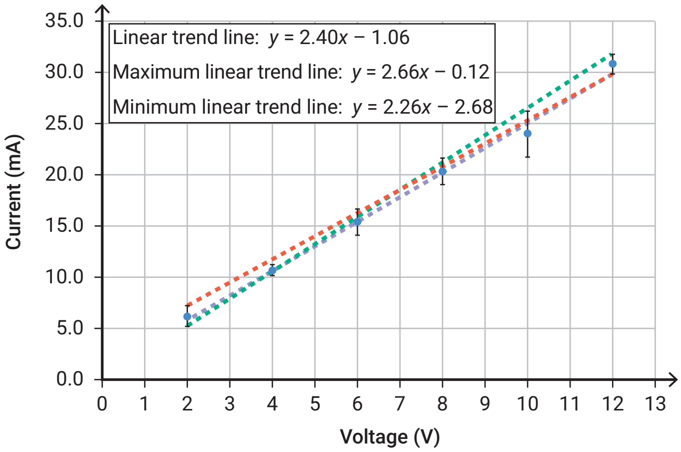
14. Analyse data

The voltage across a resistor was measured as the current through it was altered. The resulting data is graphed as shown below. **Determine** the value of the resistor used.



15. Interpret evidence

A student conducted an experiment to investigate the current in a resistor connected to a variable voltage source. The student varied the voltage applied to the resistor and measured the current on the ammeter. The data was processed and plotted in the graph below.

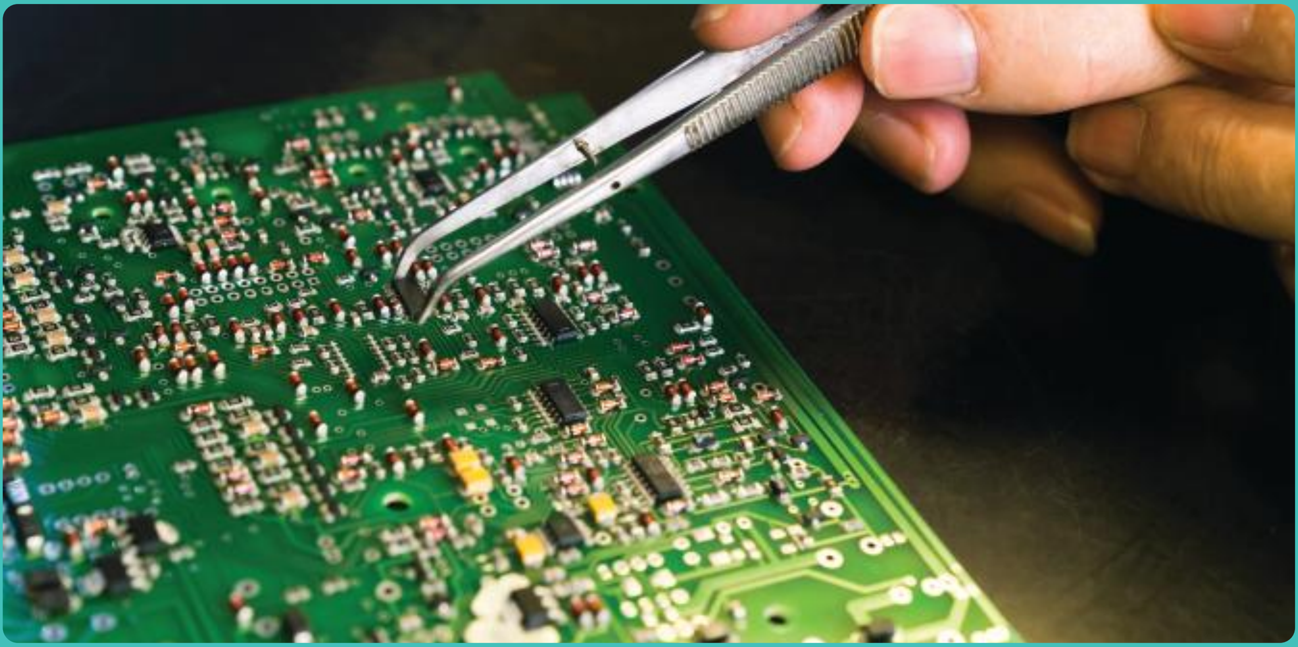


Draw a conclusion that quantifies the resistance of the resistor, including the absolute uncertainty in the value you determine. Show your reasoning.

CHAPTER

11

Circuit analysis and design

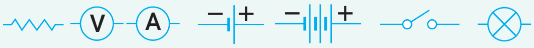


Poppy Pix/Shutterstock.com

SYLLABUS DOT POINTS

SCIENCE UNDERSTANDING

- Solve problems involving power using $P = \frac{W}{t}$.
- 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 $P = VI$, $P = I^2R$, $V_t = V_1 + V_2 + \ldots V_n$, $R_t = R_1 + R_2 + \ldots R_n$, $I_t = I_1 + I_2 + \ldots I_n$, $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$.
- Describe simple series, parallel and series/parallel circuits.

SCIENCE INQUIRY

- Investigate series and parallel circuits.
- Investigate simple circuits for specific ‘real-life’ purposes.

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Introduction

The theory behind electricity can be applied in electronic circuits and the devices that we use every day. Electronics has revolutionised the way that we live. Computers and mobile phones look very different from those of a decade ago. Technology is continually making devices faster, ‘smarter’, smaller and more user-friendly.

Practicals

- Investigating series and parallel circuits
- Designing and building simple circuits

Worksheets

- Resistor networks
- Designing a circuit

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Circuits can be set up in series, in parallel and in combination.
- ✓ Electric power is the rate of energy transformation per unit time in an electrical circuit.
- ✓ Kirchhoff's current law says the total current arriving at a junction in an electrical circuit is equal to the total current leaving the junction.
- ✓ Kirchhoff's voltage law says that for any closed loop in an electrical circuit, the sum of the potential differences must be zero.
- ✓ The relationship between resistance, voltage and current is represented by Ohm's law.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ explain the concept of power dissipation
- ✓ perform calculations to quantify power, resistance, current or voltage
- ✓ solve problems involving finding power, equivalent resistance, electrical potential difference and electric currents in series, parallel and combination circuits, using Kirchhoff's laws and other mathematical relationships
- ✓ recall and use conventional symbols used in circuit diagrams
- ✓ describe and analyse series, parallel and combination circuits
- ✓ determine the total resistance in circuits or sections of circuits
- ✓ interpret circuit diagrams to construct and analyse circuits
- ✓ design and construct circuits to analyse components
- ✓ evaluate circuit designs and their suitability in contexts such as household circuits
- ✓ recall the hazards associated with domestic electricity use and the safety devices or design features that are used to minimise risk.

11.1 Power dissipation

When electric charges run through an appliance, that appliance transforms energy for a given period of time (**Figure 11.1.1**). This is called 'power dissipation'. Given that the **potential difference** is a measure of the energy per unit of charge, and the **current** is a measure of the charge per unit of time, then the product of the potential difference and current provides a measure of the energy per unit of time. This is also known as **power**. This is shown mathematically below.

potential difference (*V*) a measure of the potential energy per unit of charge; also called voltage, $V = \frac{W}{q}$; unit: volt (V)

current (*I*) the rate of flow of charge, i.e. charge per unit time; $I = \frac{q}{t}$; unit: ampere (A)

power (*P*) a measure of the rate of energy transformation; unit: watt (W)

$$\begin{aligned}\text{Potential difference} \times \text{current} &= \frac{\text{energy difference}}{\text{charge}} \times \frac{\text{charge}}{\text{time}} \\ &= \frac{\text{energy difference}}{\text{time}} = \text{power}\end{aligned}$$

In an electrical circuit with a voltage supply and a resistor (load), such as **Figure 11.1.2**, energy is transformed and 'lost' as charge moves through the resistor. This energy difference per unit of time is the power dissipated by the resistor.

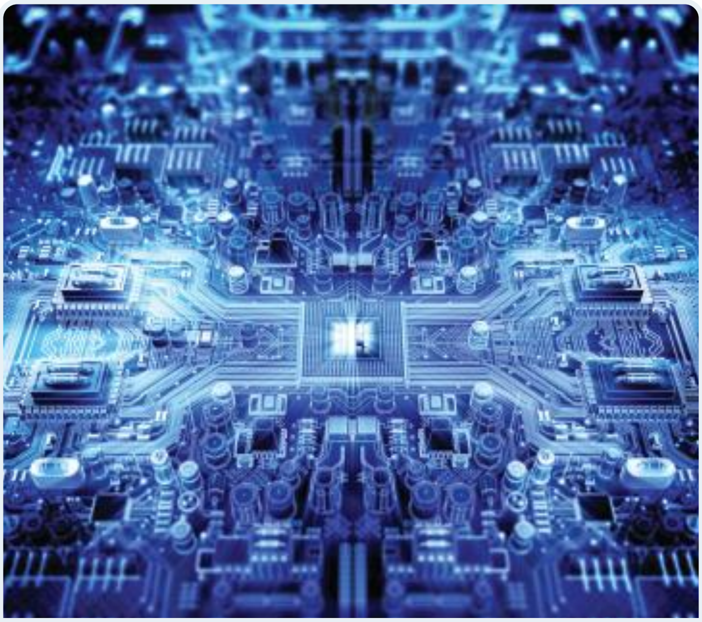

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FIGURE 11.1.1 As electronic circuits become more complex, they increase the capabilities of the electronic devices we use in daily life.

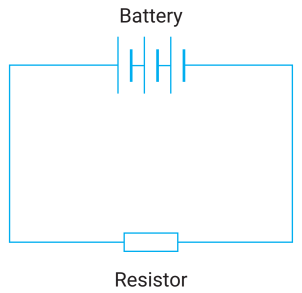


FIGURE 11.1.2 Power is dissipated as current passes through a device, such as a resistor.

Depending on the measured values available, it is often useful to combine the formula for power, $P = V \times I$ with Ohm's law, $R = \frac{V}{I}$.

It is possible to deduce new relationships between power, voltage and current.

Since $P = V \times I$ and $V = I \times R$, then:

$$P = (I \times R) \times I$$

and

$$P = I^2 \times R$$

Similarly, if $P = V \times I$ and $V = I \times R$, then:

$$P = V \times \frac{V}{R}$$

and

$$P = \frac{V^2}{R}$$

where:
V = voltage (V)
I = current (A)
t = time (s)
W = energy (J)
R = resistance (Ω)
Power is then measured in watts (W).
1.0 W = 1.0 J s^{-1} = 1.0 V A = 1.0 A^2 Ω = 1.0 V^2 $Ω^{-1}$

KEY FORMULA

Power, *P*

$$P = \frac{W}{t} = V \times I = I^2 \times R = \frac{V^2}{R}$$

where:
V = voltage (V)
I = current (A)
t = time (s)
W = energy (J)
R = resistance (Ω)
Power is then measured in watts (W).
1.0 W = 1.0 J s^{-1} = 1.0 V A = 1.0 A^2 Ω = V^2 $Ω^{-1}$

WORKED EXAMPLE 11.1.1

A 1.4 kW electric toaster is plugged into the 240 V mains supply. Calculate the:

a current drawn

b resistance of the device

c power dissipated across the resistance of the toaster

d energy lost to heat energy if the toaster is used for 30 s.

ANSWERS

a **1** **State the formula.**

$P = V \times I$

2 **Rearrange the formula to find unknown.**

$$I = \frac{P}{V}$$

3 **Substitute known values.**

$$I = \frac{1.4 \times 10^3 \text{ W}}{240 \text{ V}}$$

4 **Calculate the answer.**

$I = 5.83 \text{ A}$

b **1** **State the equation.**

$V = I \times R$

2 **Rearrange to find the unknown.**

$$R = \frac{V}{I}$$

3 **Substitute known values.**

$$R = \frac{240 \text{ V}}{5.83 \text{ A}}$$

4 **Calculate the answer.**

$R = 41.2\ \Omega$

c $P = I^2 \times R$

$= (5.83 \text{ A})^2 \times 41.2\ \Omega$

$P = 1400 \text{ W}$

d **1** **State the equation.**

$$P = \frac{W}{t}$$

2 **Rearrange to find the unknown.**

$W = P \times t$

3 **Substitute known values.**

$W = 1400 \text{ W} \times 30 \text{ s}$

4 **Calculate the answer to the correct units.**

$W = 42\,000 \text{ J}$

$= 42 \text{ kJ}$

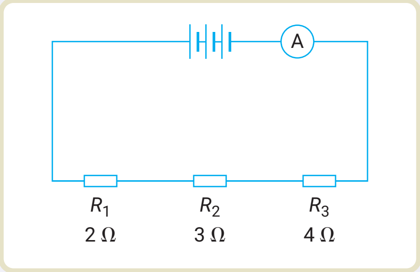
WORKED EXAMPLE 11.1.2

Determine the power dissipated across each of the resistors in the following circuit. The current measured through the circuit is 1.6 A.

ANSWER

$I = 1.6$ A

$P = I^2 \times R$



1 **For the 2 Ω resistor:**

$$P = I^2 \times R$$
$$= (1.6\text{ A})^2 \times 2\ \Omega$$
$$= 5.12\text{ W}$$

2 **For the 3 Ω resistor:**

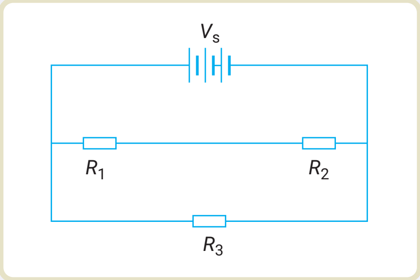
$$P = I^2 \times R$$
$$= (1.6\text{ A})^2 \times 3\ \Omega$$
$$= 7.68\text{ W}$$

3 **For the 4 Ω resistor:**

$$P = I^2 \times R$$
$$= (1.6\text{ A})^2 \times 4\ \Omega$$
$$= 10.24\text{ W}$$

WORKED EXAMPLE 11.1.3

An electrical circuit is set up with a voltage source of $V_s = 18$ V. The current splits between two parallel circuits, as shown. Determine the power dissipated across each of the resistors. $R_1 = 60\ \Omega$, $R_2 = 90\ \Omega$ and $R_3 = 20\ \Omega$.



ANSWER

1 **State the equation(s).**

$$P = \frac{V^2}{R} \quad \text{and} \quad P = I^2R$$

2 **Rearrange to find the unknown.**

For the R_1 and R_2 loop, $I = \dfrac{V}{R}$

3 **Substitute known values.**

$$I = \frac{18\text{ V}}{(60 + 90)\ \Omega}$$

4 Calculate the answer.

$$I = \frac{18\ \text{V}}{150\ \Omega}$$

$I = 0.12$ A

For the $R_1 = 60\ \Omega$ resistor:

5 State the equation.

$P = I^2 \times R$

6 Substitute the unknown values.

$P = 0.12^2 \times 60$

7 Calculate the answer.

$P = 0.86$ W

For the $R_2 = 90\ \Omega$ resistor:

8 State the equation.

$P = I^2 \times R$

9 Substitute the unknown values.

$P = 0.12^2 \times 90$

10 Calculate the answer.

$P = 1.30$ W

For the $R_3 = 20\ \Omega$ resistor:

11 State the equation

$P = I^2 \times R$

12 Substitute the known values

$P = 0.12^2 \times 20$

13 Calculate the answer.

$P = 0.288$ W

LEARNING CHECK 11.1

DESCRIBING

1 **Describe** ‘power’ in an electrical circuit.
2 **Recall** Ohm’s law.
3 Show three different equations to calculate the power dissipated from a device.

APPLYING

4 Convert:
  a 0.13 A to mA
  b 6 kW to W
  c 0.3 MV to V.
5 **Determine** the power dissipated across a 60 Ω resistor if the current measured through the circuit is 0.8 A.

11.2 Solving problems involving potential difference, current, resistance and power

WORKED EXAMPLE 11.2.1

A 0.8 kW electric kettle is plugged into the 240 V mains supply. Calculate the:

a current drawn
b resistance of the device
c power dissipated across the resistance of the kettle
d energy lost to heat energy if the kettle is used for 150 s.

ANSWERS

a **1** **State the equation.**

$P = V \times I$

2 **Rearrange to find the unknown.**

$$I = \frac{P}{V}$$

3 **Substitute known values.**

$$I = \frac{800\ \text{W}}{240\ \text{V}}$$

4 **Calculate the answer.**

$I = 3.33\ \text{A}$

b **1** **State the equation.**

$V = I \times R$

2 **Rearrange to find the unknown.**

$$R = \frac{V}{I}$$

3 **Substitute known values.**

$$R = \frac{240\ \text{V}}{3.33\ \text{A}}$$

4 **Calculate the answer.**

$R = 72.0\ \Omega$

c **1** **State the equation.**

$P = I^2 \times R$

2 **Substitute known values.**

$P = (3.33\ \text{A})^2 \times 72.0\ \Omega$

3 **Calculate the answer.**

$P = 800\ \text{W}$

d **1** **State the equation.**

$W = P \times t$

2 **Substitute known values.**

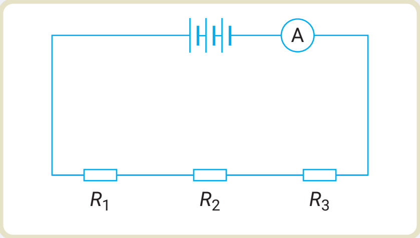
$W = 800\ \text{W} \times 150\ \text{s}$

3 **Calculate the answer.**

$$\begin{aligned} W &= 120\,000\ \text{J} \\ &= 120\ \text{kJ} \end{aligned}$$

WORKED EXAMPLE 11.2.2

Determine the power dissipated across each of the resistors $R_1 = 18\ \Omega$, $R_2 = 12\ \Omega$ and $R_3 = 24\ \Omega$ in the circuit shown. The current measured through the circuit is 0.8 A.



ANSWER

For the $R_1 = 18\ \Omega$ resistor:

1. **State the equation.**
   $P = I^2 \times R$
2. **Substitute known values.**
   $P = 0.8^2 \times 18\ \Omega$
3. **Calculate the answer.**
   $P = 11.5$ W

For the $R_2 = 12\ \Omega$ resistor:

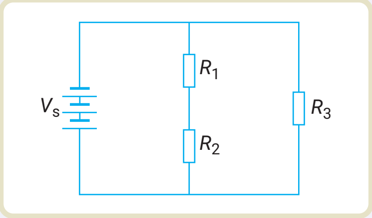
1. **State the equation.**
   $P = I^2 \times R$
2. **Substitute known values.**
   $P = 0.8^2 \times 12\ \Omega$
3. **Calculate the answer.**
   $P = 7.7$ W

For the $R_3 = 24\ \Omega$ resistor:

1. **State the equation.**
   $P = I^2 \times R$
2. **Substitute known values.**
   $P = 0.8^2 \times 24\ \Omega$
3. **Calculate the answer.**
   $P = 15.4$ W

WORKED EXAMPLE 11.2.3

An electrical circuit is set up with a voltage source of $V_s = 24$ V. The current splits between two parallel circuits, as shown. Determine the power dissipated across each of the resistors $R_1 = 6\ \text{k}\Omega$, $R_2 = 9\ \text{k}\Omega$ and $R_3 = 4\ \text{k}\Omega$.



ANSWER

1 Calculate the voltage across the circuit.

The voltage across R_1 and R_2 is shared in proportion with their resistances.

$$V_1 = 24 \times \frac{6000}{(6000 + 9000)}$$

$$= 9.6\ \text{V}$$

$$V_2 = 24\ \text{V} - 9.6\ \text{V}$$

$$= 14.4\ \text{V}$$

For the $R_1 = 6\ \text{k}\Omega$ resistor:

2 State the equation.

$$P = \frac{V^2}{R}$$

3 Substitute the known values.

$$P = \frac{9.6^2\ \text{V}^2}{6000\ \Omega}$$

4 Calculate the answer.

$$P = 0.0154\ \text{W}$$

For the $R_2 = 9\ \text{k}\Omega$ resistor:

5 State the equation.

$$P = \frac{V^2}{R}$$

6 Substitute the known values.

$$P = \frac{14.4^2\ \text{V}^2}{9000\ \Omega}$$

7 Calculate the answer.

$$P = 0.0230\ \text{W}$$

For the $R_3 = 4\ \text{k}\Omega$ resistor:

8 State the equation.

$$P = \frac{V^2}{R}$$

9 Substitute the known values.

$$P = \frac{24^2\ \text{V}^2}{4000\ \Omega}$$

10 Calculate the answer.

$$P = 0.144\ \text{W}$$

LEARNING CHECK 11.2

APPLYING

1 An 800 W electric drill is plugged into the 240 V mains supply. **Calculate** the:

  a resistance of the device
  b current drawn
  c power dissipated by the use of the drill
  d energy transformed if the drill is used for 20 min.

2 A 120 W set of electric beaters is connected to the 240 V mains supply and used for 6 min. **Calculate** the:
- **a** current drawn by the device
- **b** resistance of the beaters
- **c** power dissipated
- **d** energy lost to other forms over the time the beaters were used.

3 A 200 W electric hair straightener is plugged into the 240 V mains supply. **Calculate** the:
- **a** current drawn
- **b** resistance of the device
- **c** power dissipated from the heating element of the straightener
- **d** energy lost to heat energy if the hair straightener is used for 8 min.

4 A 2.2 kW electric radiator is plugged into the 240 V mains supply. **Calculate** the:
- **a** current drawn
- **b** resistance of the radiator
- **c** power dissipated across the resistance of the radiator
- **d** energy lost to heat energy if the radiator is used for 6 h.

11.3 Electrical circuit symbols

Electrical circuits can be complex in their design. Standard symbols are used to denote various devices and to show how they connect together. You should be able to recognise, draw and label a number of circuit symbols, including those for a resistor, a voltmeter, an ammeter, a cell, a battery, a switch and a lamp. **Figure 11.3.1** displays many of the most recognisable and useful circuit symbols. Some components, such as resistors and light globes, have more than one symbol **(Figure 11.3.2)**.

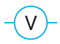
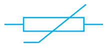
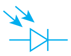
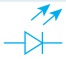
Device	Symbol	Device	Symbol	Device	Symbol	Device	Symbol
Wires crossed, not joined		Earth or ground		AC supply		Cell	
Wires joined; junction of conductor		Switch (open)		DC supply		Voltmeter	
Fixed resistor		Switch (closed)		Thermistor		Galvanometer	
Variable resistor		Diode		Light globe		Ammeter	
Light-dependent resistor		Photodiode		Battery of cells		Light globe	
Rheostat or resistor with moving contact		LED		Alternative for battery			

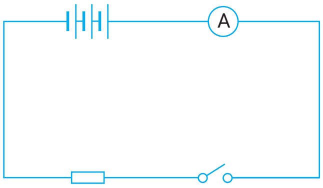
FIGURE 11.3.1 Conventional symbols used in electrical circuit diagrams

FIGURE 11.3.2 Some devices have more than one circuit symbol, such as the resistor (**a** and **b**) and the light globe (**c** and **d**). In each case, both forms are in accepted use.

WORKED EXAMPLE 11.3.1

Draw an electrical circuit with a battery of cells, a resistor and an open switch connected in series. Include an ammeter connected in series to measure the current through the circuit.

ANSWER

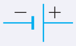


WORKED EXAMPLE 11.3.2

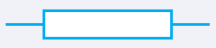
Draw and then label the following circuit symbols.

a 

b 

c 

d 

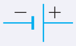
e 

ANSWERS

a 

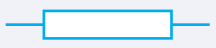
Voltmeter

b 
Light globe

c 

Cell

d 
Alternating current (AC) supply

e 
Resistor (fixed)

LEARNING CHECK 11.3

DESCRIBING

1 Draw the electrical circuit symbols for the following devices.
   - **a** Ammeter
   - **b** Voltmeter
   - **c** Cell
   - **d** Variable resistor
   - **e** Light globe

2 **Identify** two devices that have more than one accepted circuit symbol. Draw their symbols.

11.4 Series, parallel and combination circuits

There are two main types of circuits. **Series circuits** have only one path through which the current can flow **(Figure 11.4.1a)**. **Parallel circuits** have multiple paths through which current can flow **(Figure 11.4.1b)**.

In a series circuit, the charged particles only have one pathway to go along. At each point in the path, the flow of charge is the same. The current in Figure 11.4.1a is the same at points A, B and C. This is a consequence of the conservation of charge. The potential difference is shared between each of the circuit elements.

In a parallel circuit, such as in Figure 11.4.1b, there are two or more pathways for the charged particles to travel along. At a junction, charges may go either way, splitting the current. The total number of charged particles that arrive at the junction each second is the same as the total number that leave the junction each second; that is, the current into a junction equals the current out of the junction. The potential difference is the same across parallel circuit elements.

series circuit a circuit with only one path that the current can flow through

parallel circuit a circuit with multiple paths that the current can flow through

Weblink
Series and parallel circuits

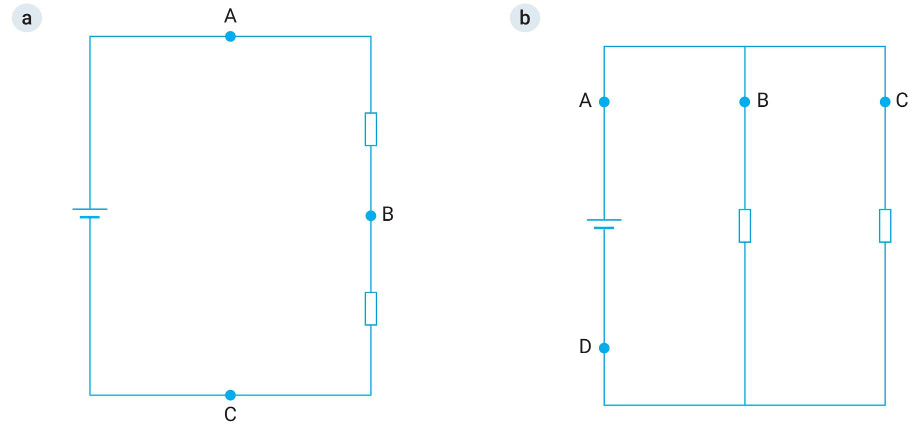


FIGURE 11.4.1 (**a**) A series circuit with two resistors. (**b**) A parallel circuit with two resistors.

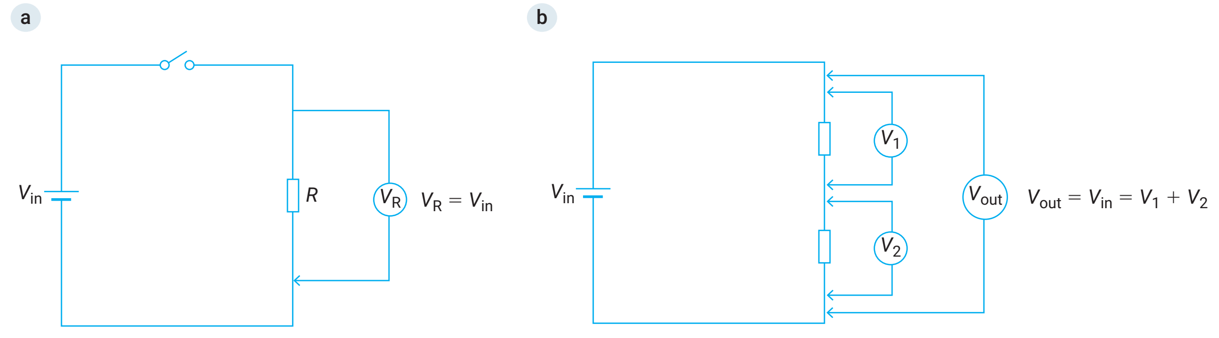


FIGURE 11.4.2 (**a**) A simple circuit comprising a source of EMF and one resistor. The potential difference across the resistor is the same as the potential difference across the source. (**b**) A series circuit comprising a potential source and two resistors in series. The sum of the potential differences across the resistors is the same as the potential difference across the source. The potential difference is shared between the resistors. The current is the same in the two resistors.

Resistors in series circuits

The potential energy per unit charge, or **EMF**, provided by a battery is used by the circuit elements. If there is one resistor in a circuit, then all the energy per unit charge, the potential difference, is applied across the resistor **(Figure 11.4.2a)**. If two resistors are placed end to end in a series circuit **(Figure 11.4.2b)**, the energy is shared between the two resistors. The current is the same in each resistor.

EMF electromotive force; source of potential energy per charge; unit: volt (V)

In a series circuit, the potential difference is shared:

$$V_t = V_1 + V_2$$

In a series circuit there are no junctions, so the current in each resistor is the same:

$$I_t = I_1 = I_2$$

Putting these together, we can deduce the equivalent resistance:

$$\frac{V_t}{I_t} = \frac{V_1}{I_1} + \frac{V_2}{I_2}$$

$$R_t = R_1 + R_2$$

Note that this result arises from the definition of resistance as the ratio of potential difference to current. It applies to all resistors connected in series. Any series circuit can be modelled by a single source and a single equivalent resistor.

From Figure 11.4.2b, you can see that the ratio of the potential differences across each resistor is equal to the ratio of the resistances. The current is the same in each resistor, so:

$$I = \frac{V_1}{R_1} = \frac{V_2}{R_2}$$

$$\frac{V_2}{V_1} = \frac{R_2}{R_1}$$

This illustrates that the potential difference is divided in the ratio of the resistances.

KEY FORMULA

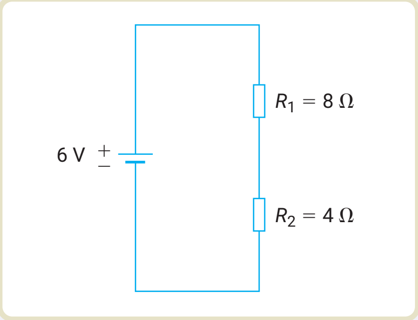
The equivalent resistance in a series circuit is the sum of all the resistances:

$$R_t = R_1 + R_2 + \ldots R_n$$

WORKED EXAMPLE 11.4.1

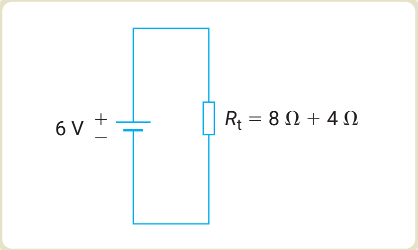
The following electrical circuit has two resistors in series.

- **a** Draw a simplified circuit.
- **b** Determine the total resistance of the circuit.
- **c** Calculate the current in the circuit.
- **d** Calculate the potential difference across:
  - **i** R_1
  - **ii** R_2



ANSWERS

a



b **1** **State the equation.**

$R_t = R_1 + R_2$

2 **Substitute the known values.**

$R_t = 8\ \Omega + 4\ \Omega$

3 **Calculate the answer.**

$R_t = 12\ \Omega$

c **1** **State the equation.**

$$R = \frac{V}{I}$$

2 **Rearrange to find the unknown.**

$$I = \frac{V}{R}$$

3 **Substitute known values.**

$$I = \frac{6\ \text{V}}{12\ \Omega}$$

4 **Calculate the answer.**

$I = 0.5$ A

d **i** **1** **State the equation.**

$V_1 = I_1 R_1$

2 **Substitute the known values.**

$V_1 = 0.5\ \text{A} \times 8\ \Omega$

3 **Calculate the answer.**

$V_1 = 4\ \text{V}$

ii **1** **State the equation.**

$V_t = V_1 + V_2$

2 **Rearrange to find the unknown.**

$V_2 = V_t - V_1$

3 **Substitute the known values.**

$V_2 = 6\ \text{V} - 4\ \text{V}$

4 **Calculate the answer.**

$V_2 = 2\ \text{V}$

Voltage dividers

voltage divider a device used to vary voltage at the output depending on a control resistor; also called a potential divider

A voltage divider is a simple series circuit in which part of the potential difference is used by each resistor. Sometimes the potential difference available from the power source is more than that required by the circuit. A **voltage divider**, or potential divider, takes advantage of the way a series circuit divides the potential difference between resistors.

The simplest voltage divider has two resistors. The potential drop across the two resistors adds to the same value as the supply voltage, V_{in}. In a voltage divider, the output voltage, V_{out}, is the potential difference across one of the resistors and so is less than V_{in}. Use Ohm's law to calculate V_{out}.

$$R_t = R_1 + R_{out}$$

From Ohm's law (transposed):

$$I = \frac{V_{in}}{R_t}$$

$$I = \frac{V_{in}}{R_1 + R_{out}}$$

and

$$I = \frac{V_{\text{out}}}{R_{\text{out}}}$$

$$\frac{V_{\text{in}}}{R_1 + R_{\text{out}}} = \frac{V_{\text{out}}}{R_{\text{out}}}$$

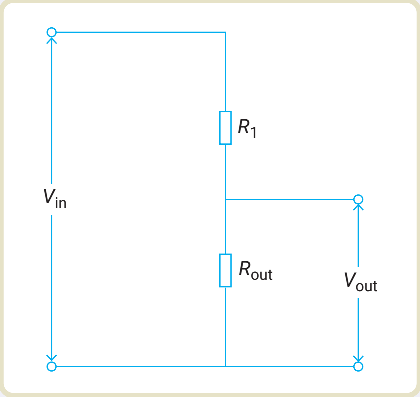
$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_{\text{out}}}{R_1 + R_{\text{out}}}$$

This is a ratio rule. The ratio of V_{out} to V_{in} is equal to the ratio of R_{out} to R_t.

Weblink
Voltage dividers

WORKED EXAMPLE 11.4.2

For the following circuit , calculate V_{out} if $V_{\text{in}} = 6.0$ V, $R_1 = 1.0$ kΩ and $R_{\text{out}} = 2.0$ kΩ.



ANSWER

1 State Ohm's law.

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{R_{\text{out}}}{R_1 + R_{\text{out}}}$$

2 Substitute the known values.

$$\frac{V_{\text{out}}}{6.0\ \text{V}} = \frac{2000\ \Omega}{1000\ \Omega + 2000\ \Omega}$$

$$\frac{V_{\text{out}}}{6.0\ \text{V}} = \frac{2000\ \Omega}{3000\ \Omega}$$

3 Calculate the answer.

$$\frac{V_{\text{out}}}{6.0\ \text{V}} = \frac{2}{3}$$

$$V_{\text{out}} = \frac{2}{3} \times 6.0\ \text{V}$$

$$= 4.0\ \text{V}$$

Resistors in parallel circuits

The energy per charge provided by a battery, the EMF, is used by the circuit elements. If two resistors are placed side by side so that the current is shared, the elements are in parallel **(Figure 11.4.3)**. Because the source of energy per charge is across both resistors, the two resistors use the same amount of energy per charge; that is, the energy per charge (potential difference) is the same across the two resistors. The current is shared between the resistors.

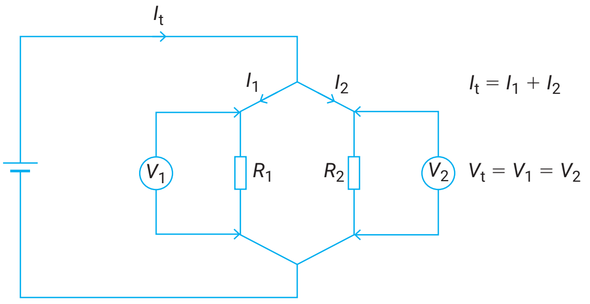


FIGURE 11.4.3 Resistors in parallel share the current and have the same potential difference.

Weblink
Resistors in series and parallel

In a parallel circuit, the potential difference is the same across each resistor:

$$V_t = V_1 = V_2$$

In a parallel circuit, the total current in the circuit is shared between the resistors:

$$I_t = I_1 + I_2$$

From this the equivalent resistance can be deduced:

$$R = \frac{V}{I}, I = \frac{V}{R}$$

Thus: $I_t = I_1 + I_2$ becomes:

$$\frac{V_t}{R_t} = \frac{V_t}{R_1} + \frac{V_t}{R_2}$$

and

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$

Note that this result arises from the definition of resistance as the ratio of the potential difference to current. It applies to all resistors connected in parallel.

Using Figure 11.4.3, we can show that the ratio of the current in each resistor is equal to the inverse ratio of the resistances. The potential difference across each resistor is the same, so:

$$V = I_1R_1 = I_2R_2$$

$$\frac{I_1}{I_2} = \frac{R_2}{R_1}$$

Worksheet
Resistor networks

KEY FORMULA

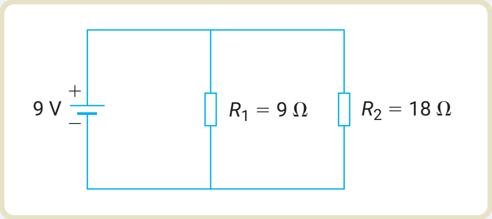
The equivalent resistance in a parallel circuit can be determined using the equation:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}$$

WORKED EXAMPLE 11.4.3

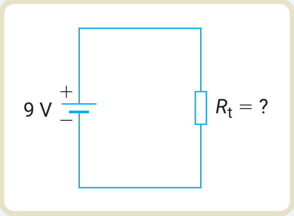
The following circuit has two resistors in parallel.

- **a** Draw a simpler circuit.
- **b** Determine the total resistance of the circuit.
- **c** Calculate the total current in the circuit.
- **d** Calculate the current through each resistor.
  - **i** R_1
  - **ii** R_2



ANSWERS

a



b **1** **State the equation.**

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$

2 **Substitute known values.**

$$\frac{1}{R_t} = \frac{2}{18\Omega} + \frac{1}{18\Omega}$$

$$\frac{1}{R_t} = \frac{1}{9\ \Omega} + \frac{1}{18\ \Omega}$$

$$\frac{1}{R_t} = \frac{3}{18\Omega}$$

3 **Rearrange to find unknown.**

$$\frac{1}{R_t} = \frac{18\ \Omega}{3}$$

4 **Calculate the answer.**

$$R_t = 6\ \Omega$$

c **1** **State the equation.**

$$R_t = \frac{V_t}{I_t}$$

2 **Rearrange to find the unknown.**

$$I_t = \frac{V_t}{R_t}$$

3 **Substitute known values.**

$$I_t = \frac{9\ \text{V}}{6\ \Omega} = 1.5\ \text{A}$$

4 **Calculate the answer**

$I_t = 1.5$ A

d **i** **1** **State the equation.**

$V_t = V_1 = V_2$

$$I_1 = \frac{V_1}{R_1}$$

2 **Substitute known values.**

$$I_1 = \frac{9\text{ V}}{9\ \Omega}$$

3 **Calculate the answer**

$I_1 = 1A$

ii **1** **State the equation.**

$I_t = I_1 + I_2$

2 **Rearrange to find the unknown.**

$I_2 = I_t - I_1$

3 **Substitute known values.**

$I_2 = 1.5 - 1.0$

4 **Calculate the answer.**

$I_2 = 0.5\text{ A}$

PRACTICAL ACTIVITY 11.4.1

INVESTIGATING SERIES AND PARALLEL CIRCUITS

Introduction

In a series circuit, there is a single path for the current to flow through, and in a parallel circuit there are multiple pathways. The type of circuit affects the way that the current and the voltage are distributed to the components.

Research question

What is the difference between series and parallel circuits when measuring current and voltage?

Aims

- To measure the change in current passing through light globes when connected in various series and parallel circuits
- To measure the voltage across circuit components

Materials

- variable DC power supply (0 to 12 V) set to 12 V
- 3 light globes rated to 12 V
- connecting wires
- 2 multimeters

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
There is a minimal risk of very small electric shock.	This risk can be managed by ensuring that the power pack is not damaged and that it is connected correctly.

Procedure

1. Connect a series circuit with one globe as shown in **Figure 11.4.4a**. Measure and record the current at each point marked A in the circuit.
2. Connect a second globe in the series circuit as shown in **Figure 11.4.4b**. Measure and record the current at each point marked A in the circuit.
3. Connect a third globe in the series circuit as shown in **Figure 11.4.4c**. Measure and record the current at each point marked A in the circuit.

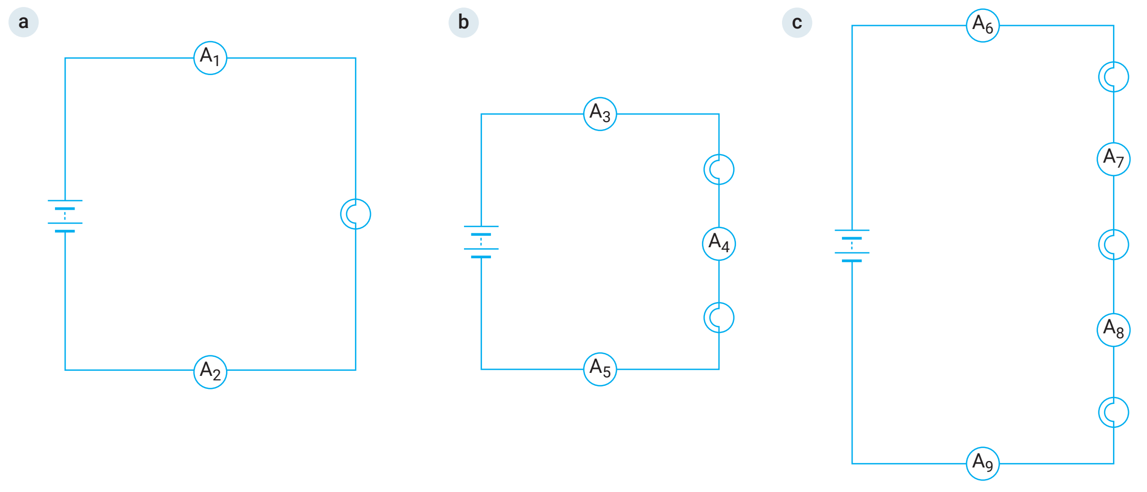


FIGURE 11.4.4 Series circuits for analysis

4 Connect two globes in parallel as shown in **Figure 11.4.5a**. Measure and record the current at each point marked A in the circuit.

5 Connect three globes in parallel as shown in **Figure 11.4.5b**. Measure and record the current at each point marked A in the circuit.

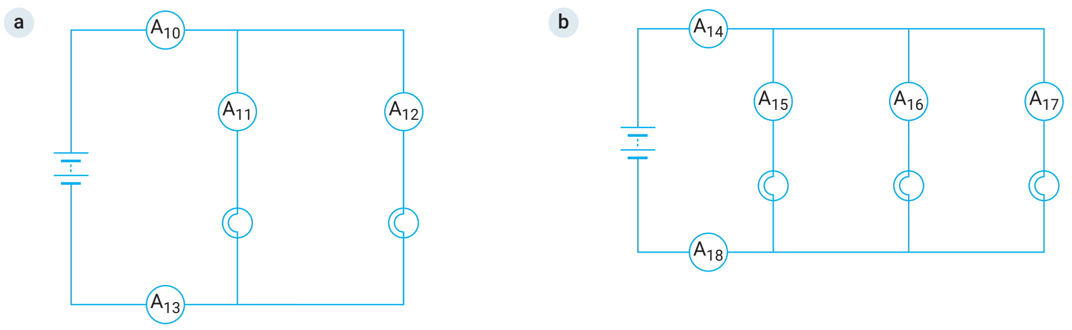


FIGURE 11.4.5 Parallel circuits for analysis

Results

Series circuit	Current	Parallel circuit	Current
1 globe	$I_1 =$	2 globes	$I_{10} =$
	$I_2 =$		$I_{11} =$
2 globes	$I_3 =$		$I_{12} =$
	$I_4 =$		$I_{13} =$
	$I_5 =$	3 globes	$I_{14} =$
3 globes	$I_6 =$		$I_{15} =$
	$I_7 =$		$I_{16} =$
	$I_8 =$		$I_{17} =$
	$I_9 =$		$I_{18} =$

Analysis of results

1 Sketch a graph comparing the number of globes on the horizontal axis with the total current on the vertical axis for the series circuit.

Interpretation

2 State what happened to the current as the number of globes increased in the series circuit. Explain how this relates to the resistance.

3 State what happened to the relative brightness as the number of globes increased in the series circuit.

4 Contrast the current values measured in the three-globe series circuit with those of the three-globe parallel circuit. Explain how this relates to the energy of each electron passing through a light globe.

Evaluation

5 What conclusions can you draw about the aims of this experiment and your findings?

Extension

6 Connect three globes in a parallel circuit as shown in **Figure 11.4.6d**. Measure and record the current at different points within the circuit.

7 Measure the potential difference across each globe for each of the four different circuits in **Figure 11.4.6**. What do you notice about the values?

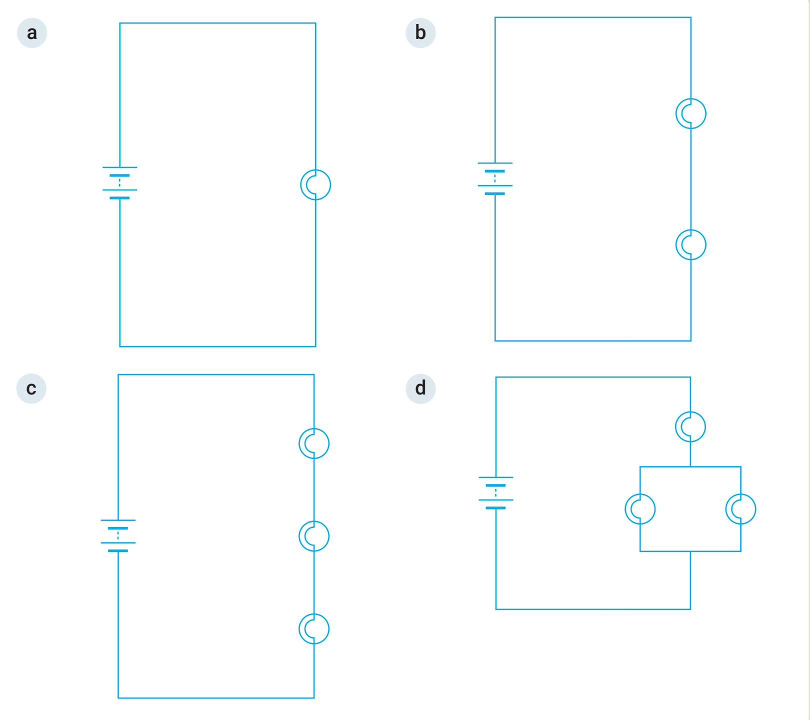


FIGURE 11.4.6 Further electrical circuits for analysis

Combination circuits

combination circuit
a circuit that contains both series and parallel components

Combination circuits have both series and parallel components, as shown in the circuit in **Figure 11.4.7**. It is particularly useful to simplify the analysis of circuits by identifying equivalent resistances. Even complex circuits can be represented in a simpler form.

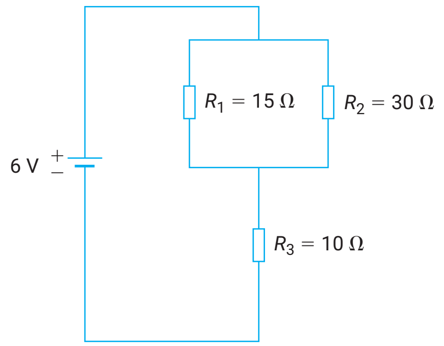


FIGURE 11.4.7 A combination circuit has both series and parallel components.

TABLE 11.4.1 Current and potential difference in series and parallel circuits

Type of circuit	Current in each circuit element is:	Potential difference across each element is:
Series	the same	shared
Parallel	shared	the same

Table 11.4.1 summarises the difference between series and parallel circuits.

Every circuit, even if it has several energy sources and several loads, can be represented by a simpler form to make it easier to analyse. A circuit can be modelled as one source of EMF that is the equivalent of all the sources, and one load that is the equivalent of all the loads.

LEARNING CHECK 11.4

DESCRIBING

1 State two other terms for the potential energy per unit of charge.

2 Complete the following statements to make them correct.

  a In a series circuit, the potential difference is ________________ .

  b In a series circuit, there are no junctions, so the current in each resistor is ________________ .

3 **Contrast** a series circuit with a parallel circuit.

4 State the rule for determining the total resistance in a series circuit.

5 State the rule for determining the total resistance in a parallel circuit.

APPLYING

6 Draw a circuit diagram with three 100 Ω resistors in series with a 60 V battery. **Calculate** the total resistance of the circuit and the current that would flow through the circuit.

7 Draw a circuit diagram with two 60 Ω resistors in parallel. **Calculate** the equivalent resistance and redraw the circuit so that it is simpler.

8 Draw a combination circuit that includes a 120 V AC supply, three 20 Ω resistors connected in parallel, and two light globes and a switch connected in series.

REFLECTING

9 Consider the steps involved in analysing circuits. Write down the main steps in order.

11.5 Circuit analysis

To analyse an electrical circuit, it is important to identify the energy source that is providing the potential difference, the components (or loads) that are transforming the energy, and the arrangement of the circuit (series, parallel or combined). It is often useful to determine equivalent resistances for parallel components and to draw simpler equivalent circuit diagrams.

You also need to apply **Kirchhoff's current law**, **Kirchhoff's voltage law** and Ohm's law for effective analysis of circuits.

Take care when applying Ohm's law, $V = IR$, to analyse combination circuits. It is important to work out which part of the circuit to apply the equation to – the whole circuit or just one component of the circuit.

To use $V = IR$ on the whole circuit, you need to know the total resistance.

To use $V = IR$ on one component, you need to know the voltage drop and/or the current in that component.

When performing calculations using Ohm's law, use $V_t = I_t R_t$ for the whole circuit and use $V_n = I_n R_n$ for individual components.

Kirchhoff's current law (first law) the total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

Weblink
Circuit analysis

Steps for analysing circuits

Analysing a combination circuit requires calculations based on the equivalent simplification of the circuit, to be able to specify the resistances, potential differences and currents of the components and of the whole circuit. A number of steps are involved in analysing a combination circuit.

1. Determine which components are connected in series, and which are in parallel.
2. Calculate the equivalent resistance across each parallel section.
3. Simplify the circuit by redrawing it, replacing the parallel resistors with a single, equivalent resistor.
4. Calculate the total current in the circuit using the total voltage and Ohm's law.
5. Use Kirchhoff's current and voltage laws, as well as Ohm's law, to determine the current through and the voltage across all components.
6. Calculate any power dissipations from the known values of current, voltage and resistance.
7. Select a value(s) to substitute back into the original problem to check your solutions.

WORKED EXAMPLE 11.5.1

Consider the following combination circuit.

a Calculate the equivalent resistance of R_1 and R_2.

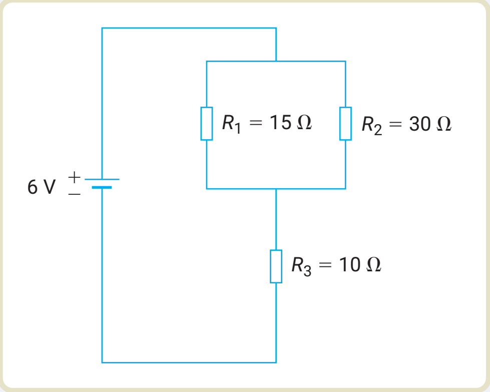
b Calculate the current in R_3.

c Draw one or more circuits to show the total resistance in the circuit as you proceed through the solution.

d Calculate the potential difference across R_3.

e Calculate the potential difference across R_1.

f Calculate the current in R_2.



ANSWERS

a 1 State the equation.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2}$$

2 Substitute known values.

$$\frac{1}{R_{eq}} = \frac{1}{15\ \Omega} + \frac{1}{30\ \Omega}$$

3 Calculate the answer.

$$\frac{1}{R_{eq}} = \frac{2}{30\ \Omega} + \frac{1}{30\ \Omega}$$

$$\frac{1}{R_{eq}} = \frac{3}{30\ \Omega}$$

$$R_{eq} = 10\ \Omega$$

b 1 State the equation.

$$V_t = I_t R_t$$

2 Rearrange to find the unknown.

$$I_t = \frac{V_t}{R_t}$$

3 Calculate the R_t.

$$R_t = R_3 + R_{eq} = 10\ \Omega + 10\ \Omega$$

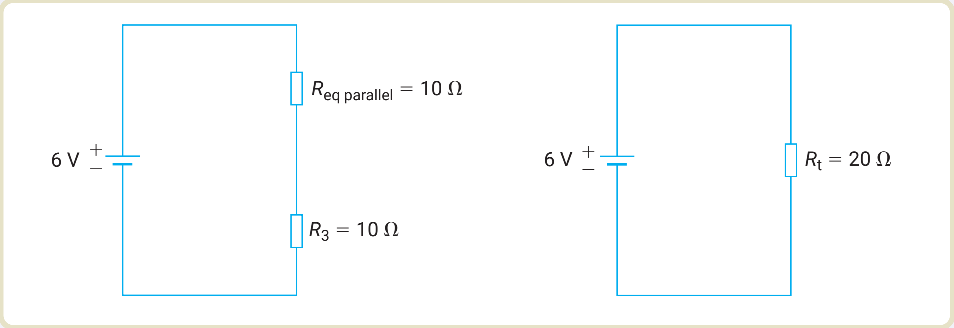
4 Substitute known values.

$$I_t = \frac{6.0\ \text{V}}{20\ \Omega}$$

5 Calculate the answer.

$$I_t = 0.3\ \text{A}$$

c Draw a series circuit with the equivalent resistance for the parallel arrangement, then redraw the circuit showing the equivalent circuit for the series arrangement.



d 1 State the equation.

$$V_3 = I_3 R_3$$

2 Substitute the known values.

$$V_3 = 0.3\ \text{A} \times 10\ \Omega$$

3 **Calculate the answer.**

$V_3 = 3\text{ V}$

e **1** **State the equation.**

$V_t = V_1 + V_3$

2 **Rearrange to find the unknown.**

$V_1 = V_t - V_3$

3 **Substitute known values.**

$V_1 = 6\text{ V} - 3\text{ V}$

4 **Calculate the answer.**

$V_1 = 3\text{ V}$

f **1** **State the equation.**

$V_2 = I_2 R_2$

2 **Rearrange to find the unknown.**

$$I_2 = \frac{V_2}{R_2}$$

3 **Substitute known values.**

$$I_2 = \frac{3\text{ V}}{30\ \Omega}$$

4 **Calculate the answer.**

$I_2 = 0.1\text{ A}$

LEARNING CHECK 11.5

DESCRIBING

1 State Kirchhoff's current and voltage laws.

2 State Ohm's law.

3 **Explain** why care must be taken when applying Ohm's law to analyse combination circuits.

APPLYING

4 Find the total equivalent resistance of a circuit if four resistors of 40 Ω were connected in:

- **a** series
- **b** parallel.

11.6 Solving further problems involving circuit analysis

WORKED EXAMPLE 11.6.1

Find the total equivalent resistance of a circuit if three resistors of 200 Ω were connected in:

a series

b parallel.

ANSWERS

In series:

a **1** **State the equation.**

$R_t = R_1 + R_2 + R_3$

2 **Substitute known values.**

$R_t = 200\ \Omega + 200\ \Omega + 200\ \Omega$

3 **Calculate the answer.**

$R_t = 600\ \Omega$

In parallel:

b **1** **State the equation.**

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

2 **Substitute the known values.**

$$\frac{1}{R_t} = \frac{1}{200\ \Omega} + \frac{1}{200\ \Omega} + \frac{1}{200\ \Omega}$$

3 **Calculate the answer.**

$$\frac{1}{R_t} = \frac{3}{200\ \Omega}$$

$$R_t = 66.67\ \Omega$$

WORKED EXAMPLE 11.6.2

Analyse the following combination circuit.

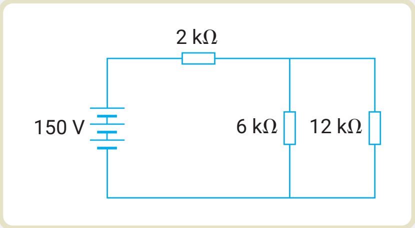
a Calculate the equivalent total resistance of the circuit.

b Redraw the circuit in a simpler form.

c Calculate the total current through the circuit.

d Calculate the potential drop across each resistor.

e Calculate the current through each resistor.



ANSWERS

a **1** **Calculate R_{eq}.**

$$\frac{1}{R_{eq}} = \frac{1}{6000\ \Omega} + \frac{1}{12\,000\ \Omega}$$

$$\frac{1}{R_{eq}} = \frac{3}{12\,000\ \Omega}$$

$$R_{eq} = 4000\ \Omega$$

2 **State the equation for total resistance.**

$R_t = 2\ \text{k}\Omega + R_{eq}$

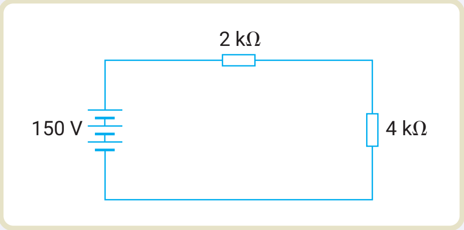
3 **Substitute known values.**

$R_t = 2\ \text{k}\Omega + 4\ \text{k}\Omega$

4 **Calculate the answer.**

$R_t = 6\ \text{k}\Omega$

b **Draw the simplified circuit.**



c 1 **State the equation.**

$V = I \times R$

2 **Rearrange to find unknown.**

$$I_t = \frac{V_t}{R_t}$$

3 **Substitute known values.**

$$I_t = \frac{150\ \text{V}}{6000\ \Omega}$$

4 **Calculate the answer.**

$I_2 = 0.025\ \text{A}$

d 1 **State the equation.**

$V = I \times R.$

For the 2 kΩ resistor:

2 **Substitute the known values.**

$V = 0.025\ \text{A} \times 2000\ \Omega$

3 **Calculate the answer.**

$V = 50\ \text{V}$

For the 6 kΩ resistor:

4 **Substitute the known values.**

$V = 150\ \text{V} - 50\ \text{V}$

5 **Calculate the answer.**

$V = 100\ \text{V}$

For the 12 kΩ resistor:

6 **Substitute the known values.**

$V = 150\ \text{V} - 50\ \text{V}$

7 **Calculate the answer.**

$V = 100\ \text{V}$

e 1 **Determine the current.**

The total current running through the circuit, $I_t = 0.025$ A, is the current running through the 2 kΩ resistor.

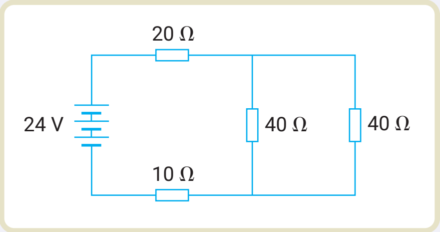
2 **Determine the current running through the resistors.**
According to Kirchhoff's current law, the total current is split between the paths through the 6 kΩ and 12 kΩ resistors unevenly, but with the same total current. Twice the amount of current will run through the 6 kΩ resistor than the 12 kΩ (as the 6 kΩ resistor has half the resistance).

3 **Calculate the answer.**

The current through the 6 kΩ resistor is $\frac{2}{3} \times 0.025\ \text{A} = 0.0167\ \text{A}$.

The current through the 12 kΩ resistor is $\frac{1}{3} \times 0.025\ \text{A} = 0.0083\ \text{A}$.

WORKED EXAMPLE 11.6.3



Analyse the following combination circuit.

a Calculate the equivalent total resistance of the circuit.
b Redraw the circuit in a simpler form.
c Calculate the total current through the circuit.
d Calculate the potential drop across each resistor.

ANSWERS

a 1 **State the relationship.**

$R_t = 20\ \Omega + R_{eq} + 10\ \Omega$

2 **State the equation and substitute the unknown values.**

To find R_{eq}:

$$\frac{1}{R_{eq}} = \frac{1}{40\ \Omega} + \frac{1}{40\ \Omega}$$

$$\frac{1}{R_{eq}} = \frac{2}{40\ \Omega}$$

3 **Calculate the R_{eq}.**

$R_{eq} = 20\ \Omega$

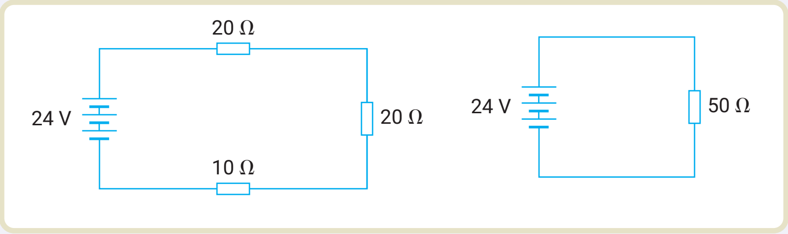
4 **Substitute known values into main equation.**

$R_t = 20\ \Omega + R_{eq} + 10\ \Omega$
$= 20\ \Omega + 20\ \Omega + 10\ \Omega$

5 **Calculate the answer.**

$R_t = 50\ \Omega$

b



c 1 **State the equation.**

$V_t = I_t \times R_t$

2 **Rearrange to find the unknown.**

$$I_t = \frac{V_t}{R_t}$$

3 **Substitute known values.**

$$I_t = \frac{24\text{ V}}{50\ \Omega}$$

4 **Calculate the answer.**

$$I_2 = 0.48\text{ A}$$

d 1 **State the equation.**

To determine the potential drop across each resistor, we need to apply Ohm's law.

Voltage drop across the 20 Ω resistor:

2 **Substitute the known values.**

$$V_{20\Omega} = I_{20\Omega} \times 20\ \Omega$$

$$V_{20\Omega} = 0.48\text{ A} \times 20\ \Omega$$

3 **Calculate the answer.**

$$V_{20\Omega} = 9.6\text{ V}$$

Voltage drop across the 40 Ω resistors:

4 **Substitute the known values.**

$$V_{40\Omega} = I_{40\Omega} \times 40\ \Omega$$

$$= 0.24\text{ A} \times 40\ \Omega$$

5 **Calculate the answer.**

$$V_{40\Omega} = 9.6\text{ V each}$$

Voltage drop across the 10 Ω resistor:

6 **Substitute the known values.**

$$V_{10\Omega} = I_{10\Omega} \times 10\ \Omega$$

$$= 0.48\text{ A} \times 10\ \Omega$$

7 **Calculate the answer.**

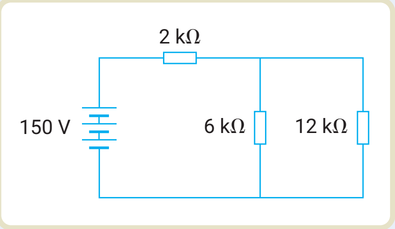
$$V_{10\Omega} = 4.8\text{ V}$$

LEARNING CHECK 11.6

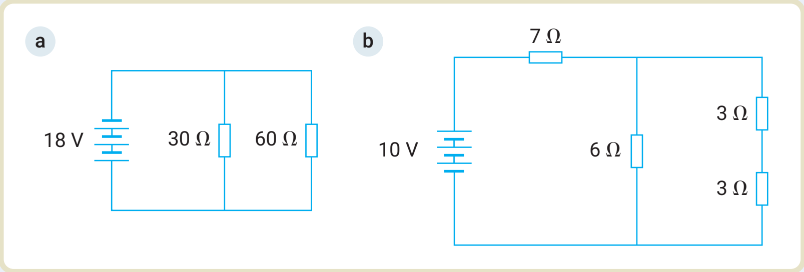
ANALYSING

1 **Analyse** the following combination circuit.

- a **Calculate** the equivalent total resistance of the circuit.
- b Redraw the circuit in a simpler form.
- c **Calculate** the total current through the circuit.
- d **Calculate** the potential drop across each resistor.
- e **Calculate** the current through each resistor.

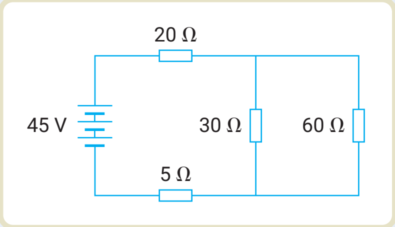


2 Simplify the following circuits by finding their equivalent resistances, then redraw the circuits in simplified form.

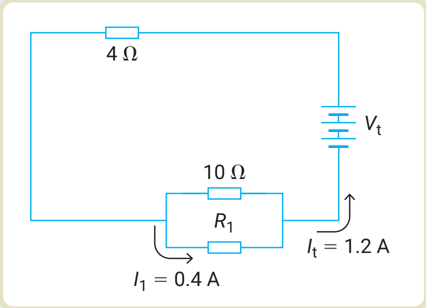


3 **Analyse** the following combination circuit.

- **a** **Calculate** the equivalent total resistance of the circuit.
- **b** Redraw the circuit in a simpler form.
- **c** **Calculate** the total current through the circuit.
- **d** **Calculate** the potential drop across each resistor.
- **e** **Calculate** the current through each resistor.

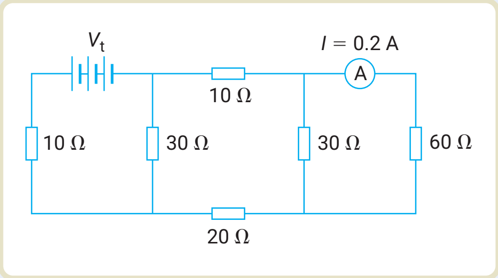


4 **Analyse** the following combination circuit to **determine** the values R_1 and V_t.



5 **Analyse** the following combination circuit to **determine** the total:

- **a** equivalent resistance
- **b** voltage supplied by the battery.



11.7 Designing circuits

Circuit design

An electrical circuit may contain many different electrical devices or components. Different circuits perform different roles, depending on whether their components are connected in series or in parallel – many circuits contain both arrangements. To design electrical circuits well, it helps to understand electrical wiring in the home **(Figure 11.7.1)**.

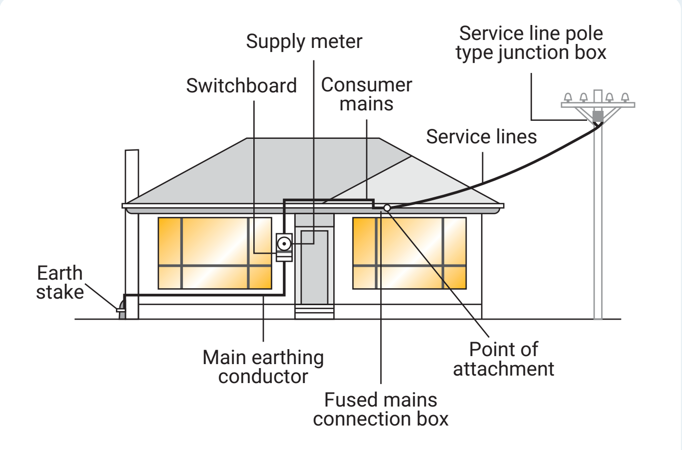


FIGURE 11.7.1 Typical household electrical supply system

Electricity in the home

The electricity supplied to houses in Australia is 240 V, 50 Hz single phase. There are two wires in the cable to the house – one is the active or phase wire and the other is the neutral wire. These come to a mains connection box that connects to the switchboard. The active lead is attached through an energy meter to the main switch and from there to a number of circuit breakers. The neutral wire is connected to a metal bar called the neutral bar, which is connected back to earth via a metal stake in the ground.

A typical electrical circuit diagram for a house can be seen in **Figure 11.7.2**. Each colour represents a circuit breaker within the switchboard. There are a

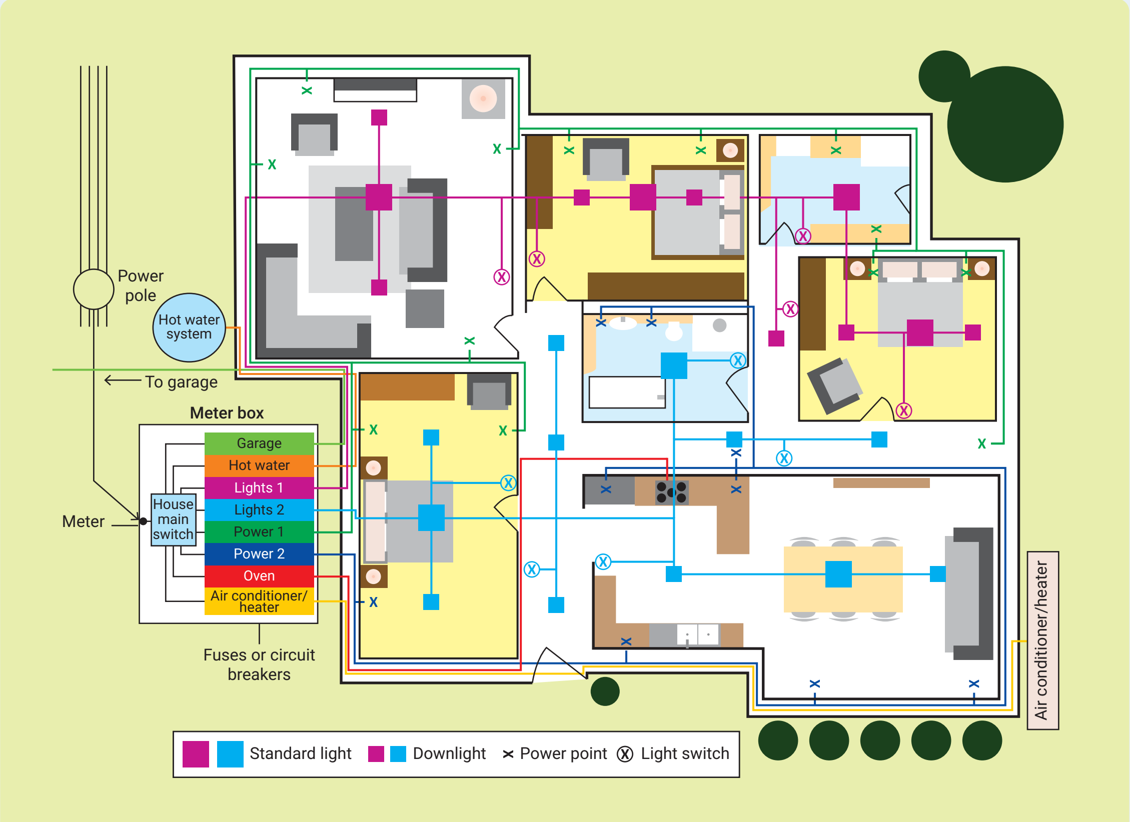


FIGURE 11.7.2 A typical electrical circuit diagram for a house

number of separate circuits for lights, power points and larger appliances. The power points and lights are connected in parallel.

Appliances are connected to the power point through a three-pin plug, or a two-pin plug if the appliance is double insulated. The active wire and the neutral wire connect to the circuit, which means that power can be supplied to the appliance. The earth wire is connected to the metal frame of the appliance so that if a fault develops, it will trip the circuit breaker.

Weblink
Tinkercad: circuits

Worksheet
Designing a circuit

Short circuits and safety devices

A **short circuit** occurs when there is a current pathway between active and neutral connecting wires, so that the current is able to bypass the appliance and use a far less resistive pathway. The effect is that, with a much smaller resistance, the current through the circuit becomes much greater than when the circuit is in normal use. This brings into play the fuse or other safety tripping device. For example, a short circuit can occur when the insulation of two wires (active and neutral) in a cord wears through and the two bare wires touch each other. Alternatively, a bare active wire may touch a metal component on an appliance that is earthed. If a person touches a 'live' appliance, they may provide the conduction path to earth, which can end in death.

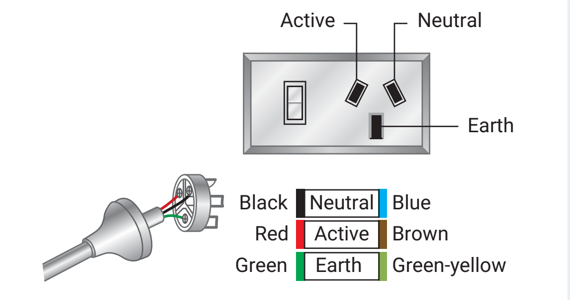


FIGURE 11.7.3 The colour code for a three-pin plug in a three-point power point

A **residual current device (RCD)**, or earth-leakage protection, provides an extra safety feature to prevent electrocution. If a person touches a live wire and electricity flows through their body, then there will be an imbalance in the amount of current flowing through the active and neutral wires. If the imbalance reaches 50 mA, then the RCD breaks the circuit within milliseconds. The RCD is typically located in the main switchboard.

It is also important to protect circuits from power surges that can damage the wiring and appliances in the home. Circuit breakers and fuses are designed to break the circuit before damage is done.

A **fuse** is a short piece of wire in the active circuit wire that melts or 'blows' when the current through it exceeds a certain value. The fuse protects the circuit from an oversupply of current. Fuses for a domestic power supply are typically rated at 30 A for appliance circuits and 15 A for lighting circuits.

A **circuit breaker** is an electromechanical device that automatically opens a switch if overload occurs. It contains an electromagnet that becomes more powerful as the current increases. When the current reaches a certain value, the electromagnet is powerful enough to force apart a contact and so break the circuit. It can do this in a very short time – less time than it takes for a piece of wire to burn through.

short circuit a connection between two points that allows current to flow with negligible resistance

residual current device (RCD) an earth-leakage protection device; safety protection against overload

fuse a temperature-dependent wire that melts if an overload occurs; safety protection against overload

circuit breaker an electromechanical switch that trips when there is an overload; safety protection against overload

PRACTICAL ACTIVITY 11.7.1

DESIGNING AND BUILDING SIMPLE CIRCUITS

Introduction

In a series circuit, there is a single path for the current to flow, whereas in parallel circuits there are multiple pathways. Combination circuits include both series and parallel components. The type of circuit affects the way that the current and the voltage are distributed to the components, and how they interact with one another.

Research question

- How does circuit design affect the brightness of a light bulb in simple circuits and how can this be applied to designing circuits in households?

Aims

- To design and build simple electrical circuits
- To model household circuits

Materials

- variable DC power supply (0 to 12 V)
- 5 light globes rated to 12 V
- resistor
- variable resistor
- 12 V electric motor
- 12 V buzzer
- 6 switches
- connecting wires

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
There is a risk of electric shock and burns.	These risks can be managed by ensuring that the power pack is not damaged and that it is connected correctly to the mains power and that circuits are turned off when not specifically required to be in use.

Switch circuits

Switches are used to operate lights, fans and other electrical appliances every day. The switch performs the function of controlling the device by completing or disconnecting the electrical circuit. The switch has contacts that, when open, break the circuit. An open switch turns the circuit off, while a closed switch turns the circuit on.

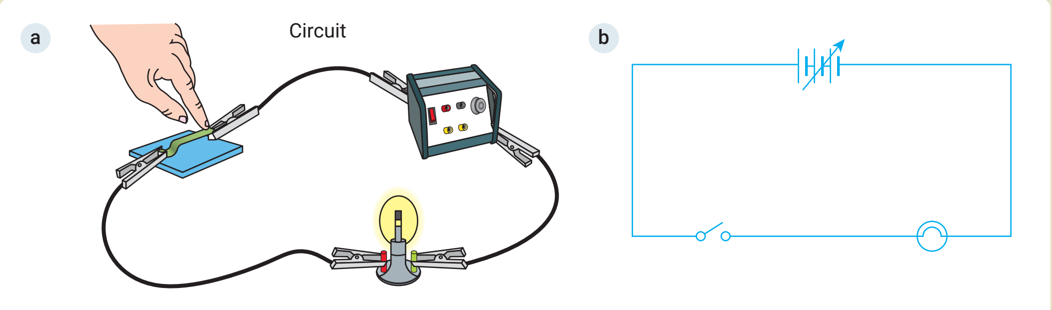


FIGURE 11.7.4 A simple switch circuit. When the switch is closed (on), the circuit is closed and the globe glows. When the switch is open (off), the power supply to the globe is shut off.

Procedure 1

1. Connect a series circuit including a variable DC power supply, a light globe and a switch, as shown in Figure 11.7.4.
2. Turn the voltage supply to 2 V and close the switch. Note the brightness of the globe.
3. Turn the voltage up to 12 V, in 2 V increments, and note the brightness of the globe as the voltage increases through 4, 6, 8, 10 and 12 V.
4. Record your observations.
5. Connect a motor or electric buzzer in series with the light globe in the circuit.
6. Turn the voltage supply to 12 V. Close the switch and observe the effect on the brightness of the globe.

Lights in series and in parallel

In a typical household, lights, power points and appliances are connected in a variety of arrangements, though frequently they are placed in parallel circuits. This allows some appliances to be left on while others are off (using switches), and allows remaining appliances to work when others have failed (e.g. a light globe blowing).

Procedure 2

1. Connect a series circuit including a variable DC power supply, two light globes and a switch, as shown in Figure 11.7.5a.

2 Turn on the voltage supply to 10 V and close the switch. Note the brightness of the globes.

3 Remove one of the light globes from its mounting – this replicates a blown light bulb.

4 Close the switch and record your observations.

5 Now connect a parallel circuit including a variable DC power supply, two light globes and a switch, as shown in Figure 11.7.5b.

6 Repeat steps 2–4 for this circuit.

Household lighting

At home, you are able to operate lights in each room independently – they don't necessarily all have to be on at once. Some lights you can dim.

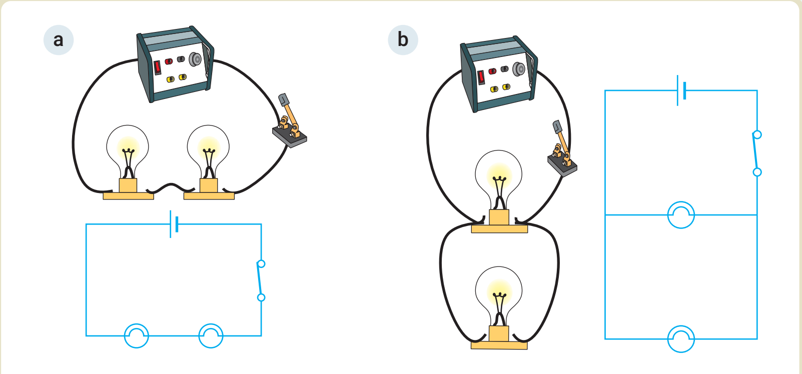


FIGURE 11.7.5 Light circuits in series and in parallel

Procedure 3

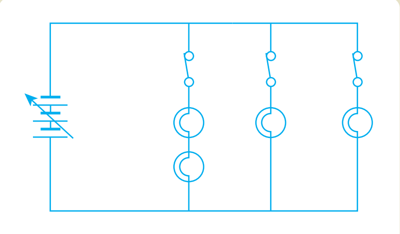


FIGURE 11.7.6 Light globes in series and in parallel circuits

1 Connect a combination circuit including a variable DC power supply and four light globes – two in series, two in separate parallel circuits as shown in Figure 11.7.6.

2 Insert a switch within each parallel circuit.

3 Turn on the voltage supply to 10 V. Close the switch on the parallel loop with two globes in series. Note the brightness of the globes.

4 Close the switch on a parallel circuit with one globe. Note the brightness of the globe.

5 Experiment with the switches for each parallel circuit, operating them independently and simultaneously. Note your observations.

Model house circuits

Or course, houses have many more circuits than simply lighting circuits. To better replicate the electrical circuitry of a house, we can construct a combination circuit with many more devices.

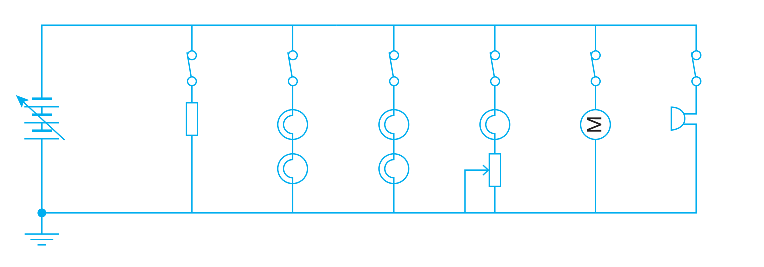


FIGURE 11.7.7 A model household combination circuit

Procedure 4

1 Connect a combination circuit including a variable DC power supply and five light globes in parallel with switches, as shown in **Figure 11.7.7**.

2 Connect a single resistor and switch in a parallel circuit. (The resistor represents a heater or toaster in the house.)

3 Connect a variable resistor (symbol ) and switch in a parallel circuit with a light globe. (The variable resistor can be used as a dimmer switch for the lighting.)

4 Connect an electric motor (symbol ) and switch in a parallel circuit. (The motor represents an appliance, such as a dishwasher, fridge or fan.)

5 Connect an electric buzzer (symbol ) and switch in a parallel circuit. (The buzzer represents a stereo.)

6 Connect a single connecting wire from the circuit to the benchtop. This represents the earth circuit.

7 Experiment with the switches for each parallel circuit, operating them independently and simultaneously. Note your observations.

Extension

Create your own household circuit, incorporating different devices. Draw the circuit diagrams for each circuit.

Results

Note your observations for each experimental procedure.

Interpretation

1 Compare your results and discuss your findings with those of other students.

2 Compare the relative brightness of bulbs as the number of globes increases in a series circuit.

3 What can you conclude about the brightness of bulbs in parallel circuits?

Evaluation

4 Identify some limitations with this experiment and the qualitative observations.

5 How could these limitations be improved?

6 What purpose do switches provide within electrical circuits?

7 What other electric appliances may be modelled with your components?

LEARNING CHECK 11.7

DESCRIBING

1 State the voltage and frequency of the mains power supply into Australian homes.

2 **Describe** the role of the residual current device, the circuit breaker and the fuse in a household electrical circuit. How are they similar and how do they differ?

3 **Explain**, with the use of a diagram, what a short circuit is.

APPLYING

4 **Explain** why there are several circuits for electric appliances within the home.

CHAPTER SUMMARY

Power

- Power is the energy difference over time. This can be expressed as:

$$P = \frac{W}{t} = V \times I$$

where: V = voltage (V)
I = current (A)
t = time (s)
W = energy (J)

- Power is dissipated as current passes through a device, such as a resistor.
- Power can be expressed as:

$$P = \frac{W}{t} = V \times I = I^2 \times R = \frac{V^2}{R}$$

where: V = voltage (V)
I = current (A)
t = time (s)
W = energy (J)
R = resistance (Ω)

Power is then measured in watts (W).

$$1.0\,\text{W} = 1.0\,\text{J}\,\text{s}^{-1} = 1.0\,\text{V}\,\text{A} = 1.0\,\text{A}^2\Omega = 1.0\,\text{V}^2\Omega^{-1}$$

- Ohm's law:

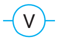
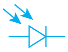
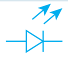
$$R = \frac{V}{I}$$

where: R = resistance (Ω)
V = voltage (V)
I = current (A)

$$1.0\,\Omega = \frac{1.0\ \text{V}}{1.0\ \text{A}} = \frac{1\ \text{volt}}{1\ \text{ampere}} = 1\,\text{V}\,\text{A}^{-1}$$

Circuit symbols

- When drawing circuit diagrams, appropriate circuit symbols need to be used.

Device	Symbol	Device	Symbol	Device	Symbol	Device	Symbol
Wires crossed, not joined		Earth or ground		AC supply		Cell	
Wires joined; junction of conductor		Switch (open)		DC supply		Voltmeter	
Fixed resistor		Switch (closed)		Thermistor		Galvanometer	
Variable resistor		Diode		Light globe		Ammeter	
Light-dependent resistor		Photodiode		Battery of cells		Light globe	
Rheostat or resistor with moving contact		LED		Alternative for battery			

- Some devices have alternative circuit symbols, such as the resistor and the light globe. In each case, both forms are in accepted use.

Series and parallel circuits

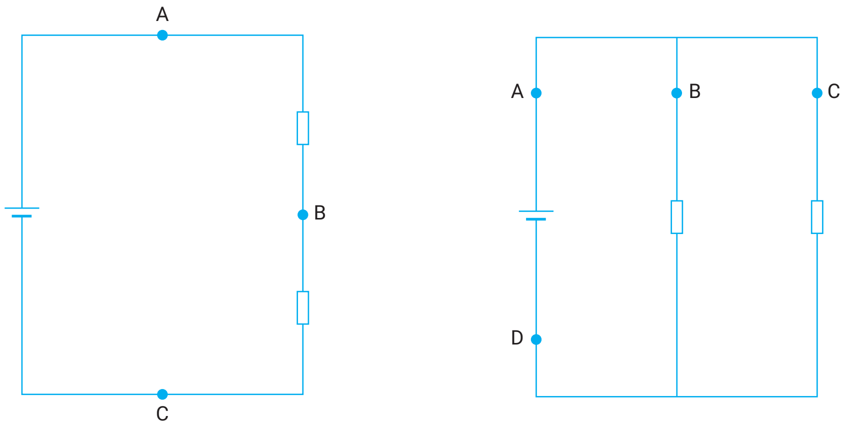
- Series circuits have components connected in a single path, whereas parallel circuits have components connected in multiple paths.
- Any series circuit can be modelled by a single source and a single equivalent resistor.
- The equivalent resistance in a series circuit is the sum of all the resistances:

$$R_t = R_1 + R_2 + . . . R_n$$

- The equivalent resistance in a parallel circuit can be determined using the equation:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + ... \frac{1}{R_n}$$

- When current flows through a device, such as a resistor, some electrical energy is converted into other forms of energy, such as heat or light.



MULTIPLE CHOICE

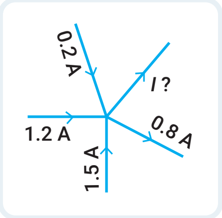
1. Which of the following statements about series and parallel circuits is incorrect?
- **A** The current within a parallel circuit splits at junctions.
- **B** The potential energy changes at different points of a series circuit.
- **C** The amount of current changes at different points of a series circuit.
- **D** The potential drop across any closed loop in a parallel circuit is equal to the supply potential.

2. The correct units for the measured values of power, current, resistance and voltage, in order, are:
- **A** P, I, Ω, V.
- **B** W, A, Ω, V.
- **C** ρ, A, Ω, mV.
- **D** P, mA, kΩ, V.

3. Which statement about parallel circuits is incorrect?
- **A** Parallel connections reduce the total resistance.
- **B** Connecting components in parallel increases resistance.
- **C** Parallel circuits are preferred for household lighting circuits.
- **D** Circuits connected in parallel may use a switch to operate independently.

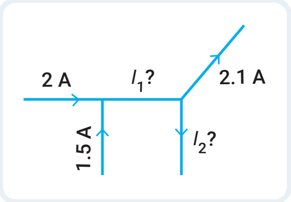
4. Which is a statement of Kirchhoff’s current law?
- **A** The total current in a parallel circuit remains the same throughout.
- **B** The total resistance within a series circuit is the sum of the individual resistances.
- **C** For any closed loop in an electrical circuit, the sum of the potential differences must be zero.
- **D** The total current arriving at a junction within an electrical circuit is equal to the total current leaving the junction.

5. What is the value of *I* in the circuit junction below?



- **A** 0.8 A
- **B** 1.2 A
- **C** 2.1 A
- **D** 3.7 A

6. The values of I_1 and I_2 respectively in the circuit below are:



- **A** 1.4 A, 3.5 A.
- **B** 2 A, 1.5 A.
- **C** 3.5 A, 1.4 A.
- **D** 5.6 A, 2.1 A.

7. What is the power consumed by a device with a current of 2 A and a resistance of 1 kΩ?

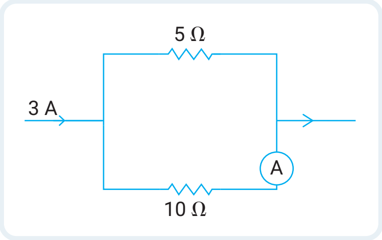
A 0.5 kW

B 2 kW

C 4 kW

D 4000 kW

8. What is the total resistance of the two resistors in the circuit below?



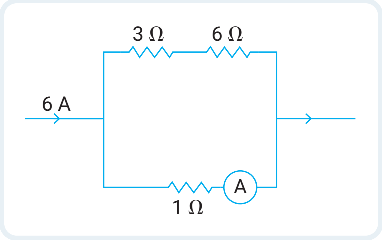
A 0.3 Ω

B 3.3 Ω

C 12.5 Ω

D 15 Ω

9. What is the total resistance in the circuit below?



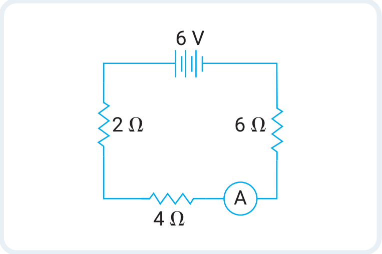
A 0.9 Ω

B 1.1 Ω

C 3 Ω

D 10 Ω

10. What will the reading on the ammeter in the circuit below be?



A 0.5 A

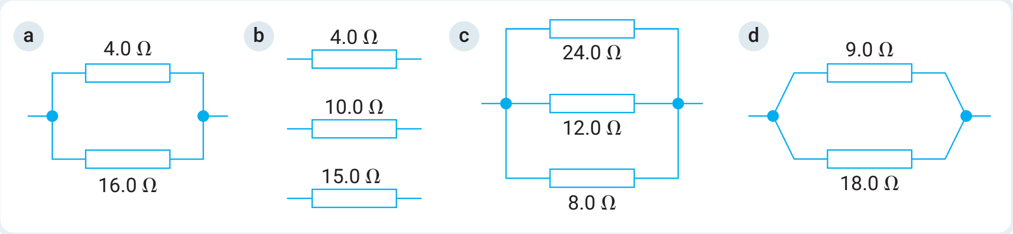
B 2 A

C 12 A

D 36 A

SHORT RESPONSE

11. Four different combinations of resistors are shown. What is the total or equivalent resistance of each combination?



CROSS-CHAPTER QUESTIONS

12. A 100 Ω resistor is placed in series with a parallel combination comprising a 200 Ω and a 500 Ω resistor. A 20 V DC power supply is connected across this combination circuit. Draw the circuit diagram and **calculate** the total resistance and voltage of the circuit as well as the current and voltages across each resistor.

13. Two 12.0 Ω resistors and one 6.0 Ω resistor are connected in series across a 6.0 V battery.

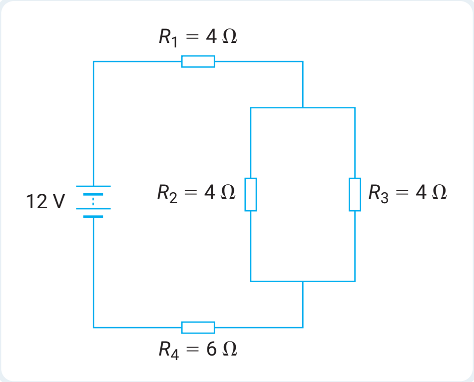
a Draw a circuit diagram to show this arrangement.

b What is the total resistance of the circuit?

c What current flows through the 6.0 Ω resistor?

d What is the potential drop across each resistor?

14. Consider the following combination circuit.



a **Calculate** the current in R_3.

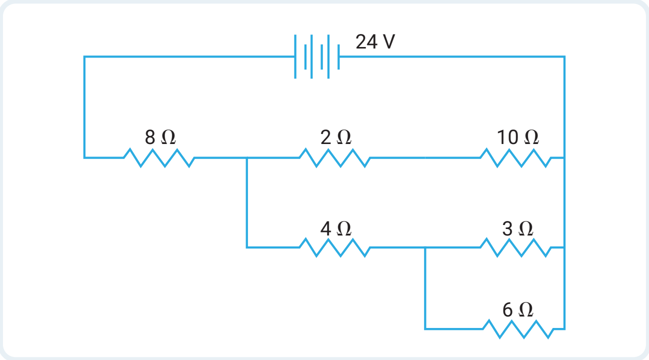
b Draw one or more circuits to show the total resistance in the circuit as you proceed through the solution.

c **Calculate** the potential difference across R_3.

d **Calculate** the potential difference across R_1.

e **Calculate** the current in R_2.

15. Consider the following combination circuit.



Use Kirchhoff's laws to **determine** the:

a current that passes through the battery
b current that passes through the 8 Ω resistor
c potential difference across the 8 Ω resistor
d potential difference across the (2 + 10) Ω resistors
e current that passes through the (2 + 10) Ω resistors
f potential difference across the 2 Ω resistor
g potential difference across the 10 Ω resistor
h current that passes through the 4 Ω resistor
i potential difference across the 4 Ω resistor
j potential difference across the 3 Ω resistor
k potential difference across the 6 Ω resistor
l current that passes through the 3 Ω resistor
m current that passes through the 6 Ω resistor.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- 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.

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Empowering a tomorrow with electrical insights

Electricity is an essential part of our modern lives, powering various aspects of our society. Here are some key uses of electricity and why understanding its physics is crucial.

- Electronics and appliances: Our smartphones, laptops, TVs and kitchen appliances all run on electricity. Knowledge of semiconductors, circuits and electromagnetism enables their design and operation.
- Medical equipment: Advanced medical devices, such as MRI machines, X-ray scanners and defibrillators, depend on electricity.
- Transportation: Electric cars, trains and trams are increasingly common. Understanding electric motors, batteries and charging systems is vital for sustainable transportation.
- Communication: The internet, mobile phones and satellites rely on electricity. Signal processing, electromagnetic waves and transmission lines play a role in global communication.

The remarkable contributions of these pioneering physicists have shaped our understanding of electrical currents and paved the way for modern electrical engineering.

Gustav Robert Kirchhoff (**Figure 1**) made fundamental contributions to electrical circuits, spectroscopy, and black-body radiation. His legacy rests on several key achievements: Kirchhoff's circuit laws: In 1845, Kirchhoff formulated his circuit laws that govern current flow and voltage distribution in complex circuits.

Georg Simon Ohm (**Figure 2**) is renowned for Ohm's law, a cornerstone of electrical theory. His groundbreaking work in the 1820s led to the understanding that the current through a conductor is directly proportional to the voltage across it and inversely proportional to its resistance. Ohm's law is succinctly expressed as $I = V/R$, where I represents current, V is voltage, and R denotes resistance.

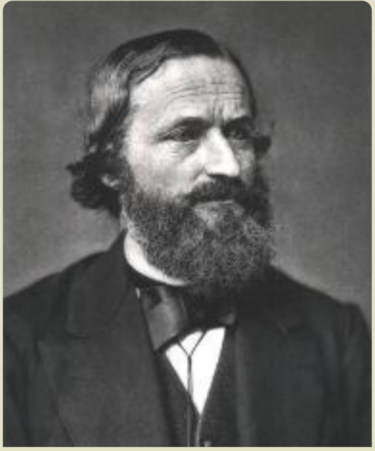


FIGURE 1 Gustav Kirchhoff

physics, Kirchhoff, G. (Gustav), 1824-1887/Smithsonian Libraries and Archives

FIGURE 2 Georg Simon Ohm

National Library of Medicine

Florence Violet McKenzie (**Figure 3**), known as 'Mrs Mac', was a trailblazer in technical education for women. Her contributions spanned mathematics, physics and engineering.

Florence Violet McKenzie, Australia's first female electrical engineer, left an indelible mark on the field.

- Wireless Shop and publications: In the 1920s and 1930s, her 'Wireless Shop' in Sydney became a hub for radio enthusiasts. She founded *The Wireless Weekly* in 1922 and authored the first 'all-electric cookbook' in 1936.
- War efforts: During World War II, McKenzie founded the Women's Emergency Signalling Corps. She successfully campaigned for female trainees to join the Royal Australian Navy, creating the Women's Royal Australian Naval Service. Her Morse code training school served more than 12 000 servicemen, and her expertise extended to civilian airlines and nautical signals.
- Voluntary contributions: McKenzie's work was largely voluntary, except for her successful electrical contracting and wireless supplies business. She dedicated her life to advancing electrical knowledge and empowering women.

FIGURE 3 Florence Violet McKenzie working with a wireless radio

State Library of New South Wales

FIGURE 4 A portrait of Hertha Ayrton

Album/Alamy Stock Photo

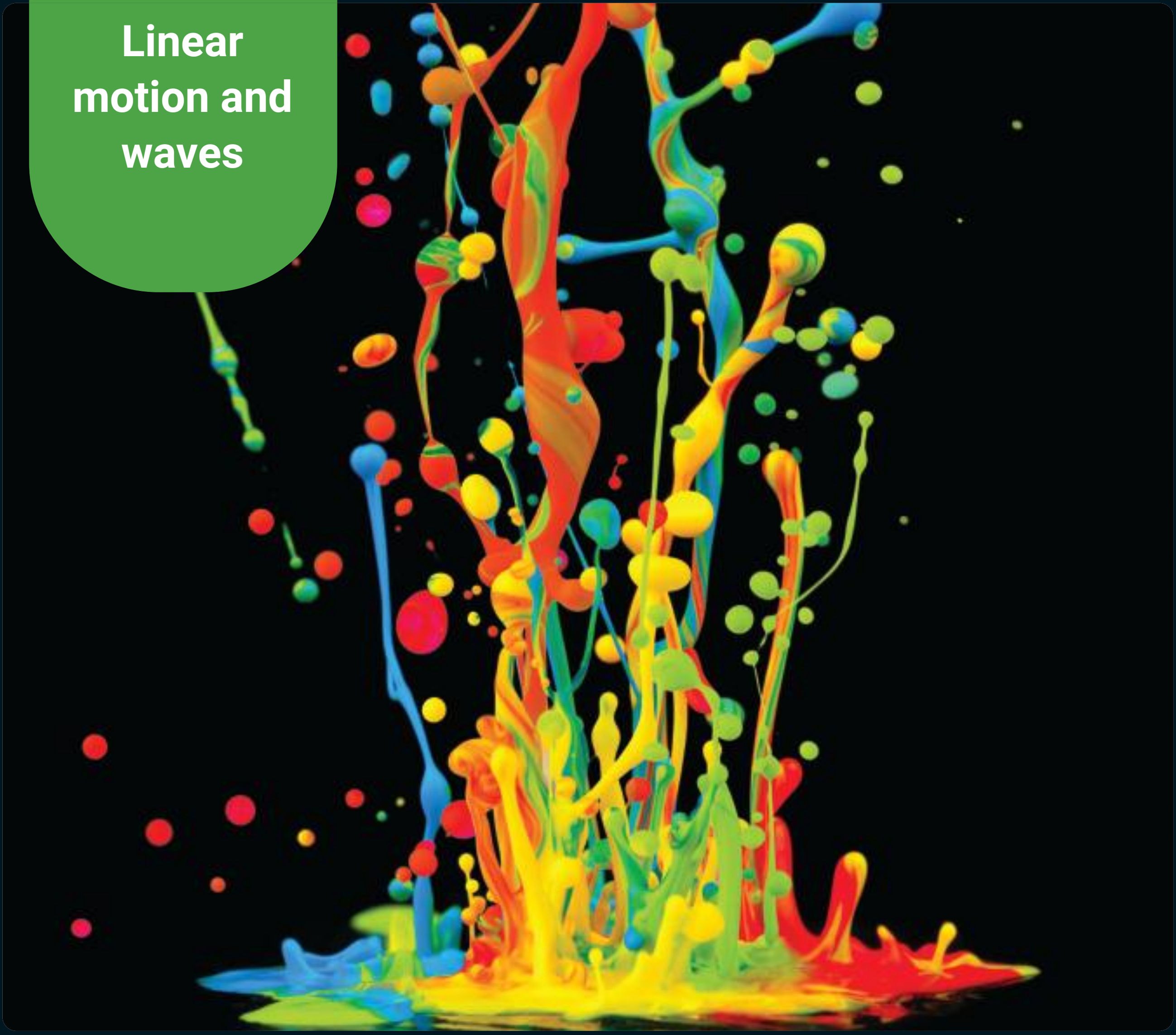
Hertha Ayrton was another prolific inventor, contributing to our understanding of many concepts in maths and physics.

- Electrical innovations: Hertha Ayrton (**Figure 4**) patented a device for dividing lines into equal parts, simplifying scaling for artists and engineers. Her inventions addressed practical challenges, making her a respected figure among Sydney radio experimenters.
- Educational advocacy: In 1934, Ayrton founded the Electrical Association for Women, promoting women's involvement in electrical fields. She believed electricity could liberate women from domestic drudgery.

In summary, these physicists and engineers – Kirchhoff, Ohm, Ayrton and McKenzie – shaped the landscape of electrical science, leaving a legacy that continues to inspire generations of scientists and engineers.

UNIT 2

Linear motion and waves



Jag_cz/Shutterstock.com

Topic 1: **Linear motion and force**

CHAPTERS RELATED TO THIS TOPIC AREA: 12–14

Topic 2: **Waves**

CHAPTERS RELATED TO THIS TOPIC AREA: 15–17

Unit 2: Linear motion and waves provides a basis for you to explore how physics is used to describe, explain and predict a wide range of phenomena. Understanding linear motion and the relationships between force, momentum and energy, as well as wave phenomena, will allow you to appreciate how physics applies in the engineering of structures and design of technologies, including accelerometers, fibre optics, lasers and car safety features. Your inquiry and analytic skills are developed through experimentation, investigation, worked examples, questions and activities that offer opportunities for interpretation, construction of algebraic, graphical and symbolic representation, and analysis of quantitative data and qualitative information.

UNIT OBJECTIVES

By the end of this unit, students should be able to:

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.

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CHAPTER 12

Vectors and linear motion


hxdyl/Shutterstock.com

SYLLABUS DOT POINTS

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. F, $\tilde{F}$ and $\vec{F}$.
- 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

- Explore the variations in final position of a person who walks 100 m.
- 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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Introduction

The boundary of a T20 cricket field is 130 m in diameter. If you walk 55 m from the centre of the cricket field, you can reach any point that is 10 m from the boundary line. This represents the distance you walked, but it does not say in which direction you walked.

In this chapter, you will consider the definition of, and differences between, quantities that have magnitude only (scalar) and those that have magnitude and direction (vector). You will also find out how to add and subtract vector quantities in one dimension, along a straight line.

The study of motion can be divided into two categories: kinematics and dynamics. Kinematics is the description of motion. Dynamics is the study of the causes and effects of motion. Kinematics is principally associated with the change of position of objects relative to other positions as time passes, including distance, displacement, speed, velocity and acceleration. Dynamics is concerned with causes of motion, including concepts of force, energy and momentum.

We will look at kinematics, in particular the simplest form of motion – a single point particle moving along a straight line. We use graphs and equations as equivalent and complementary representations of the motion of these model particles.

Practicals

- Vectors and scalars
- Gravitational acceleration
- Launch velocity

Worksheets

- Vectors
- Kinematics: analysis of data
- Kinematic graphical analysis

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Direction can be expressed in a variety of ways, including compass points and Cartesian orientation.
- ✓ The SI unit for distance is the metre (m).
- ✓ The SI unit for time is the second (s).
- ✓ The SI unit for speed is metres per second (m s^{-1}).
- ✓ You can convert between units by considering the prefixes and orders of magnitude.
- ✓ Gravity is a force that acts towards the centre of an object's (e.g. planet) mass.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ contrast vectors and scalars in relation to:
  - categorisation of physical quantities
  - representing quantities symbolically and graphically
  - calculating resultant quantities
- ✓ compare speed and velocity
- ✓ describe and explain the concepts of displacement intervals, time intervals, instantaneous time, instantaneous speed and instantaneous velocity
- ✓ calculate average speed and average velocity from numerical or graphical data
- ✓ determine instantaneous speed or velocity from numerical or graphical data
- ✓ calculate the gradient of kinematic graphs
- ✓ analyse and interpret displacement–time graphs to describe the motion of an object and to determine velocity or the presence of acceleration
- ✓ analyse and interpret velocity–time graphs to describe the motion of an object and to determine acceleration or displacement
- ✓ use the area under an acceleration–time graph to determine speed change
- ✓ interpret acceleration–time graphs to describe the motion of an object
- ✓ use algebra and kinematic equations to solve linear motion problems
- ✓ use algebra and kinematic equation to solve problems involving projectile motion in a straight line/one dimension
- ✓ perform experiments with falling objects or projectiles to determine the acceleration of gravity or launch velocity.

12.1 Scalars and vectors

A **scalar** is a quantity that has only magnitude because it uses only one scale to represent the quantity. A person who walks 55 m from a fixed point could be anywhere on a circle of radius 55 m. This would be the distance walked. **Distance** is length, without specifying where the length is leading. Distance is a scalar quantity because it is only measured on a single scale. The scale is the length scale. Area (m^2) and volume (m^3) are also scalars because they are measured using only the length scale.

scalar a quantity specified by one measurement scale only, such as magnitude

distance length, measured in metres (m)

Some scalar quantities are shown in Table 12.1.1.

TABLE 12.1.1 Scalar quantities

Quantity and usual symbol	Measurement scale
mass, *m*	kilogram, kg
distance, *d*	metre, m
time, *t*	second, s
electric current, *I*	ampere, A
temperature, *T*	kelvin, K
luminous intensity, *I*	candela, cd
amount of substance, *n*	mole, mol
energy, *E*	joule, J

Weblinks
Scalars and vectors

What is a vector?

A **vector** (from the Greek for 'to convey') quantity uses two or more measurement scales (e.g. magnitude and direction) in order to specify its full meaning. If we superimpose a compass on the 55 m walk, we can say how far and in what direction the person has walked (Figure 12.1.1).

The quantity that is specified by distance and direction from another point is the vector quantity **displacement**. Displacement is a vector quantity because it uses two scales – one to describe how far one position is away from another position (distance scale), the second to give the direction of the position relative to the other position (angle scale).

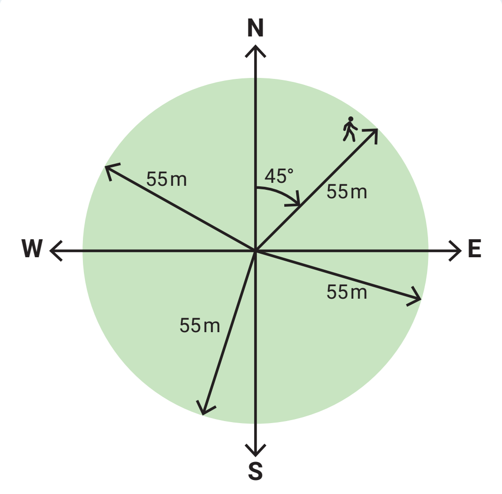


FIGURE 12.1.1 From the centre of the oval, you can walk 55 m in any direction. The position is fixed when the compass direction is specified.

Representing vectors

Vector quantities are also represented in a variety of ways. Vectors will be shown in this book as a letter symbol with an arrow on top (e.g. $\vec{A}$, $\vec{B}$, $\vec{C}$). Vectors can also be represented as bold italic letters (e.g. ***A***, ***B***, ***C***, ***s***, ***v***) or letters capped with a tilde (e.g. $\tilde{A}$, $\tilde{B}$, $\tilde{C}$). Some vector quantities are shown in Table 12.1.2.

The difference between a scalar quantity and a vector quantity is the number of measurement scales used. Scalars require one scale, whereas vectors require two or more.

vector a quantity that has magnitude and direction; quantity characterised by two or more scales

displacement position relative to another position; the difference between two positions specified with respect to an origin

TABLE 12.1.2 Some vector quantities

Quantity and usual symbol	Measurement scales
displacement, $\vec{s}$	length; m and angle
velocity, $\vec{v}$	speed; m s^{-1} and angle
acceleration, $\vec{a}$	acceleration; m s^{-2} and angle
force, $\vec{F}$	magnitude of force; N and angle
momentum, $\vec{p}$	magnitude of momentum; kg m s^{-1} and angle

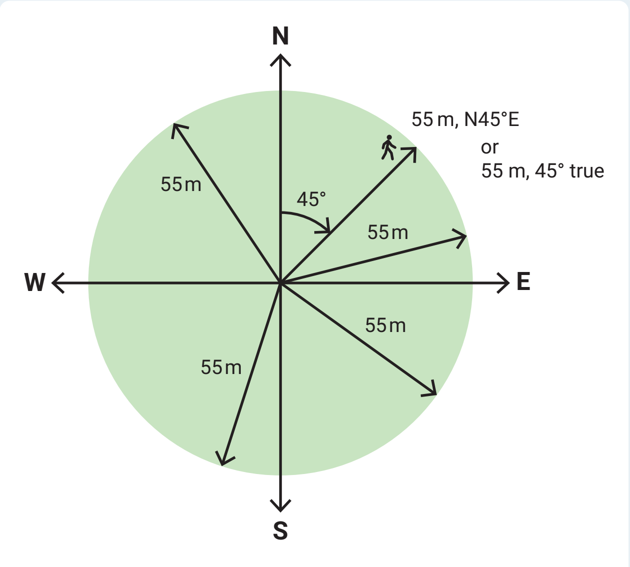


FIGURE 12.1.2 A person can walk a (scalar) distance to any point on the circle of radius 55 m. The (vector) displacement of the person shown is specified by distance (55 m) and direction (N45°E or 45° true).

Angle measures

When a compass is used for direction, the angle is given as a bearing. Bearings can be stated as quadrant bearings or true (azimuth) bearings. Quadrant bearings use the angle, usually from the north or south direction, within the relevant quarter of the compass rose **(Figure 12.1.2)**. Angles are then in the range from 0° to 90°. True or azimuth bearings take north as 0° and count 360° clockwise. For true bearings, east is 90°, south is 180° and west is 270°.

Vector arrows

Vectors are represented by arrows. Arrows have tails and heads. The arrowheads point in the direction of the quantity. The length of the arrow is proportional to the magnitude of the quantity.

If you walk from the centre of the oval a distance of 33 m east, the vector would point east and the length would be 33 m on the scale used. If you then walk 44 m north, the vector would be proportionately longer. This path leads to a point that is 55 m from the centre and in the direction N37°E. Notice that the direct distance from the starting point to the finishing point is 55 m, not 33 m + 44 m = 77 m, which is the distance actually walked. Your final displacement is 55 m, N37°E **(Figure 12.1.3)**.

Scalar multiplication

A vector can be multiplied by a scalar. The multiplier changes the magnitude of the vector **(Figure 12.1.4)**. We will see how vector multiplication applies to definitions of velocity and acceleration in section 12.3, and to force and momentum in Chapter 13.

Division by a scalar is the same as multiplying by the inverse. If you multiply the magnitudes of the three vectors in Figure 12.1.4 by $\frac{1}{11}$, which is the same as dividing the vector quantity by 11, the resultant triangle is the well-known 3, 4, 5 Pythagorean triangle.

If the multiplier is a negative value, the direction of the vector is reversed. If a north-pointing vector is multiplied by –1, the new vector points south.

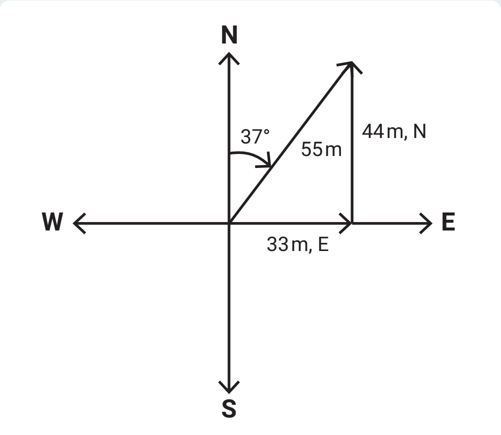


FIGURE 12.1.3 The distance travelled is 77 m but the displacement is 55 m, N37°E.

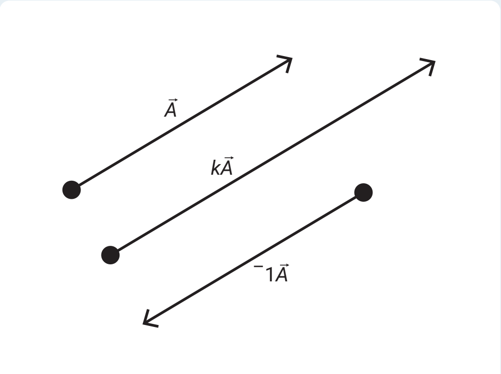


FIGURE 12.1.4 Vector arrows point from tail to head. Lengths can be changed by a scalar multiplier. Direction is reversed if the multiplier is negative.

LEARNING CHECK 12.1

DESCRIBING

1 **Describe** how to distinguish between scalar and vector.

2 **Recall** three quantities that are:
  - **a** scalar
  - **b** vector.

3 **Describe** the effect of multiplying a vector by a:
  - **a** positive number
  - **b** negative number.

APPLYING

4 **Identify** one similarity and one difference between distance and displacement.

5 **Explain** why it is useful to distinguish between distance and displacement.

6 **Identify** one similarity and one difference between quadrant bearings and true or azimuth bearings.

7 Represent the following vectors as arrows with appropriate scales.
  - **a** 10 m, N
  - **b** 100 km, W
  - **c** 25 cm, N45°E
  - **d** 45 km, 225° true

ANALYSING

8 A person cycles 20 km east, then 20 km north, then 20 km west and comes to a stop after travelling 40 km south.
  - **a** Draw the journey to scale.
  - **b** **Calculate** the distance travelled.
  - **c** State the final displacement.

9 When working with vectors, **explain** why multiplication and division can both be treated as multiplication.

Worksheet
Vectors

12.2 Movement along a straight line

Along a straight line, vector directions reduce from directions such as up, down, left or right to positive and negative. Number lines are most often drawn with the positive positions to the right of the origin and negative positions to the left (**Figure 12.2.1**). On such a number line, vectors can be added and subtracted algebraically.

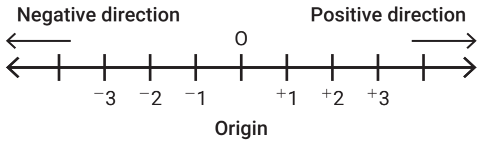


FIGURE 12.2.1 A number line showing the origin and positive and negative directions

KEY FORMULA

Along a number line, the displacement is the arithmetic difference between two positions, taking signs into account:

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

where:

$\vec{d}_1$ = initial displacement from the origin (m)

$\vec{d}_2$ = final displacement from the origin (m)

$\vec{s}$ = displacement relative to the initial position (m)

Weblink
What is displacement?

Displacement

The distance and direction between two positions is called the displacement. Along a straight line, the displacement vector for each position is either positive (to the right of the origin) or negative (to the left of the origin). Each position is at a positive or negative displacement relative to the origin. The displacement of one position on a number line relative to a second position is the difference between their positions: second position minus first position. A position on the number line is really the difference between the position and zero, the position of the origin.

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

where: $\vec{d}_1$ = initial displacement from the origin (m)

$\vec{d}_2$ = final displacement from the origin (m)

$\vec{s}$ = displacement relative to the initial position (m)

Displacement vectors may also be added to, or subtracted from, an original position displacement vector. For example, a person standing at a position of $^{+}5$ m from an origin can move a further distance of 2 m to a position either $^{+}7$ m from the origin (addition) or $^{+}3$ m from the origin (subtraction). Notice that in both cases, the person has moved 2 m, but the final positions are different.

- Addition of a positive displacement means that a person at a position, such as $^{-}6$ or $^{+}4$, moves towards the right and becomes more positive (even if the result is still on the negative side of the origin). The addition of a positively directed displacement vector to any other displacement vector always makes the resultant vector more positive.
- Subtraction of a positive displacement is really the addition of a negative displacement. Thus, subtraction of a positive displacement means that, for example, a person at a position $^{-}8$ or $^{+}5$, moves towards the left and becomes less (or more negative, even if the result is on the positive side of the origin). The subtraction of a positively directed displacement vector from another displacement vector always makes the resultant vector more negative.
- Subtraction of a negative displacement is the addition of the opposite displacement; that is, the addition of the opposite of negative, which is a positive. Thus, the subtraction of a negative displacement means that a person at a position, such as $^{-}10$ m or $^{+}2$ m, moves towards the right and becomes more positive. The subtraction of a negative displacement vector from another displacement vector always makes the resultant vector more positive.

Distance

The distance travelled is different from the displacement. Distance is the magnitude of a displacement. If an object undergoes several position changes, the distance travelled is the sum of all the different displacements that make up the journey.

If the motion involves moving from the origin a distance d and back, the displacement is zero. However, the total distance travelled is the sum of the distance of the outward displacement and the distance of the return displacement. Therefore, distance is related to the *magnitudes* of the individual changes of position. It is the sum of the magnitudes of the individual displacements.

The magnitude of a displacement is the distance. We represent the magnitude by the modulus sign ||.

For any one displacement from position 1 to position 2, the distance is given by the magnitude of the vector displacement:

$$d = \left|\vec{d}_2 - \vec{d}_1\right|$$

- The distance of a journey is the sum of all the distances.
- In practice, this process is quite straightforward; trace the movement backwards and forwards along the number line and keep count of the individual distances moved.

KEY FORMULA

For any one displacement from position 1 to position 2, the distance is given by the magnitude of the vector displacement:

$$d = \left|\vec{d}_2 - \vec{d}_1\right|$$

WORKED EXAMPLE 12.2.1

An object moves from the origin to position P at $^{+}2$ m and then to the position Q at $^{+}5$ m. Show working to calculate the:

a distance from the origin to P

b distance from the origin to Q

c distance between P and Q

d displacement of Q relative to P

e displacement of P relative to Q.

ANSWERS

a **1** **State the equation.**

$d = \left|\vec{d}_2 - \vec{d}_1\right|$

2 **Substitute the known values.**

$d = \left|^{+}2\,\text{m} - 0\,\text{m}\right|$

3 **Calculate the answer.**

$d = 2\,\text{m}$

b **1** **State the equation.**

$d = \left|\vec{d}_2 - \vec{d}_1\right|$

2 **Substitute the known values.**

$d = \left|^{+}5\,\text{m} - 0\,\text{m}\right|$

3 **Calculate the answer.**

$d = 5\,\text{m}$

c **1** **State the equation.**

$d = \left|\vec{d}_2 - \vec{d}_1\right|$

2 **Substitute the known values.**

$d = \left|^{+}5\,\text{m} - {}^{+}2\,\text{m}\right|$

3 **Calculate the answer.**

$d = 3\,\text{m}$

d **1** **State the equation.**

$\vec{s} = \vec{d}_2 - \vec{d}_1$

2 **Substitute the known values.**

$\vec{s} = {}^{+}5\,\text{m} - {}^{+}2\,\text{m}$

3 **Calculate the answer.**

$\vec{s} = {}^{+}3\,\text{m}$

Note: This answer indicates that Q is 3 m to the right relative to P.

e **1** **State the equation.**

$\vec{s} = \vec{d}_2 - \vec{d}_1$

2 **Substitute the known values**

$\vec{s} = {}^{+}2\text{ m} - {}^{+}5\text{ m}$

3 **Calculate the answer.**

$\vec{s} = {}^{-}3\text{ m}$

Note: This answer indicates that P is 3 m to the left relative to Q.

PRACTICAL ACTIVITY 12.2.1

VECTORS AND SCALARS

Research question

What is the difference between displacement and distance?

Aim

To compare measurements of displacement and distance

Materials

- large open space such as a school oval
- access to a GPS or long tape measure or trundle wheel
- compass or equivalent app
- 13 flags, stakes or cones
- mallet
- logbook or equivalent to record your actual procedure and results

Procedure

Part A

1. Identify a suitable origin and place a flag there. Mark out a 55 m radius circle. Place flags on the circumference every 45° (8 flags).
2. Walk directly north of the origin for 55 m. Place a flag at this position. Record the vector along which you have just walked.
3. Walk directly back to the origin. Record the vector along which you have just walked. When you return to the origin, record:
    - the distance you walked
    - your displacement.
4. Repeat steps 2 and 3, except now walk:
    - 55 m east of the origin and back
    - 55 m south of the origin and back
    - 55 m west of the origin and back.

Part B

1. Walk directly east of the origin for 33 m and place a flag. Record the vector along which you have just walked.
2. Walk directly north from this position until you reach the circumference of the circle. Record your estimate of:
    - the distance you travelled north
    - the vector along which you have just walked
    - the distance from the origin you walked
    - your displacement.
3. Using only the directions N–S, E–W, undertake a walk of 20 m followed by a walk that ends on the circle. Record your estimate of the:
    - distance you travelled to the circle
    - displacement from the origin.

Results

Summarise your results in visual form, such as a one-page poster or interactive slide.

Analysis and interpretation of results

1. Provide a definition and example from this practical activity of a:
   - **a** scalar
   - **b** vector.
2. Define:
   - **a** origin
   - **b** distance
   - **c** displacement.
3. Demonstrate the difference between distance and displacement by referring to your results from:
   - **a** Part A
   - **b** Part B.
4. For a position on the circle that is south-west of the origin, state the distance and the displacement.
5. Calculate the distance travelled and the final displacement from the origin for the following walks.
   - **a** 40 m E followed by 25 m W
   - **b** 55 m N followed by 110 m S
   - **c** 40 m S followed by 60 m N
   - **d** $^{-}25$ m E followed by 25 m W
6. Describe the two possible walks that start with a 33 m walk to the south and end up on the circle.
7. Would a walk of 20 m west followed by a walk of 45 m south end on the circle? Explain with reference to your data.

Evaluation

8. Explain how this practical activity has affected your understanding of directed numbers. In your answer, refer to data you collected.
9. For this practical activity, identify and describe three things you did well and three things you believe you could improve. Consider such things as preparation, recording your actual procedures, measurement strategies, time spent actually doing the measurements, recording results, summarising and completion of questions.
10. Identify three ideas that this practical activity has helped you to understand better.

LEARNING CHECK 12.2

DESCRIBING

1. **Write** the formula for.
   - **a** displacement
   - **b** distance.
2. **Explain** how magnitude is related to displacement.

APPLYING

3. Perform the following displacement calculations.
   - **a** $^{-}6\text{ km} + {}^{+}5\text{ km}$
   - **b** $^{+}4\text{ m} + {}^{+}5\text{ m}$
   - **c** $^{-}8\text{ cm} - {}^{+}2\text{ cm}$
   - **d** $^{+}5\text{ m} - {}^{+}2\text{ m}$
   - **e** $^{-}10\text{ km} - {}^{-}3\text{ km}$
   - **f** $^{+}2\text{ mm} - {}^{-}3\text{ mm}$

ANALYSING

4. **Explain** the following statement: ‘Distance is related to the *magnitudes* of the individual changes of position.’

EVALUATING

5. Consider whether the mathematical formula for distance or your own way of thinking is better for working out distances.

12.3 Linear motion: displacement, velocity and acceleration

frame of reference a system within which measurements are made; point of view

The motion of objects can be described quantitatively by measuring their positions at particular times. Position is measured by reference to a suitable **frame of reference**. For example, the motion of a car or an aeroplane can be described by assuming that Earth is stationary. A suitable origin is selected from which to measure changes in position on Earth as time changes. Change in position can then be analysed using scalar or vector quantities. Distance is a scalar quantity because it is measured using a single scale. Displacement is a vector quantity because it uses two scales: distance and direction. In straight-line motion, the vectors can be represented as movement in the positive and negative directions on a number line.

centre of mass the point in an extended particle where all the mass can be considered to be concentrated

In order to simplify this analysis, we assume that all objects are point masses. A car, a runner or an aeroplane are all modelled as though their entire mass is concentrated at their **centre of mass** (Figure 12.3.1). More detailed analysis is required to determine what happens when extended objects interact, such as deformations in car crashes.

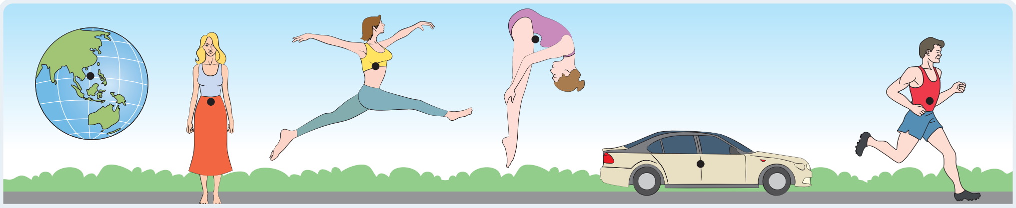


FIGURE 12.3.1 The centres of mass of some extended bodies are the points at which all the mass can be considered to be concentrated.

Movement along a straight line

Measurements of position and time are fundamental to the description of motion. If a point mass is at the same position as time passes, it is stationary. If its position changes as time changes, it must have a speed, and hence, velocity. If its speed and/or velocity changes as time changes, it is accelerating.

interval a change in a quantity, such as time interval, displacement interval or velocity interval

velocity the rate of change of displacement; speed with direction (vector) with respect to time

speed the time rate of change of distance; magnitude of velocity (scalar) with respect to time

acceleration the rate of change of velocity (vector); magnitude of rate of change of speed (scalar) with respect to time

An **interval** is any change in a quantity. A time interval is a scalar difference between two times. Differences in position are vector displacement intervals. The magnitude of a displacement interval is a scalar distance interval.

Velocity is the rate at which the displacement changes during a time interval. Because the displacement change is a vector, velocity is a vector: **speed** is its magnitude. Similarly, acceleration is a vector because the change in velocity – the velocity interval – also occurs over a time interval. The term '**acceleration**' is used both to refer to the vector acceleration and the scalar magnitude of the vector. Just like speed and velocity, acceleration is ultimately determined using measurements of position and time.

Displacement interval

An object's position is the difference between the origin and its position relative to the origin.

In Figure 12.3.2, position A has a displacement interval of $^{+}25$ cm relative to O because:

$$\begin{aligned}\vec{s} &= \vec{d}_2 - \vec{d}_1 \\ &= {}^{+}25\text{ cm} - 0\text{ cm} \\ &= {}^{+}25\text{ cm}\end{aligned}$$

Similarly, position B has a displacement interval of $^{-}40$ cm relative to O.

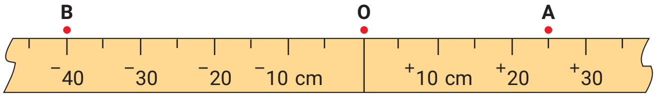


FIGURE 12.3.2 By defining a starting point or origin, opposite directions can be designated positive and negative values.

WORKED EXAMPLE 12.3.1

In Figure 12.3.2, an object moves from O to A, then from A to B.

a Calculate the final displacement at B, relative to the origin.
b Calculate the distance interval between A and B.
c What is the total distance moved by the object?

ANSWERS

a 1 **State the equation.**

$\vec{s} = \vec{d}_2 - \vec{d}_1$

2 **Substitute known values.**

$\vec{s} = {}^{-}40\ \text{cm} + {}^{+}0\ \text{cm}$

3 **Calculate the answer.**

$\vec{s} = {}^{-}40\ \text{cm}$

b 1 **State the equation.**

$\vec{d} = \left|\vec{d}_2 - \vec{d}_1\right|$

2 **Substitute the known values.**

$d = \left|25\text{cm} + 40\text{cm}\right|$

3 **Calculate the answer.**

65 cm

c 1 **Identify the relationship between total distance and displacement.**

Total distance is the sum of all the magnitudes of the displacement intervals.

2 **Substitute known values.**

$d = \left|{}^{+}25\ \text{cm} - 0\ \text{cm}\right| + \left|{}^{-}40\ \text{cm} - {}^{+}25\ \text{cm}\right|$

$= 25\ \text{cm} + 65\ \text{cm}$

3 **Calculate the answer.**

$d = 90\ \text{cm}$

Time interval

Each moment of time is measured by a clock. A particular instance of time is called **instantaneous time**, t_{inst}. A **time interval**, t, is the difference between two instantaneous time measurements, t_1 and t_2:

$$t = t_2 - t_1$$

The time of day, such as 9:00 am, is really 9:00 hours after the zero of time (midnight, 0:00 am) for the day, where $t_1 = 0$.

instantaneous time a particular moment on a clock

time interval the time between two measurements of time

Unit of time

The SI unit for time, hence time interval, is the second, s.

LEARNING CHECK 12.3

DESCRIBING

1 **Describe** the difference between distance and displacement.
2 **Explain** why any measurement of time is a measure of a time interval.
3 **Explain** why any measurement of displacement is a measure of a displacement interval.

APPLYING

4 **Calculate** the time interval between:
  - **a** 3.0 s and 7.0 s
  - **b** 0.0245 s and 1.37×10^{-2} s.

5 **Calculate** the distance interval between:
  - **a** $^{+}15.1$ m and $^{-}4.3$ m
  - **b** $^{-}0.784$ m and $^{+}9.0$ mm.

12.4 Linear motion: speed and velocity

In physics, speed relates to the distance covered (distance interval) in a time interval; velocity specifically relates to the change in displacement (displacement interval) during a time interval.

Average speed

Speed, v, is a measure of how fast something is travelling. It is the rate at which distance changes as time changes. Speed is a scalar quantity because it measures only the magnitude of the rate of change of distance, s, a scalar, as the scalar time, t, changes.

Average speed is the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in the time interval.

average speed the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in a given time interval

$$v_{av} = \frac{d}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

Note that the quantities s and t are intervals, not instantaneous values.

A flight from Coolangatta to Cairns, a distance of about 1500 km, might take 2.5 hours flying time. The average speed would be 600 km h^{-1}; however, the instantaneous speeds that occur during ascent, descent and other parts of the journey may vary considerably from the average speed.

Average velocity

Velocity, v, is a measure of how fast something is travelling in a particular direction. It is the rate at which displacement changes as time changes. Velocity is a vector quantity because it measures the rate of change of displacement, $\vec{s}$, a vector, as time, t, changes.

Average velocity, $\vec{v}_{av}$, is a vector because it is the average rate of change of displacement, a vector, as time changes.

$$v_{av} = \frac{d}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

where: v_{av} = average velocity (m s^{-1})
s = displacement interval (m)
$t = t_2 - t_1$ = time interval (s)
$\vec{d}_2 - \vec{d}_1$ = magnitude of the displacement interval (m)

Note again that the quantities, $\vec{s}$ and t are intervals, not instantaneous values. Note also that, because the displacement has been multiplied by the scalar value, $\frac{1}{t}$, the vector displacement interval, $\vec{s} = \vec{d}_2 - \vec{d}_1$, and the average velocity vector, $\vec{v}_{av}$, are in the same direction.

KEY FORMULA

$$v_{av} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

where: v_{av} = average velocity (m s^{-1})
s = displacement interval (m)
$t = t_2 - t_1$ = time interval (s)
$\vec{d}_2 - \vec{d}_1$ = magnitude of the displacement interval (m)

Unit of speed and velocity

The SI unit for speed and velocity is derived from their definitions. Both are defined in terms of the ratio of a distance measure to a time measure:

$$[v] = \frac{[s]}{[t]} = \frac{\text{metre}}{\text{second}} = \text{m/s, m s}^{-1}$$

where: $[v]$ = unit of speed or velocity (m s^{-1})
$[s]$ = unit of distance or displacement (m)
$[t]$ = unit of time (s)

Note: The square brackets mean ‘unit of’; thus $[s]$ means ‘unit of distance scale’, $[t]$ means ‘unit of time scale’.

KEY FORMULA

$$[v] = \frac{[s]}{[t]} = \frac{\text{metre}}{\text{second}} = \text{m/s, m s}^{-1}$$

where: $[v]$ = unit of speed or velocity (m s^{-1})
$[s]$ = unit of distance or displacement (m)
$[t]$ = unit of time (s)

Weblink
Speed, velocity and displacement

Instantaneous speed and instantaneous velocity

Speeds and velocities occur at particular moments, or instances, in time. But all measurements of speed and velocity depend on measurements of intervals of distance or displacement and intervals of time. If the time interval is very small, there is not much time for the speed or velocity to change markedly. For small time intervals, the difference between the average value and the instantaneous value is **negligible**. This means that the difference can be ignored for most purposes.

negligible so small it can be ignored; very little

WORKED EXAMPLE 12.4.1

A particle starts at the origin, moves 40 cm to the right before coming to rest 25 cm to the left of the origin 15 s later.

a Find the average speed.
b Calculate the average velocity.

ANSWERS

a **1** **State the equation.**

Average speed is distance covered in a time interval.

$$v_{av} = \frac{d}{t}$$

In this example, there are two separate displacements:

i from origin to $^{+}40$ cm
ii from $^{+}40$ cm to $^{-}25$ cm.

2 **Incorporate both displacements into the equation.**

$$v_{av} = \frac{\left|\vec{d}_2 - \vec{d}_1\right|_{i} + \left|\vec{d}_2 - \vec{d}_1\right|_{ii}}{t_2 - t_1}$$

3 Substitute known values.

$$v_{av} = \frac{\left|40\text{cm} - 0\text{cm}\right| + \left|{}^{-}25\text{cm} - {}^{+}40\text{cm}\right|}{15\text{ s}}$$

$$v_{av} = \frac{105\text{cm}}{15\text{s}}$$

4 Calculate the answer.

$$v_{av} = 7.0\text{ m s}^{-1}$$

b 1 State the equation.

$$v_{av} = \frac{\vec{s}}{t}$$

$$\vec{v}_{av} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

2 Substitute known values.

$$\vec{v}_{av} = \frac{{}^{-}25\text{cm} - 0\text{cm}}{15\text{s}}$$

$$= \frac{{}^{-}25\text{cm}}{15\text{ s}}$$

3 Calculate the answer.

$$v_{av} = {}^{-}1.7\text{ m s}^{-1}$$

LEARNING CHECK 12.4

DESCRIBING

1 **Describe** the difference between instantaneous speed and average speed.

2 Show how the SI unit can be deduced from the formula for speed.

3 What condition must be met so that average velocity and instantaneous velocity are regarded as the same value?

APPLYING

4 For a particle that takes 3.0 s to move along a line from $^{-}60.0$ cm to $^{-}90$ cm, **calculate** the average:

- **a** speed
- **b** velocity.

ANALYSING

5 An aircraft undertakes a return trip between Coolangatta and Cairns, a round trip of 3000 km. Its average velocity is zero. Use this example to **explain** why it is useful to distinguish between speed and velocity.

6 **Explain** how the idea of a negligible time interval helps you to understand instantaneous speed.

12.5 Interpreting graphs: straight-line motion

Weblink
Distance vs time graphs: designing a walk

One way to represent, or model, the motion of particles is by drawing graphs. The fundamental graph of motion is drawn from the basic measurements of position and time. Other graphs are derived from displacement and time data. Velocity–time graphs and acceleration–time graphs are derived from this basic data.

Displacement–time graphs

The position of a particle moving along a straight path can be recorded and plotted on a graph. The displacement from the origin is measured at various times. The position is designated by positive and negative numbers depending on which side of the origin the particle is observed. Displacement–time graphs show positive and negative distances from the origin.

Straight-line motion: constant speed and velocity

Figure 12.5.1 shows a displacement–time graph for an object moving along a straight line. The gradient of the graph is constant. This means that, in any time interval *t*, the displacement interval, $\vec{s}$, is steadily increasing. Therefore, the velocity is the same constant at every point; thus, the gradient can be used to deduce the velocity. We can say this because we note that the:

- rise up the distance axis is the displacement interval $\vec{s}$
- run along the time axis is the corresponding time interval *t*.

Thus, the gradient (rise/run) is the velocity:

$$v = \frac{s}{t} = \text{gradient of } s\text{–}t \text{ graph}$$

where: v = velocity (m s^{-1})
s = displacement change (rise of s–t graph) (m)
t = time interval (run of v–t graph) (s)

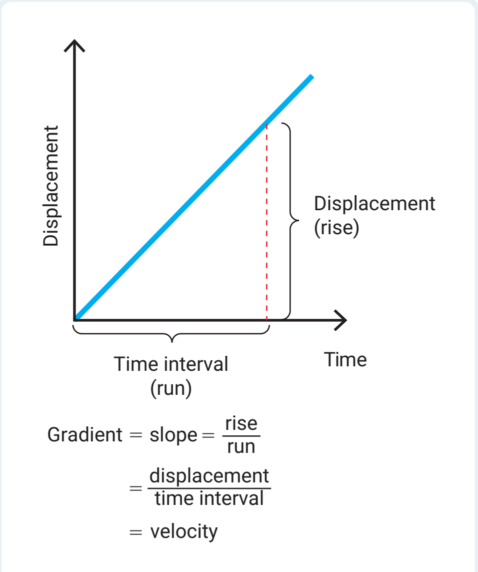


FIGURE 12.5.1 The gradient of this displacement–time graph is the constant velocity of an object.

If the displacement interval was negative (hence, leading to a negative gradient), the velocity would be in the opposite direction to the positive velocity shown in Figure 12.5.1. The particle would be travelling towards the negative end of the number line.

KEY FORMULA

$$v = \frac{s}{t} = \text{gradient of } s\text{–}t \text{ graph}$$

where: v = velocity (m s^{-1})
s = displacement change (rise of s–t graph) (m)
t = time interval (run of s–t graph) (s)

The speed for straight-line motion is the magnitude of the gradient of the displacement–time graph. For Figure 12.5.1, the distance is the magnitude of the displacement and the slope is the positive velocity.

For constant velocity, the gradient of the displacement–time graph is the same at all (instantaneous) points. The gradient at any one point is the same as the gradient calculated between any two points. Thus, the average velocity over the whole, or even any part of the journey, is the same as the instantaneous velocity at any one point in the journey.

Straight-line motion: non-constant speed and velocity

If the speed varies, the gradient of the displacement–time graph changes too. **Figure 12.5.2** shows a non-constant change of distance from the origin with change of time. Speed is varying. At point P, the average speed between two points either side of the point marked becomes closer and closer to the gradient of the tangent at the point. Thus, the gradient of the tangent at the point is the instantaneous speed at that point. Again, we note that the instantaneous speed and instantaneous velocity differ only in respect of the positive or negative sign of the gradient.

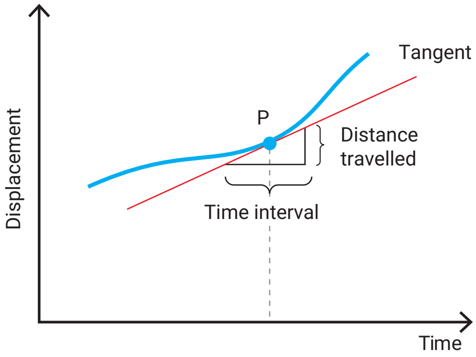


FIGURE 12.5.2 Instantaneous speed, v_{inst}, is the value of the gradient of the tangent to the distance–time graph.

Straight-line motion: constant speed–time graphs

Movement of a particle at constant speed is shown in **Figure 12.5.3**. From the definition of speed, we can deduce an algebraically equivalent equation:

$$v = \frac{s}{t}$$
$$s = vt$$

Weblink
Instantaneous speed and velocity

This algebraic equation, applied to the graph, reveals that the area under the speed–time graph between any two times (the time interval, *t*) can be used to deduce the distance travelled (distance interval, *s*) (Figure 12.5.3).

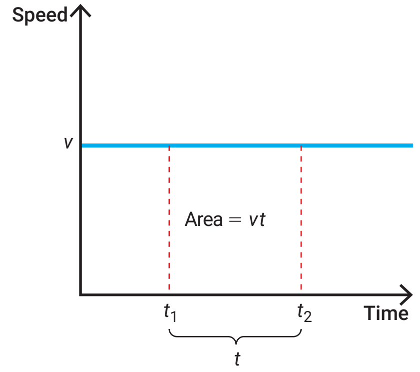


FIGURE 12.5.3 The area under this speed–time graph is the distance travelled by an object.

When an object changes from one constant speed, v_1, to another constant speed, v_2, in a very short amount of time, the change in speed is often regarded as being instantaneous. Truly instantaneous speed change is impossible for the same reasons that truly instantaneous distance change is impossible. If a particle travelling at a constant speed v_1 for a time interval t_1 changes (in a negligible time interval) to new speed v_2 for a time interval t_2 and so on, the distance travelled will be the sum of the individual distances:

$$s = v_1t_1 + v_2t_2 + \ldots$$

where: s = total distance travelled (m)

v_1t_1 = distance travelled at constant speed v_1 in first time interval t_1 (m)

v_2t_2 = distance travelled at constant speed v_2 in second time interval t_2 (m)

'…' means this goes on for as many constant speeds in time intervals as there are in the motion described by the graph.

KEY FORMULA

$$v = \frac{s}{t}$$

$$\Rightarrow s = vt$$

where: v = speed (m s^{-1})

s = distance travelled (m)

t = time elapsed (s)

KEY FORMULA

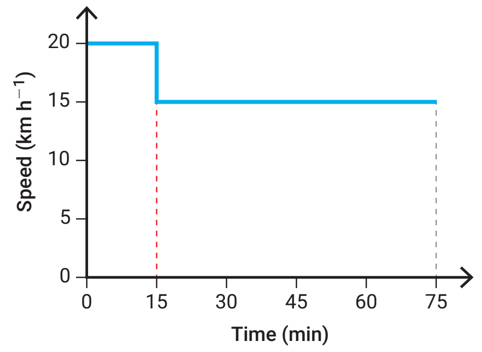
$s = v_1t_1 + v_2t_2 + \ldots$

WORKED EXAMPLE 12.5.1

An athlete runs at 20 km h^{-1} for 15 minutes. She then gets a stitch and slows to 15 km h^{-1} for the next hour. The speed–time graph is shown. Calculate how far, in kilometres, the runner travels in:

a the first 15 minutes

b total.



ANSWERS

a **1** **Identify the relationship between distance and the graph.**

Distance equals the area under the speed–time graph:

s = area

2 **Substitute the known values.**

$s = (20 \text{ km h}^{-1} \times 0.25 \text{ h})$

3 **Calculate the answer.**

$s = 5.0$ km

b **1** **State the equation.**

$s = \text{areas} = s_1 + s_2$

2 **Substitute known values.**

$s = (20 \text{ km h}^{-1} \times 0.25 \text{ h}) + (15 \text{ km h}^{-1} \times 1.0 \text{ h})$

$= 5.0 \text{ km} + 15 \text{ km}$

3 **Calculate the answer.**

$s = 20$ km

LEARNING CHECK 12.5

DESCRIBING

1 **Identify** the basic measurements from which all motion is described.

2 **Describe** how velocity can be determined from a displacement–time graph.

3 **Describe** how displacement interval can be determined from a velocity–time graph.

4 **Explain** this statement: 'Other graphs are derived from displacement and time data.'

APPLYING

5 A particle moves at a constant speed of 10 m s^{-1} for 5.0 s. Sketch the following graphs.

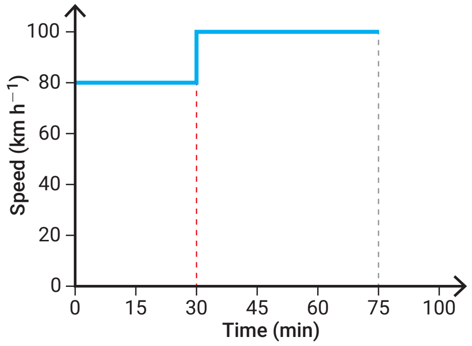
- **a** Speed–time
- **b** Displacement–time

6 **Calculate** the change of speed of a particle moving at a constant acceleration of 6.0 m s^{-2} for 3.0 s.

ANALYSING

7 **Compare** a displacement–time graph and distance–time graph, listing their similarities and differences. How would they differ in displaying motion in a forwards and backwards motion?

8 The graph shows the motion of a car.



- **a** **Calculate** how far, in kilometres, the car travels in the:
  - **i** first 30 minutes
  - **ii** total 75 minutes.
- **b** **Calculate** the average speed for the journey.

9 'Graphs are models.' **Explain** with reference to displacement–time and velocity–time graphs. Include in your answer how the models can be used to derive other quantities.

Weblink
What is acceleration?

12.6 Straight-line motion: uniformly accelerated motion

Particles may travel along a straight-line path at increasing or decreasing speeds. When the speed or velocity of a particle changes, acceleration occurs. The acceleration may be uniform or non-uniform. Non-uniformly accelerated motion is quite complicated to analyse compared to uniformly accelerated motion. Therefore, we shall only consider uniform (constant) acceleration along a straight line.

Acceleration

Acceleration is the rate of change of velocity. Velocity change always occurs over a time interval, t. Thus:

$$\vec{a} = \frac{\vec{v}}{t}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\vec{v}$ = velocity change (m s^{-1})
t = time interval (s)

Note that $\vec{v}$ and t are intervals of velocity change and time change respectively.

KEY FORMULA

$$\vec{a} = \frac{\vec{v}}{t}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\vec{v}$ = velocity change (m s^{-1})
t = time interval (s)

Unit of acceleration

The SI unit for acceleration is derived from the definition of speed or velocity change and time interval:

$$[a] = \frac{[v]}{[t]} = \frac{\text{m s}^{-1}}{\text{s}} = \text{m s}^{-2}$$

The unit can be read as 'metres per second of speed change in each second (metres per second) per second'.

Uniform acceleration along a straight line: graphically

Graphs are a very powerful way to represent straight-line motion. We shall look at two graphical ways to represent uniform acceleration along a straight line: velocity–time and acceleration–time graphs.

Velocity–time graphs

Uniform acceleration means that the rate of change of velocity is constant. This means that the velocity–time graph has a constant gradient **(Figure 12.6.1)**.

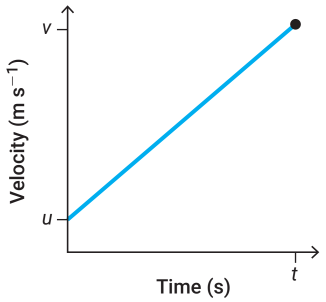


FIGURE 12.6.1 For constant acceleration, the velocity–time graph has a constant gradient.

In any time interval t, the velocity interval $\vec{v}$ is steadily increasing – there is a uniform change in velocity. Thus, the gradient can be used to deduce the acceleration. This can be said because the:

- rise up the velocity axis is the velocity interval or velocity change, $\vec{v}$
- run along the time axis is the corresponding time interval, t.

KEY FORMULA

$$\vec{a} = \frac{\vec{v}}{t}$$

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\vec{v} = \vec{v}_2 - \vec{v}_1$ = velocity change (m s^{-1})
$t = t_2 - t_1$ = time interval (s)

Thus, the gradient (rise/run) is the acceleration:

$$\vec{a} = \frac{\vec{v}}{t}$$

Note that the quantities $\vec{v}$ and t are intervals, not instantaneous values. The equation can be written:

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\vec{v} = \vec{v}_2 - \vec{v}_1$ = velocity change (m s^{-1})
$t = t_2 - t_1$ = time interval (s)

Note also that, because the velocity interval $\vec{v} = \vec{v}_2 - \vec{v}_1$ has only been multiplied by the scalar value, $\frac{1}{t}$, the velocity interval and the acceleration vector, $\vec{a}$, are in the same direction.

If the velocity interval were negative (negative gradient), the acceleration would be in the opposite direction to the positive acceleration shown; that is, it would be a negative acceleration (**deceleration**). Compared to movement towards the positive direction, negative acceleration may be a reduction in speed with no change in direction. It may also be an increase of speed in the negative direction.

deceleration negative acceleration

Each instantaneous point on the velocity–time graph has the same gradient as the average gradient; thus, the average and instantaneous accelerations have the same value throughout the motion.

Acceleration–time graphs

The acceleration–time graph for uniformly accelerated motion looks like **Figure 12.6.2**.

From the definition of acceleration, we can deduce an algebraically equivalent equation:

$$a = \frac{v}{t}$$

$$v = at$$

This algebraic equation, applied to the graph, reveals that the area under the acceleration–time graph can be used to deduce the speed change (Figure 12.6.2).

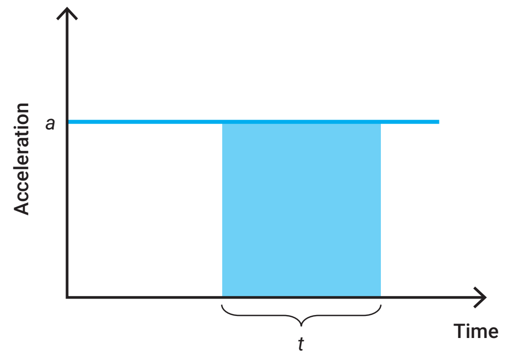


FIGURE 12.6.2 The area under this acceleration–time graph is the change in speed of an object.

LEARNING CHECK 12.6

DESCRIBING

1 a **Identify** the meaning of each symbol in the equation:

$$\vec{a} = \frac{\Delta \vec{v}}{t}$$

  b State the direction of the acceleration vector.

2 Write the unit for acceleration in words to show how it relates to velocity change.

3 State what is represented by the area under an acceleration–time graph.

4 **Explain** how a velocity–time graph can be used to derive acceleration.

5 **Explain** what is meant by negative acceleration (deceleration).

APPLYING

6 A particle that is travelling along a straight line at 5.0 m s^{-1} accelerates for 4.0 s at a rate of 3.0 m s^{-2}.

  a Sketch the acceleration–time graph.
  b Find the final speed of the particle.
  c Find the speed increase between 2.0 s and 3.0 s.

ANALYSING

7 **Explain** how a train can have a negative acceleration yet still be travelling in the positive direction.

8 Both the definition of velocity and the definition of acceleration involve the idea of interval. **Describe** how you use this when analysing graphs.

12.7 Interpreting graphs

When interpreting graphs, the following should be considered:

- Type of graph: displacement–time; velocity–time; acceleration–time
- Axis scale: vertical (displacement, velocity, acceleration); horizontal (time)
- Gradient: displacement–time (velocity); velocity–time (acceleration)
- Area under graph: velocity–time (change of displacement – displacement interval); acceleration–time (change in velocity – velocity interval)

Worksheet
Kinematics: analysis of data

WORKED EXAMPLE 12.7.1

A snail starts at a position 20 cm from the origin and then moves to a new position 40 cm further away before going back past the origin to a position 20 cm on the other side of the origin. It finally ends up at the origin. The positions are shown in Figure 12.7.1.

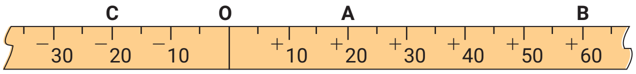
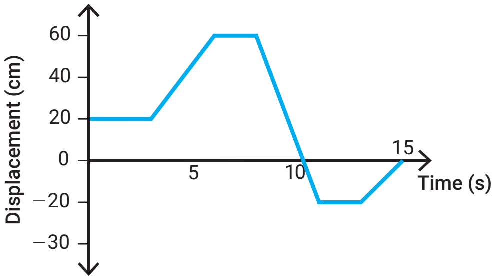


FIGURE 12.7.1 A snail moves along a straight line from $^{+}20$ cm to $^{+}60$ cm then to $^{-}20$ cm and ends up at the origin, O.

The displacement–time graph of the motion is shown.



a Calculate the distance travelled by the snail.

b Find the final displacement of the snail relative to the:

  i starting point

  ii origin.

c Calculate the average velocity between 3 s and 6 s.

d Calculate the velocity at:

  i 4 s

  ii 10 s.

ANSWERS

This question involves analysing a displacement–time graph. Key ideas are displacement–time graph, axis values and gradient.

a **1** **Use the graph and identify the relationship between distance and the graph.**

By reading from the axis:

$d =$ sum of individual distances

2 **Substitute known values.**

$$d = \left|{}^{+}60\text{ cm} - {}^{+}20\text{ cm}\right| + \left|{}^{+}60\text{ cm} - {}^{-}20\text{ cm}\right| + \left|0\text{ cm} - {}^{-}20\text{ cm}\right|$$

$$= 40\text{ cm} + 80\text{ cm} + 20\text{ cm}$$

3 **Calculate the answer.**

$s = 140$ cm

b **i** **1** **State the equation**

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

2 **Substitute the known values.**

$$\vec{s} = 0\text{ cm} - {}^{+}20\text{ cm}$$

3 **Calculate the answer.**

$$\vec{s} = {}^{-}20\text{ cm}$$

i.e. the snail is 20 cm to the left of the starting point.

ii The graph shows the snail at the origin after the movement:

⇒ relative to origin, $s = 0$ cm

c By calculating the gradient:

$$\vec{v}_{av} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

$$\Rightarrow \vec{v}_{av} = \frac{^{+}60\text{ cm} - {}^{+}20\text{ cm}}{6\text{ s} - 3\text{ s}}$$

$$= \frac{^{+}40\text{cm}}{3\text{ s}}$$

$$= {}^{+}13.3\text{cm s}^{-1}$$

d **i** $\vec{v}_{av}(3\text{s to }6\text{s}) = v_{inst}(4\,s)$

$\Rightarrow v_{inst}(4\text{s}) = {}^{+}13.3\text{ cm s}^{-1}$

ii $\vec{v}_{av}(8\text{ s to }11\text{ s}) = v_{inst}(10\text{ s})$

$$\Rightarrow v_{inst}(10\text{ s}) = \frac{^{-}20\text{cm} - {}^{+}60\text{cm}}{3\text{ s}}$$

$$= \frac{^{-}80\text{cm}}{3\text{ s}}$$

$$= {}^{-}27\text{cm s}^{-1}({}^{-}26.7\text{cm s}^{-1})$$

WORKED EXAMPLE 12.7.2

Use the velocity–time graph for an object moving along a straight line shown to answer the following questions.

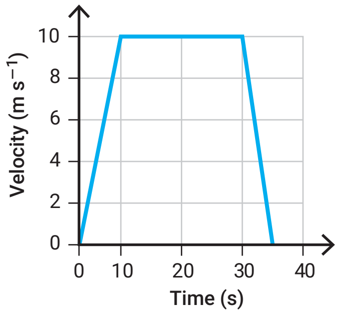
a Find the speed at:
  - **i** 20 s
  - **ii** 32 s.

b Calculate the acceleration:
  - **i** between 0 s and 10 s
  - **ii** at 32 s.

c Find the distance travelled:
  - **i** in the first 10.0 s
  - **ii** between 10.0 s and 30.0 s
  - **iii** between 30.0 s and 34.0 s
  - **iv** in the first 15 s.

d Find the time taken for the object to travel 70 m.

e Find the average speed of the object for the trip.



ANSWERS

This question is about analysing a velocity–time graph. The key ideas are velocity–time graph, axis values, gradient and area.

a **1** **Read the graph at the relevant time points.**

By reading from the axis:

i $10\ \text{m s}^{-1}$

ii $2.5\ \text{m s}^{-1}$.

b **i** **1** **Identify the relationship between acceleration and the graph.**

The acceleration can be found by finding the gradient of the graph.

2 **Substitute known values.**

$$\vec{a}_{av}(0\,\text{s to}\,10\,\text{s}) = \frac{{}^{+}10\ \text{m s}^{-1} - 0\ \text{m s}^{-1}}{10\,\text{s} - 0\,\text{s}}$$

$$a_{inst} = \frac{{}^{+}10\ \text{m s}^{-1}}{10\ \text{s}}$$

3 **Calculate the answer.**

$a_{inst} = {}^{+}1.0\ \text{m s}^{-2}$

ii **1** **Identify the relationship between acceleration and the graph.**

Acceleration at any instantaneous time between 0 s and 10 s is the same value (${}^{+}1.0\ \text{m s}^{-2}$).

$\vec{a}_{av}(30\ \text{s to}\ 34\ \text{s}) = a_{inst}(32\,\text{s})$

2 **Substitute the known values.**

$$a_{inst}(32\,\text{s}) = \frac{0\ \text{m s}^{-1} - {}^{+}10\ \text{m s}^{-1}}{34\ \text{s} - 30\ \text{s}}$$

$$= \frac{{}^{-}10\ \text{m s}^{-1}}{4\ \text{s}}$$

3 **Calculate the answer.**

$a_{inst} = {}^{-}2.5\ \text{m s}^{-2}$

c **i** **1** **Identify the relationship between distance and the graph.**

d = area under v–t graph

2 **Substitute known values.**

$$d = \frac{1}{2}(10\ \text{m s}^{-1} \times 10\ \text{s})$$

3 **Calculate the answer.**

$d = 50\ \text{m}$

ii **1** **Identify the relationship between distance and the graph.**

d = area under v–t graph

$= 10\ \text{m s}^{-1} \times (30\ \text{s} - 10\ \text{s})$

$= 10\ \text{m s}^{-1} \times 20\ \text{s}$

$= 200\ \text{m}$

iii **1** **Identify the relationship between distance and the graph.**

d = area under v–t graph

2 **Substitute known values.**

$$d = \frac{1}{2}(10\ \text{m s}^{-1} \times (34\ \text{s} - 30\ \text{s})$$

$$= \frac{1}{2}(10\ \text{m s}^{-1} \times 4\ \text{s})$$

3 **Calculate the answer.**

$d = 20\ \text{m}$

iv **1** **Identify the relationship between distance and the graph.**

d = area under v–t graph

2 Substitute known values.

$d = 50\text{ m} + 10\text{ m s}^{-1} \times (15\text{ s} - 10\text{ s})$

$= 50\text{ m} + 10\text{ m s}^{-1} \times 5\text{ s}$

3 Calculate the answer.

$d = 100\text{ m}$

d 1 Identify the relationship between distance and the graph.

d = area under v–t graph

2 Substitute known values.

$d = 50\text{ m} + 10\text{ m s}^{-1} \times (t - 10)\text{ s} = 70\text{ m}$

$= 50\text{ m} + 10\text{ m s}^{-1} \times t - 10\text{ m s}^{-1} \times 10\text{ s} = 70\text{ m}$

$= 10\text{ m s}^{-1} \times t = 70\text{ m} - 50\text{ m} + 100\text{ m}$

3 Rearrange to find the unknown.

$$t = \frac{120\text{ m}}{10\text{ m s}^{-1}}$$

4 Calculate the answer.

$t = 12\text{ s}$

e 1 State the equation.

$$v = \frac{d}{t}$$

2 Substitute known values.

$$\vec{v}_{av} = \frac{^{+}50\text{ m} + 200\text{ m} + 20\text{ m}}{34\text{ s} - 0\text{ s}}$$

$$= \frac{^{+}270\text{ m}}{34\text{ s}}$$

3 Calculate the answer.

$v_{av} = {}^{+}7.9\text{ m s}^{-1}$

Note: Average speed is found by finding the total distance and dividing by time.

WORKED EXAMPLE 12.7.3

A cruise ship accelerates at a constant rate for 10.0 minutes until it reaches a speed of 10 m s^{-1}. It then continues to travel in a straight line for 20.0 minutes at 10 m s^{-1}.

a Sketch a graph of velocity (m s^{-1}) versus time (s) for the ship for the 30 minutes.

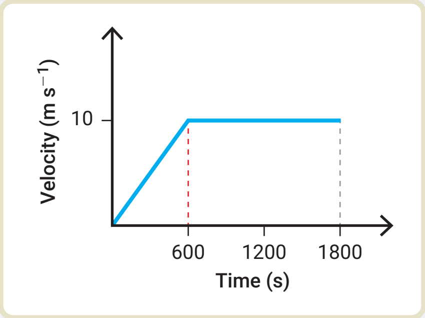
b Calculate the ship's acceleration for the first 10.0 minutes, in m s^{-2}.

c Sketch an acceleration–time graph for the ship for the 30 minutes.

ANSWERS

a This is a question about sketching a velocity–time graph. The key ideas are velocity–time graph, axis values, gradient and area.

- Convert minutes to seconds, so that the time axis goes from 0 to 1800 s.
- Velocity axis goes from 0 m s^{-1} to 10 m s^{-1}.
- Mark appropriate given values and calculated values on the axes, as shown below.



b **1** **Identify the relationship between acceleration and the graph.**

$\vec{a} = \text{gradient of } \vec{v} - t \text{ graph}$

2 **State the equation.**

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

3 **Substitute the known values.**

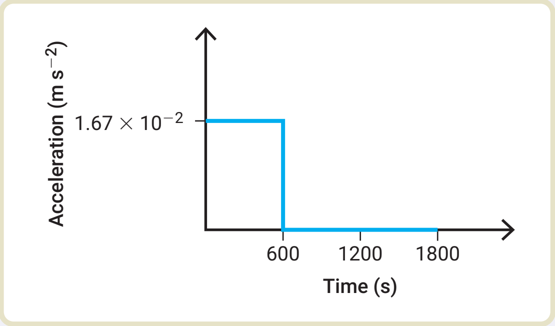
$$\vec{a} = \frac{10\text{ m s}^{-1} - 0\text{ m s}^{-1}}{600\text{ s} - 0\text{ s}}$$

$$= \frac{10\text{ m s}^{-1}}{600\text{s}}$$

4 **Calculate the answer.**

$\vec{a} = 1.7 \times 10^{-2}\text{ m s}^{-2} (1.67 \times 10^{-2}\text{ m s}^{-2})$

c Mark appropriate given values and calculated values on the axes, as shown below.



WORKED EXAMPLE 12.7.4

A car initially travelling at a speed of 4.0 m s^{-1} accelerates at 2.0 m s^{-2} for 12 s.

a Sketch the acceleration–time graph for the car.

b Find the velocity, *v*, of the car after 12.0 s.

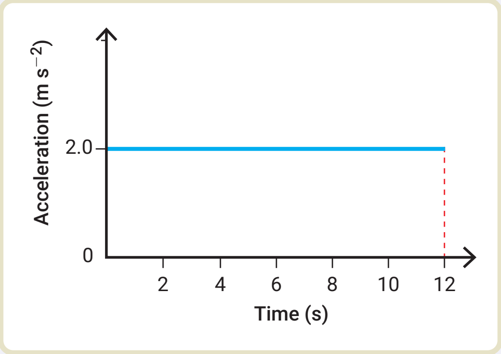
c Sketch the velocity–time graph.

d Find the distance moved by the car in 8.0 s.

ANSWERS

This is a question about analysing an acceleration–time graph. The key ideas are acceleration–time graph, axis values and area.

a Mark appropriate given values on the axes, as shown below.



b **1** **Identify the relationship between velocity and the graph.**

Area under a–t graph = *change* in velocity

2 **Substitute the known values.**

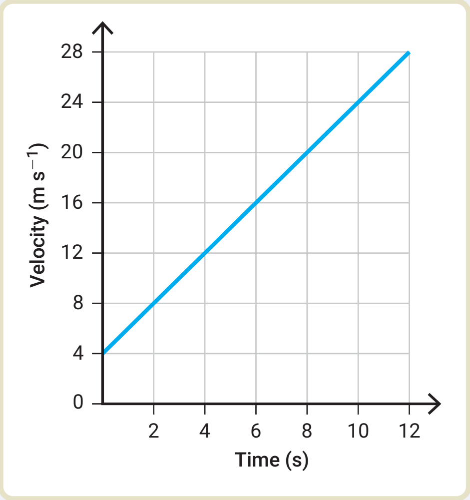
$\Delta v = 2 \text{ m s}^{-2} \times 12 \text{ s}$

$v = 24 \text{ m s}^{-1} + 4 \text{ m s}^{-1}$

3 **Calculate the answer.**

$v = 28 \text{ m s}^{-1}$

c



d **1** **Read velocity value from the graph.**

$v_{8\text{ s}} = 20 \text{ m s}^{-1}$

2 **State the equation.**

Area of a trapezium = average height × base

$$= \frac{(a+b)}{2} \times \text{base}$$

3 **Substitute known values.**

$$\text{Area} = d = \frac{4\,\text{m}\,\text{s}^{-1} + 20\,\text{m}\,\text{s}^{-1}}{2} \times 8\text{s}$$

$$= 12\,\text{m}\,\text{s}^{-1} \times 8\text{ s}$$

4 **Calculate the answer.**

$d = 96 \text{ m}$

LEARNING CHECK 12.7

DESCRIBING

1 List the four things that should be considered when solving problems involving graphs.

2 Copy and complete the following table.

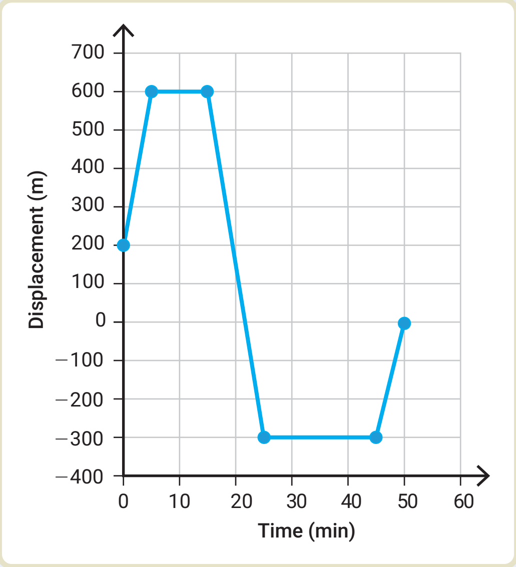
Type of graph	Gradient represents	Area represents

3 **Explain** how the concept of interval relates to the gradient of kinematic graphs.

4 **Explain** how the concept of interval relates to the area of kinematic graphs.

APPLYING

5 The graph shows a walk undertaken by Simi from school to home. She visits shops and a friend along the way.



Worksheet
Kinematic graphical analysis

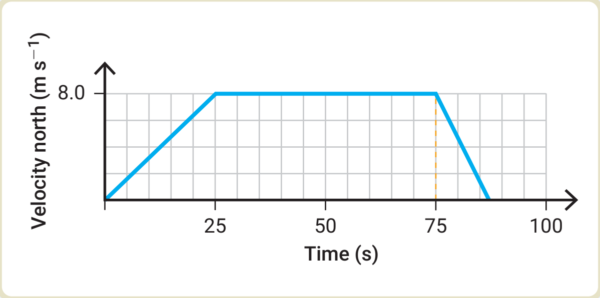
a Find the displacement of school from Simi's home.

b Find Simi's velocity, in m s^{-1}:

- **i** between school and the shops
- **ii** 20 minutes after leaving school.

c **Calculate** the distance Simi walked.

6 A train accelerates uniformly from rest to 8.0 m s^{-1} in 25 s. It then travels for 50 s at 8.0 m s^{-1} before slowing uniformly to a stop in 12 s, as shown in the graph.



a Find the distance travelled by the train in the first 20 s.

b **Calculate** the distance between the two stops.

c Find the acceleration of the train in the:

- **i** first 10 s of the train's motion
- **ii** last 10 s of the train's motion.

d Sketch the acceleration–time graph for the motion of the train.

e **Calculate** the time taken for the train to travel 300 m.

7 A car travels at 70 km h^{-1} for 1.0 h and then at 80 km h^{-1} for 2.0 h. Explain why the average speed is not 75 km h^{-1}.

12.8 Solving problems using algebra

The motion of a particle that is accelerating uniformly along a straight-line path can be represented in numerous ways: described in words, captured through multi-flash photographs, recorded on video, measured in relation to position and time and drawn on graphs or by using algebraic equations. All of these representations are models that describe the same motion and are therefore equivalent representations.

Graphical representations and algebraic representations are the most common ways by which we analyse uniformly accelerated motion. Algebraic representations or equations and graphical representations say the same thing.

For example, consider an object – it might be a car or a bicycle – that has an initial velocity of u at the moment we start making measurements. It is accelerating at a constant rate a, as shown by the straight line on the graph **(Figure 12.8.1)**. After a time interval, t, its final velocity is v, which is greater than its initial speed. Note that the time interval, t, is taken from $t_1 = 0$. During the time interval, the object covers a distance interval of s.

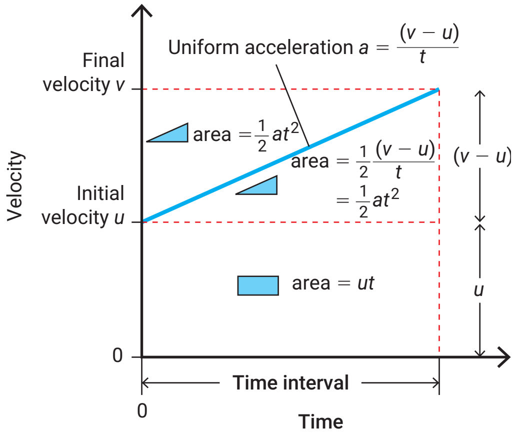


FIGURE 12.8.1 The generalised motion of an object accelerating uniformly with increasing speed along a straight line

The equations are derived for constantly accelerated motion in a straight line where:

- initial speed $= u$
- final speed $= v$
- acceleration $= a$
- time interval $= t$ (t is not an instantaneous time)
- distance interval $= s$ (s is not a particular point on a line).

Note that the vector sign from the variables u, v and a have been removed. The sign convention for positive motion and the oppositely directed negative motion variables are relied upon.

From the definition of acceleration, the gradient of the line can be determined:

$$a = \frac{v-u}{t}$$
$$\Rightarrow v - u = at$$
$$\Rightarrow v = u + at$$

This equation connects u, v, a and t.

Finding the area under the graph as the sum of the small rectangle and the triangle gives:

$$\begin{aligned} s &= ut + \frac{1}{2}(v - u)t \\ &= ut + \frac{1}{2}(at)t \\ &= ut + \frac{1}{2}at^2 \end{aligned}$$

This equation connects s, u, a and t.

Alternatively, finding the area under the graph as the difference between the large rectangle and the triangle gives:

$$s = vt - \frac{1}{2}at^2$$

This equation connects s, v, a and t.

Another useful equation that can be derived from these two equations can be found using algebra on the first two equations:

$$v = u + at$$

Squaring both sides:

$$\Rightarrow v^2 = (u + at)^2$$

$$v^2 = u^2 + 2uat + a^2t^2$$

Keeping in mind that $s = vt - \frac{1}{2}at^2$, we can factorise this expression, to find another equation:

$$v^2 = u^2 + 2a\left(ut + \frac{1}{2}at^2\right)$$

$$\Rightarrow v^2 = u^2 + 2as$$

This equation connects s, u, v and a.

Using the same graph, finding the area under the graph as a trapezium gives:

$$s = \text{average height} \times t$$

$$s = \frac{1}{2}(u + v) \times t$$

This equation connects s, u, v and t.

Motion in a straight line at constant acceleration

The two main methods used for analysing motion in a straight line are graphical and algebraic. Graphical analysis is often a simpler, more visual way that will give the same answer to a problem as algebraic techniques. Graphical analysis should be attempted wherever possible.

Graphically

v = gradient of the s–t graph

s = area under the v–t graph

a = gradient of the v–t graph

Speed change, v = area under the a–t graph

Algebraically

The equations for straight-line motion with constant acceleration are:

$$v = u + at$$

$$s = ut + \frac{1}{2}at^2 \qquad s = vt - \frac{1}{2}at^2$$

$$s = \frac{u+v}{2}t$$

$$v^2 = u^2 + 2as$$

These are sometimes referred to as the *suvat* equations. Each of these equations involves four variables: s, u, v, a or t. When solving problems algebraically, you will need to know or deduce the values of three of the five variables s, u, v, a, t. The fourth can be found by simple substitution in the appropriate equation. It is then possible to use another equation to find the fifth variable. Note that s and t are intervals in these equations.

KEY FORMULA

$$v = u + at$$

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$

Where:

v = final velocity (ms^{-1})
u = inital velocity (ms^{-1})
s = displacement (m)
t = time (s)
a = acceleration (ms^{-2})

WORKED EXAMPLE 12.8.1

An aeroplane travelling at 40 m s^{-1} accelerates to 100 m s^{-1} in 40 s.

a Calculate the acceleration of the aeroplane.

b Determine how far the aeroplane travels while accelerating.

ANSWERS

a 1 State the equation.

$v = u + at$

2 Rearrange to find the unknown.

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

3 Substitute known values.

$$\Rightarrow a = \frac{100\text{ m s}^{-1} - 40\text{ m s}^{-1}}{4.0\text{s}}$$

$$\Rightarrow a = \frac{60\text{ m s}^{-1}}{4.0\text{ s}}$$

4 Calculate the answer.

$\Rightarrow a = 15\text{ m s}^{-2}$

b 1 State the equation.

$$s = ut + \frac{1}{2}at^2$$

2 Substitute known values.

$$s = 40\text{ m s}^{-1} \times 4.0\text{ s} + \frac{1}{2} \times 15\text{ m s}^{-2} \times (4.0\text{ s})^2$$

$$= 160\text{ m} + 120\text{ m}$$

3 Calculate the answer.

$s = 280\text{ m}$

Solving kinematic problems

Use these steps to solve most kinematic problems involving particles moving along a straight line with uniform acceleration:

- Assign values to s, u, v, a, t.
  (Remember that s and t are intervals, not instantaneous values.)
- Identify any missing values.
- Sketch a v–t graph or an s–t graph as appropriate.
- Write known values onto the graph.
- Assess whether it is possible to find the:
  - gradient (acceleration)
  - area (distance or displacement).
- Use the graph to solve for the missing values.
- Use *suvat* formulas if necessary.

Graphical analysis is often simpler and more obvious than algebraic analysis. Acceleration (gradient) and distance (area) can often be calculated easily once a v–t graph has been sketched and relevant data points identified.

Both methods yield the same answers because they are both models of the same motion.

LEARNING CHECK 12.8

DESCRIBING

1 Consider uniformly accelerated motion where the initial velocity is non-zero.
  a Sketch the velocity–time graph that represents the motion. Indicate on the graph how to find acceleration and displacement.
  b Write down the equations that represent the motion (*suvat* equations). **Define** each of the variables.

2 **Explain** how the suvat equations can be used to find all five variables when you only have three variables.

3 **Compare** the use of graphical and algebraic methods of analysing motion, providing one similarity and one difference.

APPLYING

4 A cyclist accelerates from 5.0 m s^{-1} to 8.0 m s^{-1} in 15 s.
  a **Calculate** the acceleration of the cyclist.
  b **Determine** how far the cyclist travels while accelerating.

5 A car travels 50.0 m from a standing start in 2.5 s. **Calculate** its:
  a acceleration
  b final speed.

ANALYSING

6 A driver travelling at 10 m s^{-1} sees a child run onto the road 10 m away. The driver takes 0.2 s to respond (reaction time). The maximum braking acceleration of the car is $^{-}8.0$ m s^{-2}.
  a Sketch the velocity–time graph.
  b Find how far the car travels before the driver applies the brakes (reaction distance).
  c Find the time taken to come to a stop (braking time).
  d Find the distance travelled by the car while braking (braking distance).
  e Find the total distance travelled before coming to a stop (stopping distance).

7 Both the definition of velocity and the definition of acceleration involve the idea of interval. **Describe** how you will keep this in mind when using algebraic formulas to solve problems.

12.9 Acceleration due to gravity

An interesting example of constantly accelerated motion in a straight line is when an object falls or is thrown straight down, or is projected upwards vertically. The object accelerates uniformly because the acceleration of all masses near Earth's surface is constant. Consequently, these up or down motions can be treated as uniformly accelerated motions.

Projectile motion in a constant gravitational field

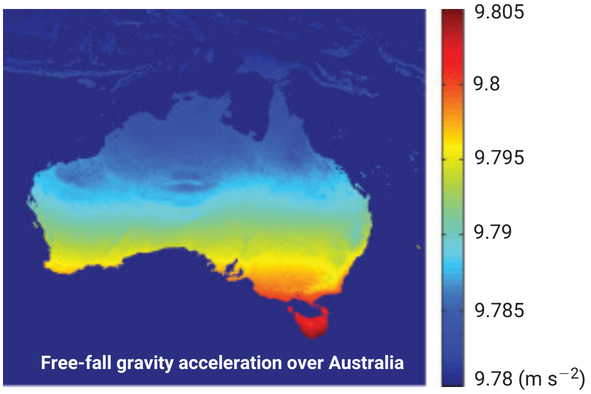
Every mass produces a gravitational field around it. This gravitational field applies gravitational force on other masses. Therefore, gravitational force is the force applied by the gravitational field of one mass on another mass. This force is usually referred to as gravity.

Earth has a large mass of 5.98×10^{24} kg. Its gravitational field is proportionately much larger than the gravitational field surrounding familiar objects. In the model world of point masses, air resistance and buoyancy forces can be regarded as negligible. Therefore, once an object is released or thrown, the only (non-negligible) force acting upon it is the gravitational force applied by Earth's gravitational field.

Near Earth's surface, gravity causes a force on an object, which results in that object accelerating vertically downwards with a constant acceleration. This is known as gravitational acceleration, and is given the symbol *g*. The value of *g* that gives sufficiently accurate answers for most purposes is:

$$g = 9.80\,\mathrm{m\,s^{-2}}$$

The value of *g* varies slightly around the world. In Australia, *g* is greatest in southern Tasmania ($9.805\,\mathrm{m\,s^{-2}}$). Across Queensland, its value varies by about 1% from Brisbane ($9.79\,\mathrm{m\,s^{-2}}$) to Cairns ($9.78\,\mathrm{m\,s^{-2}}$) **(Figure 12.9.1)**.



Hirt, C., S.J. Claessens, T. Fecher, M. Kuhn, R. Pail, M. Rexer (2013), New ultra-high resolution picture of Earth's gravity field, Geophysical Research Letters, Vol 40, doi: 10.1002/grl.50838.

FIGURE 12.9.1 Variations of the acceleration due to gravity across Australia

The effect of Earth's gravitational field, the gravitational acceleration, gets smaller the greater the distance from Earth; nevertheless, for distances somewhat above where aeroplanes usually fly, the change is very slight. Therefore, the difference between Earth's gravitational field at the ground and well beyond is regarded as negligible. An object falling down gains 9.80 metres per second every second, reaching $35\,\mathrm{km\,h^{-1}}$ after 1 second. After the next second, it will be falling with twice that speed ($19.6\,\mathrm{m\,s^{-1}}$; $70\,\mathrm{km\,h^{-1}}$). After 10 s, an object would be falling at $98\,\mathrm{m\,s^{-1}}$ ($350\,\mathrm{km\,h^{-1}}$), ignoring air resistance.

Objects falling directly downwards

When analysing the motion of a falling object, we use the following conventions.

- The origin is the point at which the object starts to move.
- Downwards direction is positive.
- *suvat* variables are all positive, including $a = g = {}^{+}9.8\,\text{m}\,\text{s}^{-1}$.

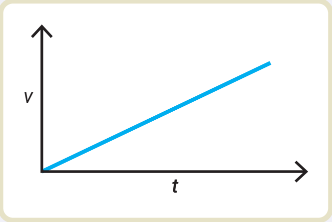
WORKED EXAMPLE 12.9.1

The watch of a climber on the Sydney Harbour Bridge falls from their wrist. It takes 2.5 s before hitting a car below.

a Sketch a velocity–time graph of this motion.
b Calculate the velocity with which the watch hits the car.
c Calculate the distance the watch falls.
d Show how these results can be obtained by using only the graph in part **a**.

ANSWERS

a



b **1** **State the equation.**

$v = u + at$

2 **Substitute known values.**

$\Rightarrow v = 0\text{ m s}^{-1} + 9.8\text{ m s}^{-2} \times 2.5\text{ s}$

3 **Calculate the answer.**

$\Rightarrow v = {}^{+}24.5\text{ m s}^{-1}$ (down is positive)

c **1** **State the equation.**

$$s = ut + \frac{1}{2}at^{2}$$

2 **Substitute known values.**

$$s = 0\text{ m} + \frac{1}{2} \times {}^{+}9.8\text{ ms}^{-2} \times (2.5\text{s})^{2}$$

3 **Calculate the answer.**

$s = 31\text{ m}$

d **1** **State the equation for gradient.**

$$\text{Gradient, } g = \frac{v}{t}$$

2 **Rearrange to find the unknown.**

$\Rightarrow v = gt$

$\Rightarrow v = {}^{+}9.8\text{ m s}^{-2} \times 2.5\text{ s}$

3 **Calculate the velocity.**

$\Rightarrow v = {}^{+}24.5\text{ m s}^{-1}$

4 **State equation for area.**

$$\text{area, } s = \frac{1}{2}vt$$

5 **Substitute the known values.**

$$\Rightarrow s = \frac{1}{2} \times 24.5\ \text{ms}^{-1} \times 2.5\ \text{s}$$

6 **Calculate the answer.**

$s = 31\ \text{m}$

Objects projected upwards

When analysing the motion of a vertically projected object, we use the following conventions.

- The origin is the point at which the object starts its motion.
- The upwards direction is positive.
- Acceleration is downwards: $a = {}^{-}9.8\,\text{m}\,\text{s}^{-2}$.
- The *suvat* variables are positive if directed upwards and negative if directed downwards.

WORKED EXAMPLE 12.9.2

A firework ball is launched directly upwards with an initial speed of $35\ \text{m}\ \text{s}^{-1}$. It explodes at the highest position reached.

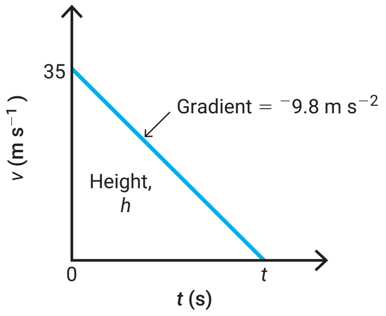
a Sketch the v–t graph for the firework ball until it explodes.

b Find the height at which the firework ball explodes.

c Find the time it takes from launch until the firework ball explodes.

ANSWERS

a The velocity–time graph is shown here.



By gradient:

$$\text{Gradient, } a = \frac{0\ \text{m s}^{-1} - 35\ \text{m s}^{-1}}{t - 0\ \text{s}} = {}^{-}9.8\ \text{m s}^{-2}$$

$$\Rightarrow t = \frac{-35\ \text{m s}^{-1}}{-9.8\ \text{m s}^{-2}} = 3.6\ \text{s}$$

By area:

$$s = \frac{1}{2}t \times 35 = h$$

$$h = \frac{1}{2}(35\ \text{m s}^{-2} \times t)$$

$$= \frac{1}{2} \times 35\ \text{m s}^{-1} \times 3.6\ \text{s}$$

$$= 63\ \text{m}$$

b 1 **Solution by graphical model.**

The graph enables the solution to be calculated 'by gradient' and 'by area'. It relies on the known gradient ($^-9.8\ \text{m s}^{-2}$) and the area of a triangle. It is a simpler, quicker solution than the algebraic method shown below.

2 **Solution by algebraic model.**

$s = ?$, $u = 35\ \text{m s}^{-1}$, $v = 0\ \text{m s}^{-1}$, $a = {}^-9.8\ \text{m s}^{-2}$, $t = ?$

$$v^2 = u^2 + 2as$$

$$s = \frac{v^2 - u^2}{2a}$$

$$\Rightarrow s = \frac{(0\ \text{m s}^{-1})^2 - (35\ \text{m s}^{-1})^2}{2 \times {}^-9.8\ \text{m s}^{-2}}$$

$$\Rightarrow s = 63\ \text{m}\ (62.5\ \text{m})$$

c $s = 62.5\ \text{m}$, $u = 35\ \text{m s}^{-1}$, $v = 0\ \text{m s}^{-1}$, $a = {}^-9.8\ \text{m s}^{-2}$, $t = ?$

$$v = u + at$$

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

$$= \frac{0\ \text{m s}^{-1} - 35\ \text{m s}^{-1}}{{}^-9.8\ \text{m s}^{-2}}$$

$$= 3.6\ \text{s}$$

Projectiles follow symmetrical paths

By symmetry, for a projectile falling back to the same place from which it was launched:

$$v = -u$$

The acceleration due to the gravitational field is always the same. It cannot be turned off. This is always true, no matter whether the object's velocity is directed upwards (positive), downwards (negative) or momentarily stopped at the top position. Remember, for as long as the object is above the ground, the acceleration due to the gravitational field is constant: $g = {}^-9.8\ \text{m s}^{-2}$, downwards.

The result of this is that when the velocity is upwards, the object's speed is decreasing. It will stop momentarily at the highest point of the flight. Then, its speed starts to increase as it begins to fall back down again. The momentary stop does not cause gravity to turn off. At the top, the instantaneous *change* in velocity is always $^-9.8\ \text{m s}^{-2}$, even if the instantaneous velocity is zero. At every instant, including for the instant of time at the top of the flight, the velocity is *changing*.

WORKED EXAMPLE 12.9.3

An arrow is fired vertically upwards with an initial speed of $18.8\ \text{m s}^{-1}$. It lands next to the place from which it was launched.

a Sketch a velocity–time graph for this motion.

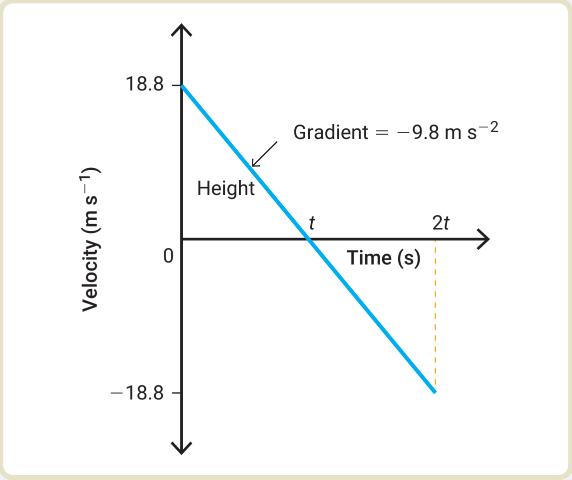
b Find the time for which the arrow remains in flight.

c Find the maximum height reached by the arrow.

d Compare the distance and the displacement of the arrow at the end of its flight.

ANSWERS

a



b Solving graphically:

1 **State the equation.**

gradient, $g = \frac{v}{t}$

2 **Rearrange to find the unknown.**

$t = \frac{v}{g}$

3 **Substitute known values.**

$t = \frac{18.8\ \text{m s}^{-1}}{9.8\ \text{m s}^{-2}}$

4 **Calculate the answer.**

$t = 1.92\ \text{s}$

5 **State the equation relating to symmetry.**
By symmetry, $T = 2t$

6 **Substitute known values.**
$\Rightarrow T = 2 \times 1.92\ \text{s}$

7 **Calculate the answer.**
$\Rightarrow T = 3.84\ \text{s}$

Solving algebraically:

1 **State the equation.**
$v = u + at$

2 **Rearrange to find the unknown.**

$$t = \frac{v - u}{a}$$
$$= \frac{0\ \text{m s}^{-1} - 18.80\ \text{m s}^{-1}}{^{-}9.8\ \text{m s}^{-2}}$$

3 **Calculate the answer.**

$t = 1.92\ \text{s}$

4 **State the equation relating to symmetry.**
By symmetry, $T = 2t$

5 **Substitute the known values.**
$\Rightarrow T = 2 \times 1.92\ \text{s}$

6 **Calculate the answer.**
$\Rightarrow T = 3.84\ \text{s}$

c Solving graphically:

1 **Identify the relationship between height and the graph.**
height, h_{top} = area to 't'

2 **Substitute known values.**
$$h_{\text{top}} = \frac{1}{2} \times 18.8\ \text{m s}^{-1} \times 1.92\ \text{s}$$

3 **Calculate the answer.**
$h_{\text{top}} = 18\ \text{m}$

Solving algebraically:

1 **State the equation.**
$v^2 = u^2 + 2as$

2 **Rearrange to find the unknown.**
$$s = \frac{v^2 - u^2}{2a}$$

3 **Substitute known values.**
$$s = \frac{(0\ \text{m s}^{-1})^2 - (18.80\ \text{m s}^{-1})^2}{2 \times ({}^{-}9.8\ \text{m s}^{-2})}$$

4 **Calculate the answer.**
$s = {}^{+}18\ \text{m}$

d Displacement:

1 **State the equation.**
$\vec{s} = \vec{d}_2 - \vec{d}_1$

2 **Subsitute known values.**
$s = 0\ \text{m} - 0\ \text{m}$

3 **Calculate the answer.**
$s = 0\ \text{m}$

Distance:

1 **State the equation.**
$d = \left|\vec{d}_2 - \vec{d}_1\right| + \left|\vec{d}_1 - \vec{d}_2\right|$

2 **Substitute known values.**
$d = \left|{}^{+}18\ \text{m} - 0\ \text{m}\right| + \left|0\ \text{m} - {}^{-}18\ \text{m}\right|$

3 **Calculate the answer.**
$d = 36\ \text{m}$

PRACTICAL ACTIVITY 12.9.1

GRAVITATIONAL ACCELERATION

Introduction

For a falling object not affected significantly by air resistance, the value of the gravitational acceleration, *g*, can be found by collecting first-hand information.

Research question

What is the relationship between a falling object's displacement and time?

Aim

To find the value of the gravitational acceleration, *g*

Materials

- ruler
- ball bearing
- electronic timer or timing photogate

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The ball bearing may cause injury if thrown, dropped or stood on.	Never throw ball bearings. Manage the use of the ball bearing carefully. Never leave the ball bearing lying on the ground.

Procedure

1 Set up the electronic timing apparatus.

2 Carefully measure the vertical distance, *s*, that the ball bearing will fall.

3 Use the timing apparatus to measure the time, *t*, taken for the ball bearing to fall through the known vertical height when released from rest from the upper position.

4 Repeat this several times.

5 Change the height of the fall and repeat the procedure.

6 Record sufficient data to plot a graph.

Results

1 Record all raw and derived data in a correctly constructed data table.

2 Plot the data as it is collected.

3 Estimate and record uncertainties in the data.

Analysis of results

1 Plot s–t_{av}, showing uncertainty bars.

2 Draw a line of best fit.

3 From the line of best fit, construct a data table of data points, (t_{av}, s). Add an extra column for $(t_{av})^2$.

4 Plot s–$(t_{av})^2$.

5 Draw a straight line of best fit and calculate the gradient.

6 Show that the equation can be used to find the acceleration from the gradient of the s–$(t_{av})^2$ graph.

Interpretation

7 Justify the best estimate of the value of the acceleration due to gravity, *g*, found in this experiment.

8 Use the least and greatest possible values of the gradient of the s–$(t_{av})^2$ graph to estimate the uncertainty in the experimental value of *g*. (Do not use the regression equation from your calculator!)

Evaluation

9 Suggest ways in which this experiment could be made more accurate.

10 Evaluate the reliability of this procedure by analysing the variation in the separate measurements of time taken by the ball bearing before the average was found.

11 Suggest why a ball bearing was used rather than a tennis ball or other similar object.

12 Summarise the experiment in one or two sentences.

13 Provide a precise value for g (best estimate ± uncertainty limits).

14 Identify at least two difficulties you had when undertaking this experiment.

15 Describe changes that could be made to overcome these difficulties.

PRACTICAL ACTIVITY 12.9.2

LAUNCH VELOCITY

Introduction

The time of flight of a projectile can be used to calculate its initial velocity if other variables are known.

Research question

How can the initial velocity of a vertical projectile be derived experimentally?

Aim

To find the initial vertical velocity of a launched projectile

Materials

- apparatus that will launch an object vertically
- video camera or similar
- ruler or measuring tape
- safety glasses

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
Some objects and launch speeds may pose a risk to eyes and faces.	Wear safety glasses. Do not put your face over the launcher.

Procedure

1 Arrange the apparatus so that the object is launched vertically from the edge of a desk or benchtop, and lands on the floor beside the desk, as shown in Figure 12.9.2.

2 Measure s, the displacement of the object from its launch position.

3 Launch the object and record its motion until it hits the ground.

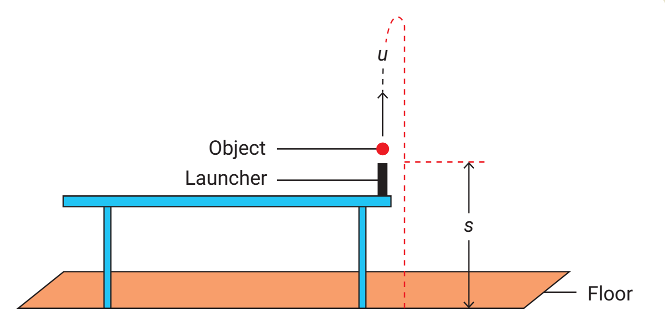


FIGURE 12.9.2 The experimental set-up

Results

1 Use the recording to produce s–t, v–t and a–t graphs for the motion.

2 Estimate the uncertainty in each of the data points and show these on your graphs.

3 Repeat the experiment for a different launch speed but the same final displacement.

Analysis of results

1 Describe the main features of each of the graphs. Include, where appropriate, the meaning of the:
   - **a** *y* intercept
   - **b** gradient
   - **c** area under the graph.

2 Explain how to use the graphs to find the:
   - **a** initial speed
   - **b** acceleration due to the gravitational field.

3 State, with an appropriate estimate of the uncertainty, the value of the:
   - **a** initial speed
   - **b** acceleration due to the gravitational field, *g*.

Interpretation

4 Compare the value of *g* found in this experiment with the accepted value of *g* and its uncertainty at your latitude (see Figure 12.9.1). Explain whether your experiment confirmed or did not confirm the accepted value of *g*, within the uncertainty of the data.

Evaluation

5 Explain how the experimental data-collection method could be improved in order to increase the level of confidence in the launch speed reported.

6 Write a short sentence that describes the purpose of, and the method used in, this experiment.

7 State the precise value of the initial speed of the projectile.

8 Indicate any other worthwhile data, such as maximum height attained and value of *g*, that were found during the experiment.

LEARNING CHECK 12.9

DESCRIBING

1 **Describe** the difference between gravitational force and gravitational acceleration.

2 State the magnitude of the gravitational acceleration near Earth.

3 **Describe** and **explain** the conditions for which the gravitational acceleration near Earth's surface is usually taken to be:
   - **a** positive
   - **b** negative.

APPLYING

4 A rock dropped from a cliff hits the ocean with a speed of 44.1 m s^{-1}.
   - **a** Sketch the velocity–time graph for this motion.
   - **b** Find the time taken for the rock to fall to the ground.
   - **c** Find the height of the cliff.
   - **d** Show how these results can be obtained by an alternative method (graphical or algebraic representation) to the one you used to solve part **b** and part **c**.

5 Jan stands exactly 5.0 m vertically below a window. She throws a set of keys vertically upwards so that the keys are stationary when level with the windowsill.
   - **a** Find the time taken for the keys to reach the windowsill.
   - **b** Determine the speed with which Jan should throw the keys.

6 For vertical projectile motion, evaluate your responses to the following statements and suggest ways to improve your skills if necessary:
   - **a** 'I readily understand and can use positive and negative values for the gravitational acceleration.'
   - **b** 'I am confident that I use both algebraic and graphical solution methods with ease.'

CHAPTER SUMMARY

Vectors

- A vector gives information about both magnitude and direction.

Some vector quantities

Quantity and usual symbol	Measurement scales
displacement, $\vec{s}$	length; m and angle
velocity, $\vec{v}$	speed; m s^{-1} and angle
acceleration, $\vec{a}$	acceleration; m s^{-2} and angle
force, $\vec{F}$	magnitude of force; N and angle
momentum, $\vec{p}$	magnitude of momentum; kg m s^{-1} and angle

- Vectors can be represented by arrows. The direction the arrow points signals the direction of the quantity, and the length of the arrow is proportional to the magnitude of the quantity.

Displacement and distance

- Along a number line, the displacement is the arithmetic difference between two positions, taking signs into account:

$$\vec{s} = \vec{d}_2 - \vec{d}_1$$

where: $\vec{d}_1$ = initial displacement from the origin (m)
$\vec{d}_2$ = final displacement from the origin (m)
$\vec{s}$ = displacement relative to the initial position (m)

- For any one displacement from position 1 to position 2, the distance is given by the magnitude of the vector displacement:

$$d = \left|\vec{d}_2 - \vec{d}_1\right|$$

- The distance of a journey is the sum of all the distances.

Speed and velocity

- Speed measures how fast something is travelling, whereas velocity measures how fast something is travelling in a particular direction.
- Units for both speed and velocity are m/s or m s^{-1}.
- Average speed can be expressed as:

$$v_{av} = \frac{d}{t} = \frac{\left|\vec{d}_2 - \vec{d}_1\right|}{t_2 - t_1}$$

where: v_{av} = average speed (m s^{-1})
d = distance interval (m)
$t = t_2 - t_1$ = time interval (s)
$\left|\vec{d}_2 - \vec{d}_1\right|$ = magnitude of the displacement interval (m)

- Average velocity can be found using:

$$\vec{v}_{av} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$

where: $\vec{v}_{av}$ = average velocity (m s^{-1})
$\vec{s} = \vec{d}_2 - \vec{d}_1$ = displacement interval (m)
$t = t_2 - t_1$ = time interval (s)

Interpreting displacement–time graphs

- The gradient of a displacement time graph is the velocity of the object.

$$v = \frac{s}{t} = \text{gradient of } s\text{–}t \text{ graph}$$

where: v = speed (m s^{-1})
s = distance change (rise of s–t graph) (m)
t = time interval (run of s–t graph) (s)

- The area under a speed–time graph between two time intervals is used to calculate the distance travelled:

$$s = vt$$

where: v = speed (m s^{-1})
s = distance travelled (m)
t = time elapsed (s)

- When particles are moving at different speeds over different time intervals, the total distance travelled is the sum of the individual distances:

$$s = v_1t_1 + v_2t_2 + \ldots$$

where: s = total distance travelled (m)
v_1t_1 = distance travelled at constant speed v_1 in first time interval t_1 (m)
v_2t_2 = distance travelled at constant speed v_2 in second time interval t_2 (m)

'...' means this goes on for as many constant speeds in time intervals as there are in the motion described by the graph.

Acceleration

- Acceleration is the rate of change of velocity. It can be expressed as:

$$a = \frac{v - u}{t} = \frac{\text{m s}^{-1}}{\text{s}} = \text{m s}^{-2}$$

where: a = unit of acceleration (m s^{-2})
v = unit of final speed or velocity (m s^{-1})
u = unit of initial speed or velocity (m s^{-1})
t = unit of time (s)

- In velocity–time graphs, acceleration is the gradient of the graph. It can be found using:

$$\vec{a} = \frac{\vec{v}}{t}$$

$$\vec{a} = \frac{\vec{v}_2 - \vec{v}_1}{t_2 - t_1}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\vec{v} = \vec{v}_2 - \vec{v}_1$ = velocity change (m s^{-1})
$t = t_2 - t_1$ = time interval (s)

- With a constant acceleration, the area under an acceleration–time graph over time is the change in speed of an object:

$$a = \frac{v}{t}$$

where: v = speed (m s^{-1})
t = time interval (s)
a = constant acceleration (m s^{-2})

Acceleration and gravity

- An object travels at constant accelerated motion in a straight line when falling, thrown straight down or projected vertically upwards.
- Gravitational acceleration (g) is 9.0 m s^{-2}.

CHAPTER EXAM

MULTIPLE CHOICE

1. Which of the following lists contains two scalar quantities and two vector quantities?

A Length, mass, velocity, time
B Mass, distance, time, energy
C Mass, displacement, time, length
D Mass, displacement, distance, force

2. A ball is thrown 40 m east, picked up and thrown a further 40 m south. The displacement of the ball is nearest to:

A 56 m.
B 80 m.
C 56 m, S45°E.
D 80 m, E45°S.

3. A particle moves along a number line. Starting at $^{+}15$ cm, it moves to $^{+}20$ cm, then $^{-}30$ cm before stopping at the origin. The distance moved and the displacement relative to the starting position are, respectively:

A 20 cm; $^{-}20$ cm.
B 20 cm, 0 cm.
C $^{+}85$ cm; 0 cm.
D 85 cm; $^{-}15$ cm.

4. A particle moves from $^{+}1.23$ mm to $^{+}62.7$ μm. The change in displacement is closest to:

A $^{+}63.93$ mm.
B $^{-}61.5$ μm.
C $^{-}1.17 \times 10^{-3}$ m.
D $^{-}0.12$ cm.

5. Instantaneous and average speed are the same only for:

A constantly accelerated motion.
B time intervals that are negligible.
C velocity intervals that are negligible.
D distance intervals that are negligible.

6. For a speed–time graph, the gradient and area can be used to determine, respectively:

A acceleration and position.
B position and distance interval.
C acceleration and velocity interval.
D change in velocity and acceleration.

7. A particle accelerates uniformly from rest to a speed of 8.0 m s^{-1} in 2.0 s. It continues to accelerate at the same rate. What is its speed after 5.0 s?

A 16.0 m s^{-1}
B 28.0 m s^{-1}
C 32.0 m s^{-1}
D 40.0 m s^{-1}

8. An object accelerates at 6.0 m s^{-2} from rest. How far does it travel in the first 3.0 s?

A 2.0 m
B 9.0 m
C 18 m
D 27 m

9. An object is launched vertically upwards at a speed of 5.0 m s^{-1}. How long does it take to return to the launch site?

A 0.51 s
B 1.02 s
C 1.96 s
D 3.92 s

10. A ball is dropped from a roof at the same time as another ball is thrown upwards from the roof. The two balls:

A reach the ground at the same time.
B have the same velocity when they reach the ground.
C have different accelerations when they reach the ground.
D none of the above.

SHORT RESPONSE

11. A sprinter accelerates from rest up to a top speed of 10 m s^{-1} in only 10 m.

a **Determine** how long the sprinter accelerated for.
b **Calculate** the acceleration of the sprinter in m s^{-2}.
c If the sprinter maintains this top speed for the remainder of the 100 m event, **calculate** the time for the event.

12. A ship sails at a constant velocity of 30 km h^{-1}.

a **Calculate** how far the ship will travel in a day.
b **Determine** how long it would take for the ship to travel 500 km.

13. A girl throws a ball 20 m vertically into the air.

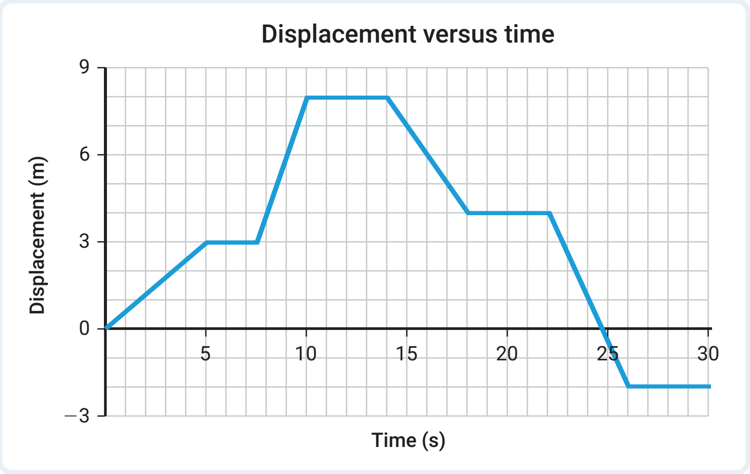
a **Calculate** how long she would have to wait to catch the ball on the way down.
b **Calculate** the initial velocity of the ball.
c **Identify** the final velocity of the ball.

14. A stone is dropped from the roof of a high-rise office building. Tamara was sitting in her office looking out the window when she saw the stone go past. It took the stone 0.22 s to pass her window and the height of the window was 2.1 m. How far below the roof of the building is the top of Tamara's window?

DATA ANALYSIS

15. Analyse data

The following graph displays the displacement of a toy train (in a northern direction along a long straight track) versus time.



Use the graph to answer the following questions.

a **Identify** the displacement of the train after:

- **i** 5.0 s
- **ii** 12.5 s
- **iii** 17.0 s
- **iv** 23.5 s.

b **Calculate** the average velocity of the train:

- **i** in the first 5 s
- **ii** in the first 10 s
- **iii** in the first 14 s
- **iv** in the first 20 s
- **v** in the first 30 s
- **vi** in the second 10 s
- **vii** from $t = 5.0$ s to $t = 15.0$ s.

c **Calculate** the instantaneous velocity of the train at:

- **i** 0.0 s
- **ii** 4.0 s
- **iii** 6.5 s
- **iv** 9.0 s
- **v** 17.0 s
- **vi** 21.25 s
- **vii** 25.0 s
- **viii** 28.5 s.

CHAPTER

13

Forces

iStock.com/SteveMcsweeny

SYLLABUS DOT POINTS

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 $a_{\text{net}} = \frac{F_{\text{net}}}{m}$.
- 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

- 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.

SCIENCE INQUIRY

- Explore the role physics plays in improving the performance of elite athletes.

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Introduction

Athletes push against the ground to run and jump. They throw balls and strike them with bats to make them change direction and speed. They lift weights by pushing against gravity. Gymnasts pull on ropes and bars. Muscles push and pull in order to run and jump, throw and strike and lift. Pushes and pulls are forces applied to objects. Therefore, an understanding of forces is crucial to understanding how to perform better as an athlete.

Practicals

- Law of conservation of momentum and Newton's third law
- Momentum during a collision

Worksheets

- Newton's third law
- Seatbelts and air bags
- Force versus time

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Forces can be balanced or unbalanced, and contact or non-contact.
- ✓ Vector quantities have a direction as well as magnitude.
- ✓ The SI unit for mass is the kilogram (kg).

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain what a force is
- ✓ categorise forces as contact, non-contact or action-at-a-distance
- ✓ describe the application of forces in terms of agents and receivers
- ✓ use agent–receiver nomenclature to describe forces
- ✓ recall the four fundamental forces
- ✓ describe and explain frictional force, tension, gravitational force, weight, centripetal force, magnetic force, electrostatic force and normal force
- ✓ use trigonometry to explain how the components of a force can be determined
- ✓ describe and explain Newton's first law and the concept of inertia
- ✓ perform calculations using Newton's second law
- ✓ describe and explain the link between Newton's first law and the calculation of weight from an object's mass
- ✓ describe and explain Newton's third law
- ✓ use and interpret free-body diagrams to investigate forces
- ✓ solve problems involving forces, weight and acceleration
- ✓ describe and explain the concepts of momentum and impulse
- ✓ describe and explain the law of conservation of momentum
- ✓ solve problems pertaining to momentum, impulse and the law of conservation of momentum
- ✓ perform experiments investigating Newton's third law and the law of conservation of momentum
- ✓ solve problems involving collisions
- ✓ analyse and interpret force–time graphs
- ✓ consider the historical development of classical physics and how it has impacted the modern world.

13.1 Forces acting on an object

Forces are external actions applied by objects on objects. Objects do not own a particular force inside them. Force can be applied by direct physical contact, a **contact force**, or over a distance, a **non-contact force**, including through a vacuum. This distinction is a useful starting point. At a more basic level, all forces turn out to be non-contact, or **action-at-a-distance forces**. Forces – pushes or pulls – affect the motion of objects. Force has a magnitude and a direction; therefore, force is a vector.

contact force a force applied by one object on another when they are close enough to appear to be touching

non-contact force a force applied by one object on another when they are separated by distance

action-at-a-distance forces a non-contact force

Forces affect the motion of objects. Isaac Newton (1643–1727) pioneered a way of understanding everyday forces and their effects. He built his understanding on developments that had evolved over centuries in the study of astronomy and movement (**Figure 13.1.1**).

To understand motion, consider a very simple case: a single point mass object subjected to a single external force. The state of motion of the object changes when a force is applied to it.

If it is stationary, it will start to move. If it is moving, it will speed up, slow down or change direction. Both speed and direction may change simultaneously when a force is applied. When this object collides with another object, it applies a force. At the same time, the second object applies a force to the first one.


Alamy Stock Photo/North Wind Picture Archives

FIGURE 13.1.1 Isaac Newton said in 1676, 'If I have seen further, it is by standing on the shoulders of giants.'

Forces are applied externally by agents on receivers

Force is applied by one object on another object. Neither object has a particular amount of force inside it. Strictly speaking, it is incorrect to talk about 'the force of an object'. 'Force of' suggests that an object owns a particular amount of force. It is obvious that the same object may apply a large force on one object and a small force on another object. How then could it have or own a particular single force?

The interaction between objects reveals the forces applied. A force is always applied externally by something (the agent) on something else (the receiver). We write:

$$F(\text{by agent on receiver})$$

The interaction between objects is mutual:

- Object A exerts a force on object B: $\vec{F}$(by A on B).
- Object B exerts a force on A: $\vec{F}$(by B on A) (Figure 13.1.2).

Note that the decision about which object is the agent and which object is the receiver depends on the object of interest. Usually, the object of interest is treated as the receiver.

KEY FORMULA

Force nomenclature

Object A exerts a force on object B:

$$\vec{F}(\text{by A on B})$$

Object B exerts a force on A:

$$\vec{F}(\text{by B on A})$$

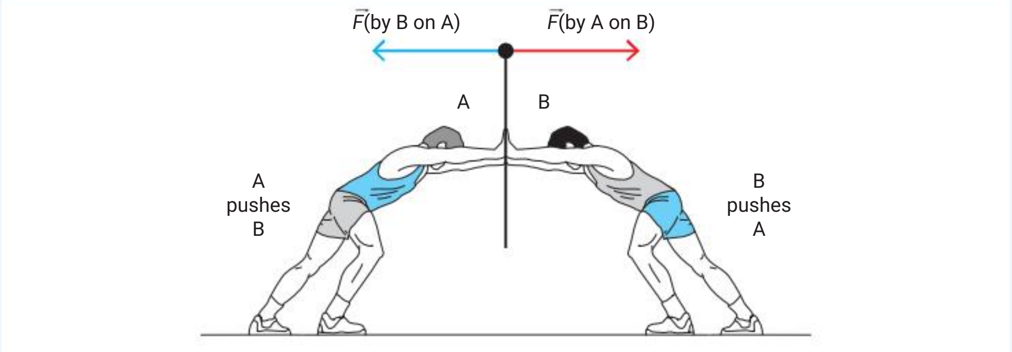


FIGURE 13.1.2 Person A contacts person B, so A acts on B: $\vec{F}$(by A on B). At the same time, B contacts A, so B acts on A: $\vec{F}$(by B on A).

Types of forces

Forces are interactions between objects that may cause changes in their motion or shape. They are described by their magnitude, direction (they are vector quantities) and point of application. Understanding forces is crucial in physics because they explain how objects move and interact with each other in the world around us.

There are several types of forces, and there are four fundamental forces. The unit of force is the newton (N).

As a first approximation, a distinction can be made between contact forces and non-contact forces.

Contact forces

Contact forces are forces that involve two objects that appear to be touching each other.

Syllabus link
Units 3 & 4 discuss the concept of fields, non-contact forces and the way forces are mediated by fields.

Non-contact forces

Non-contact forces occur when objects that are clearly not touching experience a force. Non-contact forces are also known as 'action-at-a-distance' forces. The three most familiar non-contact forces are the electrostatic force, the magnetic force and the gravitational force.

The fundamental forces

There are four fundamental forces that shape how matter and energy behave and interact in the universe. The four fundamental forces are the:

- gravitational force, which pulls objects towards each other due to their masses. It is responsible for the weight of objects and is the reason objects fall towards Earth.
- electromagnetic force, which acts between charged particles. It is responsible for phenomena like friction, magnetism and static electricity.
- strong nuclear force, which holds atomic nuclei together. It is responsible for the stability of atoms.
- weak nuclear force, which is responsible for certain types of radioactive decay, such as beta decay.

Syllabus link
Chapter 6 describes the four fundamental forces.

However, other forces exist too, including the:

- frictional force, which opposes the motion of objects in contact. It is due to the roughness of surfaces and can act in the direction opposite to the motion (or impending motion).
- normal force, which acts perpendicular to the surface of contact between objects. For example, when you stand on the ground, the ground exerts an upward normal force to support your weight.
- tension force, which arises when a flexible object (such as a rope or wire) is pulled at both ends. It acts along the length of the object and keeps it from stretching or breaking.
- centripetal force, which is a centre-seeking force that is provided by another force, such as force tension in a string, force electrostatic between charged particles or force gravitational between masses.

Force components

It is often necessary to determine components of forces to solve problems, such as a component of gravity acting parallel to the plane, or the component of gravity acting perpendicular to the plane **(Figure 13.1.3)**.

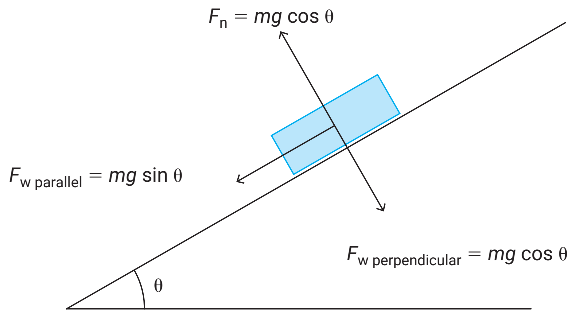


FIGURE 13.1.3 A diagram of the force of a mass released on an inclined plane

Electrostatic force

Every charged particle exerts an electrostatic force on every other charge. There are two forms of charge: positive and negative. Charged particles repel each other if they carry the same sign. Two oppositely charged objects attract each other **(Figure 13.1.4** and **Table 13.1.1)**. Electrostatic force is responsible for lightning, the way dry hair stands up when being combed, and why sparks are sometimes seen when taking off a jumper in the dark.

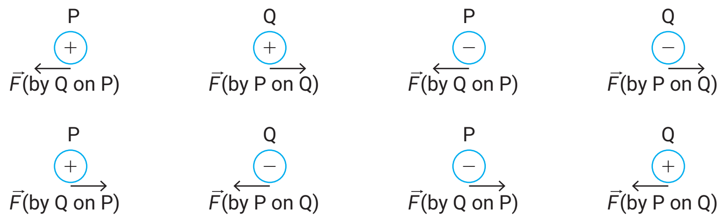


FIGURE 13.1.4 Charge P and charge Q apply action-at-a-distance forces on each other. The forces are repulsive if the charges on P and Q have the same sign and attractive if P and Q are oppositely charged.

TABLE 13.1.1 Charges of the same sign repel; charges of different signs attract

	+	−
+	Repel	Attract
−	Attract	Repel

Magnetic force

A magnet is an extended object that applies a magnetic force on other magnets and magnetic materials. Earth can be modelled as a very large magnet. The poles of a magnet are called north and south poles. This is determined by reference to the general direction to which they point when allowed to swing freely near Earth. A north pole is a north-seeking pole that points more or less towards Earth's geographic north, and a south pole points more or less towards Earth's geographic south. The direction the magnet points is determined by the direction of Earth's magnetic field.

When two magnets are brought near to each other, opposite poles attract and like poles repel **(Figure 13.1.5** and **Table 13.1.2)**.

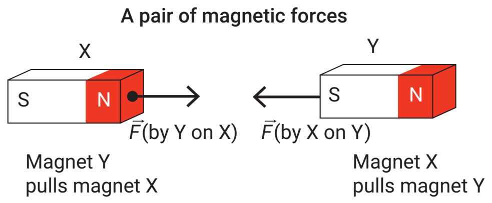


FIGURE 13.1.5 A pair of magnetic forces; opposite poles attract.

TABLE 13.1.2 Like magnetic poles repel; unlike magnetic poles attract

	North pole	South pole
North pole	Repel	Attract
South pole	Attract	Repel

Gravitational force

Every mass exerts a gravitational force on every other mass. For example, two small isolated masses, m and M, far out in space are gravitationally attracted; mass m attracts mass M, and mass M attracts mass m **(Figure 13.1.6)**.

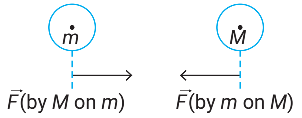


FIGURE 13.1.6 Two masses are mutually attracted.

Earth's gravitational force

Earth's mass applies an observable gravitational force on masses such as the Moon, satellites and things on the surface **(Figure 13.1.7)**. It is an action-at-a-distance or non-contact force because the masses are clearly not touching, yet a force is being applied.

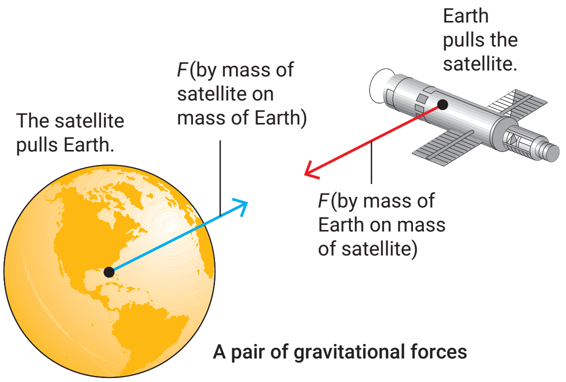


FIGURE 13.1.7 Gravitational force is an action-at-a-distance force. The mass of Earth attracts the mass of the satellite. Simultaneously, the mass of the satellite attracts the mass of Earth.

gravity the gravitational force applied by Earth's mass on smaller masses on or near Earth; by extension, the force applied by a large celestial mass, such as a moon or a planet, on nearby masses

The very large mass of Earth applies a gravitational force on the much smaller masses situated on Earth. In everyday language, this force is called **gravity**, but it is usual for physicists to speak of gravitational force by mass on mass more generally.

Mass of Earth (agent) acts on a very much smaller mass (receiver):

$$\vec{F}\text{(by mass of Earth on mass of object)}$$

This is the force we are usually interested in.

The smaller mass also exerts a gravitational force on the larger mass:

$$\vec{F}\text{(by mass of object on mass of Earth)}$$

Usually, we are not concerned about the effects of the smaller mass on Earth's mass.

Weight

On Earth, the term '**weight**' is used to mean the gravitational force applied by the mass of Earth on a much smaller mass; for example, a person.

Weight is a force, measured in newtons. It is not a mass (which is measured in kilograms). This can be confusing. Typical bathroom scales measure the weight force applied to them. The scale is then converted to read the mass that would experience that force, on Earth. For example, a 60 kg person applies a 588 N force on the weighing machine. The weighing machine measures a force of 588 N and converts it to 60 kg on the scale. The person would then say they have a weight of 60 kg. Strictly speaking, the person has a mass of 60 kg and exerts a force on the weighing machine equivalent to the force due to gravity – the force applied by the mass of Earth – on a 60 kg mass. Be careful to ensure everyday language does not affect the way you understand physics ideas.

weight the gravitational force on mass; force exerted by mass of Earth on masses 'near Earth'; by extension, the force by any large mass in the universe, such as the Moon, on any smaller mass 'nearby'

$$\vec{w} = \vec{F}\text{ (by mass of Earth on mass of object)}$$

where: $\vec{w}$ = weight force (N)

No object has a weight, because that would mean that an object contains a force, which is incorrect. However, objects do have mass because that is a measure of their substance.

If the 60 kg person and the weighing machine were taken to the Moon, the scale would show that the person weighs about 10 kg. This is because the Moon exerts a gravitational force that is about one-sixth the gravitational force applied by Earth. The person does not lose any of their substance, their mass, by travelling to the Moon. They must still have 60 kg of substance. But the force applied by the mass of the Moon on a 60 kg mass is equivalent to the force applied to a 10 kg mass on Earth.

KEY FORMULA

$$\vec{w} = \vec{F}\text{(by mass of Earth on mass of object)}$$

where: $\vec{w}$ = weight force (N)

LEARNING CHECK 13.1

DESCRIBING

1 **Describe** three ways in which a force can affect the motion of a point mass.

2 Give an example scenario for the following:
  - a contact force
  - b non-contact force
  - c gravitational force
  - d electrostatic force.

3 When talking about force, what do the following terms mean?
  - a Agent
  - b Receiver

APPLYING

4 **Explain** why force is a vector.

5 'Strictly speaking, it is incorrect to talk about the force of an object'. **Explain** this statement.

6 Two rugby players, Ben (B) and Matt (M), collide. Use the agent–receiver nomenclature to **describe** the forces involved in the interaction.

7 **Explain** the difference between mass and weight.

8 **Compare** the physical quantity that typical bathroom scales measure and the reading on the scale.

ANALYSING

9 A 30 kg box and the bathroom scales that were used to measure it were taken to the Moon. **Explain** why the box weighs about 5.0 kg on the Moon.

13.2 Newton’s three laws

Forces acting externally on stationary objects can cause them to move. The stationary object gains a non-zero velocity. A force applied externally on a moving object changes its speed, its direction of motion or both its speed and direction. Change of speed and change of velocity mean that the object accelerates. These ideas are not necessarily intuitive, but they are essential to understand motion and its causes.

Newton summarised the causes of motion in three laws. These laws are not simply mathematical formulas to be remembered. They are a summary of a new way of thinking. Even today, many physics students think in old-fashioned, Aristotelian terms; that is, that forces are in objects or natural to objects and that forces cause things to move at uniform velocity, including zero velocity. Galileo and Newton overthrew Aristotelian thinking.

Newton’s three laws relate to the sum of forces (net force) applied externally on a point mass.

Newton’s first law

A force applied on a point mass will cause the point mass to change its velocity. If the mass is stationary, the force will cause it to start moving; the velocity of the mass will change. If the mass is already moving at constant velocity, the force will cause the velocity to change – speed will change (without change of direction) or direction will change (without change of speed), or speed and direction will both change simultaneously. That is, a body will not change its motion unless forced to do so. This is Newton’s first law, which can be stated as:

> A body will continue in its state of rest or of uniform motion in a straight line unless compelled by a net external force to change that state.

The emphasis in Newton’s first law is on change of velocity. A change of velocity means acceleration. Thus, Newton’s first law directs attention to the effect of force, namely, acceleration.

where: $\sum \vec{F}(\text{on receiver})$ = sum of forces on receiver

From this, we can deduce that, if the acceleration of a mass is zero, the net force on that mass must be zero:

$$\text{If } \vec{a} = 0$$
$$\text{then } \sum \vec{F}(\text{on receiver}) = 0$$

where: $\sum \vec{F}(\text{on receiver})$ is the vector sum of all forces applied to the receiver object

$\vec{a}$ = the acceleration of the receiver (m s^{-2})

KEY FORMULA

In mathematical terms, Newton’s first law can be written as:

$$\sum \vec{F}(\text{on receiver}) = 0\ \text{N}$$
$$\text{if } \vec{a} = 0\ \text{ms}^{-2}$$

where:

$\sum \vec{F}(\text{on receiver})$ is the vector sum of all forces applied to the receiver object (N)

$\vec{a}$ = the acceleration of the receiver (m s^{-2})

Inertia

The tendency of a body to continue in its state of rest or of uniform motion in a straight line is called **inertia**. It is a kind of resistance to the forces that would change the state of motion. Since inertial mass is the quantity that is resisting the change, 'inertial mass' and 'inertia' can be used interchangeably. A distinction is made between inertial mass and gravitational mass. Inertial mass is affected by external forces of all kinds. **Gravitational mass** is the mass of an object that acts at a distance on other masses via gravitational force. For current purposes, this distinction will not be pursued.

inertia, inertial mass the tendency of a body to continue in its state of rest or of uniform motion in a straight line

gravitational mass the mass of an object that acts at a distance on other masses via gravitational force

Newton's second law

The acceleration of a mass is affected by the net force applied to it as well as its inertial mass.

For a particular mass, m, the larger the net force, $\sum \vec{F}_{\text{net}}$, the greater the acceleration, a.

$$\vec{a} \propto \sum \vec{F}_{\text{net}}$$

For a given net force, the larger the mass, the smaller the acceleration:

$$\vec{a} \propto \frac{1}{m}$$

Altogether, the relationship between the dependent variable, $\vec{a}$, and the two independent variables, $\sum \vec{F}$ and m, is:

$$\vec{a} = \frac{\sum \vec{F}_{\text{net}}}{m}$$

The constant of proportionality has been set at 1. The SI unit system has been constructed such that, by definition, a net force of 1.0 N applied to an inertial mass of 1.0 kg produces an acceleration of 1.0 m s^{-2}.

Newton's second law is just the mathematical expression of Newton's first law applied to a mass, m.

$$\text{If } \sum \vec{F}_{\text{net}} = 0, \quad \text{then } \vec{a} = 0.$$

$$\text{If } \vec{a} = 0, \quad \text{then } \sum \vec{F}_{\text{net}} = 0.$$

Newton's second law is also encountered in the algebraically equivalent statement:

$$\sum \vec{F}_{\text{net}} = m\vec{a}$$

This suggests that 'force' is 'mass times acceleration'. But this is untrue. It is obvious that a force is not two numbers multiplied together. It is true that a value for the magnitude of a force can be determined by calculating the product of mass and acceleration. Further, this form of the law incorrectly suggests that mass and acceleration cause force, since the net force is in the dependent variable position in the equation.

In mathematical terms, Newton's second law can be written as:

$$\vec{a} = \frac{\sum \vec{F}_{\text{net}}}{m}$$

where: $\vec{a}$ = acceleration (m s^{-2})

$\sum \vec{F}_{\text{net}}$ = net force (N)

m = mass (kg)

KEY FORMULA

In mathematical terms, Newton's second law can be written as:

$$\vec{a} = \frac{\sum \vec{F}_{\text{net}}}{m}$$

where:

$\vec{a}$ = acceleration (m s^{-2})

$\sum \vec{F}_{\text{net}}$ = net force (N)

m = mass (kg)

Acceleration due to gravity

Near Earth, every 1.0 kg of mass experiences the same force of 9.8 N.

For example, an extended mass of 2.0 kg experiences two lots of 9.8 N of gravitational force, one lot of 9.8 N for each kilogram. Therefore, the force on a 2.0 kg mass is 19.6 N. The weight force applied to the 2.0 kg mass, colloquially known as 'the weight of the mass', is 19.6 N.

From Newton's second law:

$$a = \frac{F}{m}$$

$$a = \frac{9.8\text{ N}}{1.0\text{ kg}}$$

$$a = 9.8\text{ m s}^{-2}$$

This is the constant acceleration due to gravity, *g*, that Galileo first identified by rolling balls down inclined planes. It was Newton's genius that extended gravitational analysis out into space. Nevertheless, to a good approximation for ordinary experience near Earth, the acceleration due to gravity is constant.

$$g = 9.8\text{ m s}^{-2}$$

The weight force, F_w, due to gravity that is applied on a mass is:

$$F_w = mg$$

where: F_w = weight force (N)
m = mass (kg)
g = acceleration due to gravity (m s^{-2})

KEY FORMULA

$$F_w = mg$$

where:
F_w = weight force (N)
m = mass (kg)
g = acceleration due to gravity (m s^{-2})

Newton's third law

Forces are only revealed in an interaction between two objects. The interaction involves forces of the same type: electrostatic, magnetic or gravitational. For two objects A and B, the interaction demonstrates the action of two forces: a force by A on B and, simultaneously, a force by B on A. The labels 'agent' and 'receiver' are applied differently depending on the object of interest. If we are interested in the effect of B on A, then B is the agent and A is the receiver. If we are interested in the effect of A on B, then A is the agent and B is the receiver.

The forces are equal in magnitude but oppositely directed.

Newton's third law can be written as:

For every action there is an equal and opposite reaction.

When two objects A and B interact, the action–reaction pair of forces are:

$$\vec{F}(\text{by } A \text{ on } B) \text{ and } \vec{F}(\text{by } B \text{ on } A)$$

Four conditions must be satisfied for these to be an action–reaction or Newton's third law pair of forces:

- Same fundamental type
- Equal in magnitude
- Opposite in direction
- Act on different objects

KEY FORMULA

Newton's third law can be written as:
For every action there is an equal and opposite reaction.
When two objects A and B interact, the action–reaction pair of forces are:

$$\vec{F}(\text{by } A \text{ on } B) \text{ and } \vec{F}(\text{by } B \text{ on } A)$$

The last criterion – that forces act on different objects – is especially significant. In many situations, the forces are equal in size and opposite in direction but act on the same object. This means that the net force on the object is zero. An action–reaction pair of forces cannot be added to each other to form a net force because they act on different objects: A acts on B and B acts on A.

Weblink
Newton's three laws with a bicycle

Worksheet
Newton's third law

LEARNING CHECK 13.2

DESCRIBING

1 Write each of Newton's three laws in words and symbols.

2 **a** List the four requirements that must be met for a pair of forces to be considered as an action–reaction pair.
  b State the one condition that must be met for a net force to be identified.

3 **a** **Describe** inertia.
  b Write the equation that connects mass and weight.

4 **Explain** what the symbol $\sum \vec{F}_{\text{net}}$ means.

5 **Explain** why an action–reaction pair of forces cannot be added together.

APPLYING

6 For some time during a 100 m sprint, an athlete runs at a constant 8.0 m s^{-1}. **Describe** the magnitude of the horizontal forces applied to the athlete.

ANALYSING

7 A basketball player jumps vertically to shoot. **Explain** what needs to be considered by the basketballer if the player was:
  a on the way up
  b on the way down
  c at the top of the jump.

8 **Explain** why the formula $a = \frac{F}{m}$ expresses the physical cause of motion better than its algebraic equivalent $F = ma$.

9 **Explain** how your understanding of action–reaction forces and net force has developed.

13.3 Free-body diagrams

A free-body diagram is a model of forces acting on a point particle, which allows us to strip away all the surrounding aspects of an object and treat it as a single point. The forces applied on the object become the forces applied on the point. We use arrows to indicate the direction and magnitude of the forces. There are three rules for force vectors on free-body diagrams:

- The tail starts at the point mass.
- The head points in the direction of the force.
- The length represents the magnitude of the force.

Drawing free-body force diagrams

Drawing free-body force diagrams in physics is a crucial skill because they provide a clear visual representation of all the forces acting on an object, and allow you to systematically analyse motion or equilibrium. They are essential because they identify and organise forces, simplifying complex physical situations by isolating the object and illustrating forces acting on it. They sum up the forces and allow you to calculate the resultant force. Drawing free-body force diagrams will help you to develop a systematic approach to analysing forces and motion problems, and lead to a deeper understanding of fundamental concepts and principles in physics.

A suggested sequence of steps for drawing free-body force diagrams in physics is as follows.

1. **Identify the object**
   Begin by identifying the object for which you want to draw the free-body diagram (e.g box, block, car).
2. **Draw the object**
   Sketch a simple representation of the object as a box, including its surroundings (inclined planes, cables, supports).
3. **Identify forces**
   Identify all the forces acting on the object. Common forces include gravity, normal force, tension, friction and applied force. Also include any other relevant forces.
4. **Label forces**
   Label each force with a clear abbreviation or symbol; for example, 'F_{gravity}' for gravitational force, 'F_{normal}' for the normal force, 'F_{friction}' for the force of friction.
5. **Determine force directions**
   Determine the direction of each force. Consider the object's motion and any constraints in the scenario. For example, gravity acts downward, normal force acts perpendicular to the surface, and friction opposes motion.
6. **Draw force vectors**
   Draw arrows representing each force. The length of the arrow should represent the comparative magnitude of the force, and the direction should match the direction determined in the previous step.
7. **Label axes (optional)**
   If needed, label the coordinate axes on the diagram to help with calculations and further analysis.
8. **Check for completeness**
   Ensure that you have accounted for all the relevant forces acting on the object. Every force should be represented on the diagram.

These examples cover different scenarios, including blocks on a surface, a hanging mass and a block on an inclined plane to illustrate the process of drawing free-body force diagrams.

WORKED EXAMPLE 13.3.1

BLOCK ON A HORIZONTAL SURFACE

- Object: block (mass of 5 kg) resting on a horizontal surface
- Forces: gravity (downwards), normal force (upwards)

Draw the block as a rectangle. Label the forces and determine their directions. Calculate the force vectors.

ANSWER

1 **State the equation.**

$F_w = mg$

2 **Substitute known values.**

$F_w = 5.0 \text{ kg} \times 9.80 \text{ m s}^{-2}$

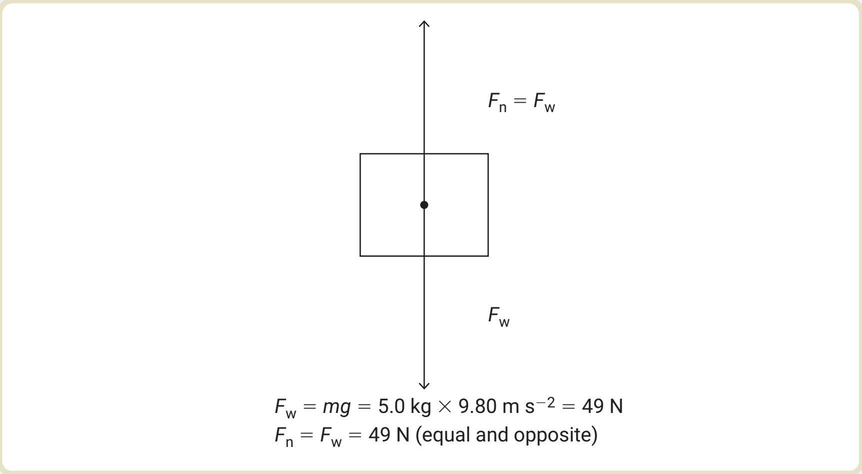
3 **Calculate the answer.**

$F_w = 49 \text{ N}$

$F_n = F_w = 49 \text{ N}$ (equal and opposite)

4 **Draw the diagram.**

Draw force vectors (equal in magnitude but opposite in direction – downwards arrow for gravity, upwards arrow for normal force).



WORKED EXAMPLE 13.3.2

HANGING MASS CONNECTED BY A ROPE

- Object: mass hanging from a rope
- Forces: gravity (downwards), tension (upwards)

Draw a box to represent the mass (2 kg). Label the forces and determine their directions. Calculate the force vectors.

ANSWER

1 **State the equation.**

$F_w = mg$

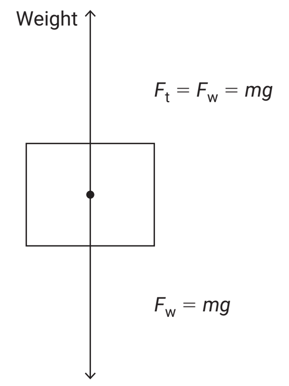
2 **Substitute known values.**

$F_w = 2.0 \text{ kg} \times 9.80 \text{ m s}^{-2}$

3 **Calculate the answer.**

$F_w = 19.6 \text{ N}$

4 **Identify the relationship between F_t and F_w.**
$F_t = F_w = 19.6$ N (equal and opposite)
Draw force vectors (downwards arrow for gravity, upwards arrow for tension).



$F_w = mg = 2.0 \text{ kg} \times 9.80 \text{ m s}^{-2} = 19.6 \text{ N}$
$F_t = F_w = 19.6$ N (equal and opposite)

WORKED EXAMPLE 13.3.3

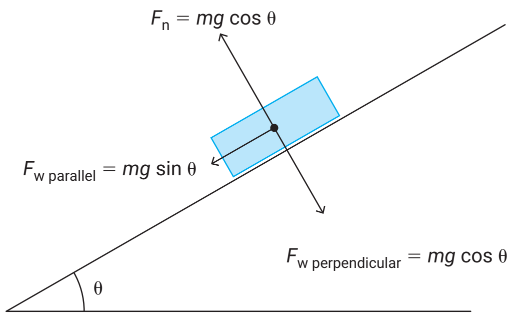
BLOCK ON AN INCLINED PLANE

- Object: block on an inclined plane
- Forces: gravity (downward), normal force (perpendicular to the surface), friction (opposing motion), component of gravity parallel to the plane ($mg \sin\theta$), component of gravity perpendicular to the plane ($mg \cos\theta$)

Draw the block as a rectangle. Label the forces and determine their directions. Calculate the force vectors.

ANSWER

1 **Draw a block shape tilted to represent the inclined plane.**
2 **Label the angle θ from the horizontal.**
3 **Label forces and determine their directions.**
4 **Draw force vectors (e.g. components of gravity parallel and perpendicular to the plane, normal force, force of friction).**



Force on an object in one dimension

Free-body diagrams can be drawn in one, two or three dimensions. Here we will only discuss one-dimensional motion; that is, motion along a straight line. In these circumstances, we can use the positive and negative directions to represent the vector nature of forces and accelerations. This is entirely similar to the way we have analysed motion along a straight line from a kinematic point of view.

Standing and moving on a surface

Every object that is in contact with a surface applies a force on the surface and the surface applies a force on the object. These forces act at right angles to the surface. The force is an electrostatic force. For an object standing on the ground the electrostatic pair of action–reaction forces are:

$$F(\text{by object on surface})_{\perp}$$
$$F(\text{by surface on object})_{\perp}$$

Note the symbol $\perp$ in each case. The symbol means that the force is at right angles, or perpendicular, to the surface. All surfaces apply forces on objects that are at right angles to the surface. This perpendicular force is called the **normal force**, F_n.

A person standing on a surface is not accelerating. This means that the net force on the person is zero. The net force applied on the person comprises the normal (electrostatic) force by the surface and the weight (gravitational) force (Figure 13.3.1):

normal force the force applied by a surface at right angles (normal) to the surface

$$\sum \vec{F}_{\text{net}}(\text{on person}) = \vec{F}_{\text{n}} + -\vec{F}_{\text{w}} = 0$$

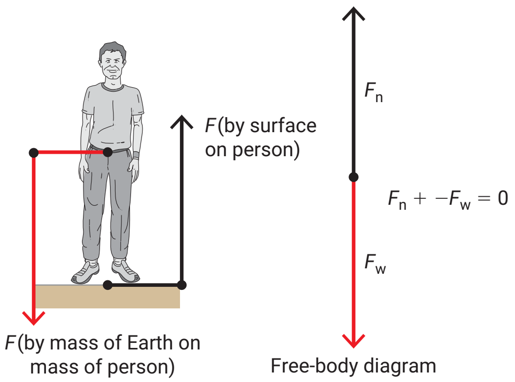


FIGURE 13.3.1 The forces applied to a person standing on the surface are the normal force and the weight force.

The normal force and the weight force are equal in magnitude and opposite in direction. Nevertheless, they are technically not an action–reaction pair of forces. The forces are not of the same type and they are not acting on different objects. Further, the normal force is different for different masses located at that position on the surface. This means that the surface applies different forces in different circumstances. This demonstrates that the surface does not contain or own a particular force. It is this capacity of surfaces to provide different external forces on objects that enables you to jump up.

Athletes and force

In jumping up vertically, an athlete pushes down on the surface. This increases the reaction or normal force applied on the athlete. There is a non-zero net force on the athlete because the athlete accelerates from the surface into the air. During the time when the athlete is in contact with the surface, the net force on the athlete includes the weight force on the athlete, *w*, and the normal force, *N* **(Figure 13.3.2)**:

$$\sum F_{\text{net}}(\text{on athlete}) = F_{\text{n}} - F_{\text{w}} > 0$$

where: $\sum F_{\text{net}}(\text{on athlete})$ = net force on athlete (N)
F_{n} = force by surface on athlete perpendicular to the surface (N)
F_{w} = weight force on athlete (N)

KEY FORMULA

$$\sum F_{\text{net}}(\text{on athlete}) = F_{\text{n}} - F_{\text{w}} > 0$$

where:
$\sum F_{\text{net}}(\text{on athlete})$ = net force on athlete (N)
F_{n} = force by surface on athlete perpendicular to the surface (N)
F_{w} = weight force on athlete (N)

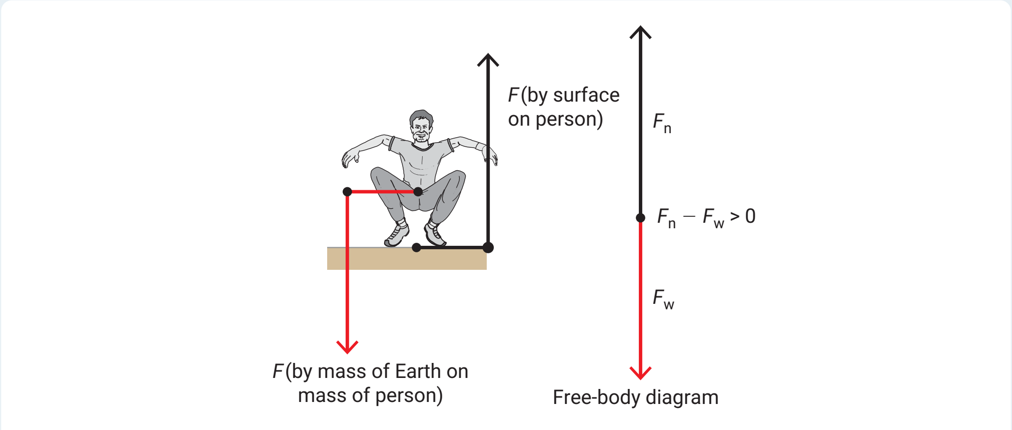


FIGURE 13.3.2 The forces applied by a surface on an athlete while in contact with the surface are the normal force and the weight force.

Subjectively, athletes know that they do the jumping because they do whatever it takes to push down as hard as possible. However, it is also true to say that 'the surface jumps the athlete', since it is the surface that provides the normal force large enough to overcome the gravitational force.

When an object moves horizontally, it applies a force on the surface and the surface applies a force on the object. These forces are an action–reaction pair that act parallel to the surface.

For an object moving parallel to a surface, the electrostatic pair of action–reaction forces are:

$$F(\text{by object on surface})_{||}$$
$$F(\text{by surface on object})_{||}$$

friction force the force applied by a surface parallel to the surface

The force on the object that is applied parallel to the surface is the **friction force**, *f*.

At the start of a sprint race, the athlete increases the friction force by pushing against the starting blocks **(Figure 13.3.3)**. Consequently, the forwards reaction or friction force increases. Without the blocks, it is more difficult to push against the surface of the track so as to ensure a large forwards friction force by the surface on the athlete. Note that it is the forward frictional force by the surface on the athlete that causes the athlete to accelerate from the blocks.

Shutterstock.com/dotshock

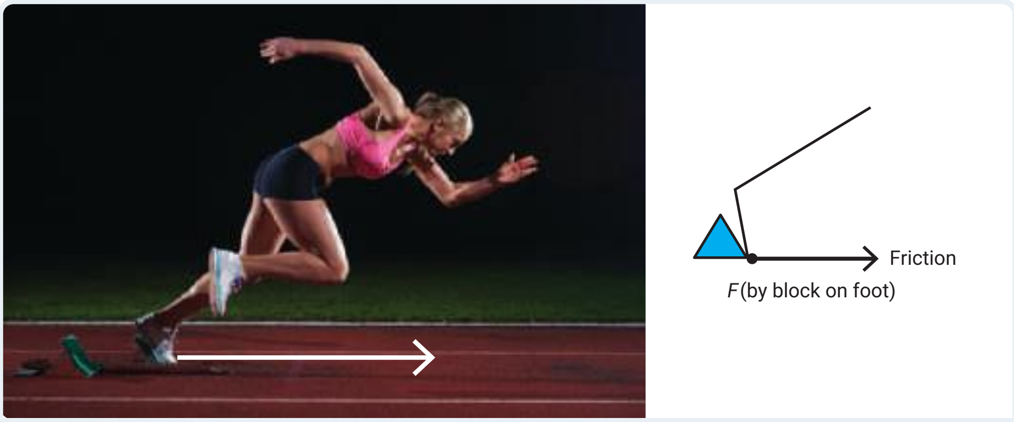


FIGURE 13.3.3 Sprint athletes increase friction by the surface by using starting blocks.

LEARNING CHECK 13.3

DESCRIBING

1 **Describe** the rules for using vectors on free-body diagrams.

2 Name and **identify** the type of force that always acts at right angles to a surface.

3 **Define**, in terms of agent and receiver:

  a normal force, *N*

  b friction, *f*

APPLYING

4 **Explain** why it is necessary to separate the force by the surface on an object into a force perpendicular to and a force parallel to the surface.

5 For a person standing on a surface, **explain** why the weight force and the normal force are not an action–reaction pair, despite being equal in size and opposite in direction.

6 **Explain** this statement: ‘Friction is the force that enables a person to walk.’

7 **Explain** this statement: ‘The ground jumps you up.’

ANALYSING

8 Many people believe that friction always opposes motion. **Discuss** whether this is true.

13.4 Solving problems involving forces

When solving problems involving forces:

- read the question carefully
- visualise or sketch the situation described
- draw a free-body diagram
- identify each force acting on the object in question
- write each force in the form *F*(by A on B), or use the symbols provided in the question

- if necessary, write the Newton's third law pair of forces
- identify the direction of the net force (or acceleration)
- add any data provided in the question
- consider Newton's laws. Ask:
  - How does Newton's first law apply?
  - How does Newton's second law apply?
  - How does Newton's third apply?
- set up any equations, using the symbols from the free-body diagram
- recall any kinematic formulas that may be useful, e.g. $a = \frac{v - u}{t}$
- solve the equations
- check to ensure that your answer responds to the question asked.

WORKED EXAMPLE 13.4.1

An 85 kg cyclist travelling at a constant speed of 12 m s^{-1} is subjected to 35 N of frictional resistance forces, *f*.

Calculate the:

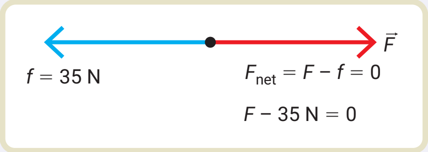
a acceleration of the cyclist.

b total forwards force by the cyclist, *F*(cyclist).

ANSWERS

a The acceleration is zero (Newton's first law: at constant speed, there is no change of velocity, hence zero acceleration).

b **1 Draw the free-body diagram.**



2 Use Newton's second law.

$$\sum F_{net} = ma$$

$$F(\text{cyclist}) - f = 0\text{ N}$$

3 Substitute the known values.

$$F(\text{cyclist}) - 35\text{ N} = 0\text{ N}$$

4 Calculate the answer.

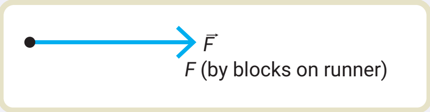
$$F(\text{cyclist}) = 35\text{ N}$$

WORKED EXAMPLE 13.4.2

At the start of a sprint race, an 85 kg runner pushes off the blocks and reaches a speed of 4.0 m s^{-1} after 0.40 s.

Calculate the net force applied by the runner on the blocks. Justify your answer.

ANSWER



1 State Newton's second law.

F(by blocks on runner) = ma

2 Substitute known values.

$$F\text{(by blocks on runner)} = 85\text{ kg} \times \frac{(4.0\text{ m s}^{-1} - 0\text{ m s}^{-1})}{0.40\text{ s}}$$

$$= 85\text{ kg} \times 10\text{ m s}^{-2}$$

3 Calculate the answer.

F(by blocks on runner) = 850 N

4 Apply Newton's third law.

F(by runner on blocks) = F(by blocks on runner)

= 850 N

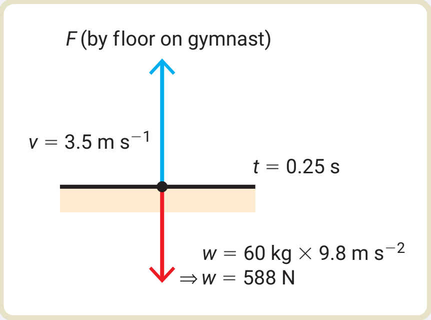
WORKED EXAMPLE 13.4.3

The feet of a 60 kg gymnast performing a vertical standing jump are on the floor for 0.25 s while jumping. The vertical speed attained at take-off is 3.5 m s^{-1}.

a Calculate the net force applied on the gymnast.
b Calculate the force applied by the floor on the gymnast.
c Find the force applied by the gymnast on the floor.

ANSWERS

a



1 State Newton's second law.

$\sum F_{\text{net}}$(on gymnast) = ma

2 Substitute known values.

$$\sum F_{\text{net}}\text{(on gymnast)} = 60\text{ kg} \times \frac{(3.5\text{ m s}^{-1} - 0\text{ m s}^{-1})}{0.25\text{ s}}$$

$$= 60\text{ kg} \times 14\text{ m s}^{-2}$$

3 Calculate the answer.

$\sum F_{\text{net}}$(on gymnast) = 840 N

b 1 Apply Newton's second law.

$\sum F_{\text{net}}$(on gymnast) = F(by floor on gymnast) – F(by mass of Earth on gymnast)

2 Substitute known values.

$F(\text{by floor on gymnast}) - 60\text{ kg} \times 9.8\text{ m s}^{-2} = 840\text{ N}$

$F(\text{by floor on gymnast}) - 588\text{ N} = 840\text{ N}$

$F(\text{by floor on gymnast}) = 840\text{ N} + 588\text{ N}$

3 Calculate the answer.

$F(\text{by floor on gymnast}) = 1428\text{ N}$

c Apply Newton's third law.

$F(\text{by floor on gymnast}) = 1428\text{ N}$

$F(\text{by gymnast on floor}) = 1428\text{ N}$

LEARNING CHECK 13.4

DESCRIBING

1 Write down the steps to follow in order to solve problems involving forces.

APPLYING

2 A person jumps up vertically from the floor. Draw a free-body diagram to represent the forces applied to the person when their feet are:
  - **a** on the floor
  - **b** in the air.

3 A 105 kg kayaker travelling at a constant speed of 4.0 m s^{-1} is subjected to 57 N of frictional resistance forces, f.
  - **a** **Calculate** the total forwards force applied by the kayaker, F(by kayaker).
  - **b** **Determine** the acceleration of the kayaker.
  - **c** **Determine** the normal force applied by the seat of the kayak on the kayaker.

4 A 50 kg box on a horizontal surface is being pulled in the same direction by two people holding separate ropes. The tension in one rope is 50 N and it is 40 N in the other. The friction force by the surface on the box is 15 N.
  - **a** Draw a free-body diagram to show this situation.
  - **b** **Calculate** the net force on the box.
  - **c** Find the acceleration of the box.

5 The acceleration of a 36 kg object sliding along a surface is 4.0 m s^{-2}. If the friction force is 12 N, **calculate** the force required.

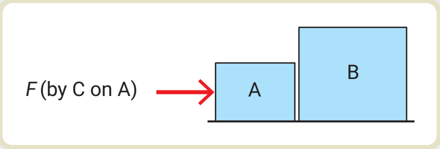
6 A 70 kg diver takes 125 ms to jump up vertically from the 10 m high tower platform with a speed of 2.5 m s^{-1}.
  - **a** **Calculate** the average acceleration of the diver during take-off.
  - **b** **Calculate** the net force applied on the diver.
  - **c** **Determine** the force applied by the diver on the high platform.

7 A 45 kg box sliding on a horizontal surface is subjected to a 15 N and a 30 N force to the right and a 10 N force to the left. There is a friction force of 5 N.
  - **a** Draw a free-body diagram to show this situation.
  - **b** **Calculate** the net force on the box.
  - **c** **Calculate** the acceleration of the box.

8 A 1.5 tonne load is attached to a cable and lifted. **Calculate** the force applied by the cable when the load is:
  - **a** accelerated from start to 2.0 m s^{-1} in a distance of 5.0 m
  - **b** lifted at 2.0 m s^{-1} for 15 s.

ANALYSING

9 Block A, of mass 2.0 kg, is touching block B of mass 3.0 kg. A third object, C, applies a force of 20 N to the right as shown below.



- **a** **Explain** why the acceleration of the two blocks, block A and block B, is the same.
- **b** **Calculate** the acceleration of block A.
- **c** Find:
  - **i** *F*(by A on B)
  - **ii** *F*(by B on A).

13.5 Conservation of momentum

impulse the action of a force over a time interval; $\vec{J} = \vec{F}t$

momentum the quantity of motion calculated by the product of mass and velocity; $\vec{p} = m\vec{v}$

It always takes time to exert a force on an object. For a particular force, the longer the time interval over which it acts, the greater the effect. The effect is the change in the velocity of the object. An analysis of Newton's second law shows how this works:

$$a = \frac{\vec{F}}{m}$$

$$\frac{\vec{F}}{m} = \frac{\vec{v}}{t}$$

$$\vec{F}t = m\vec{v}$$

Remember that the symbols $\vec{v}$ and t are intervals: change in velocity and change in time, respectively.

The quantity $\vec{F}t$ is called the **impulse** of the force, $\vec{J}$. It is the action of a force exerted over a time interval.

The quantity $m\vec{v}$ is the change of momentum of the body. **Momentum** is defined as the product of mass and velocity:

$$\vec{p} = m\vec{v}$$

where: $\vec{p}$ = momentum, in kilogram metre per second (kg m s^{-1})
m = mass (kg)
$\vec{v}$ = velocity (m s^{-1})

For an object that is initially travelling at velocity $\vec{u}$, and which changes to velocity $\vec{v}$, caused by the impulse, $\vec{F}t$, the momentum change is:

$$\vec{p}_2 - \vec{p}_1 = m\vec{v} - m\vec{u}$$

where: $\vec{p}_1$ = initial momentum (kg m s^{-1})
$\vec{p}_2$ = final momentum (kg m s^{-1})
m = mass (kg)
$\vec{u}$ = initial velocity (m s^{-1})
$\vec{v}$ = final velocity (m s^{-1})

In summary, the impulse of a force (i.e. the effect of a force acting for a time interval) causes the momentum of an object to change.

KEY FORMULA

$$\vec{p} = m\vec{v}$$

where:
$\vec{p}$ = momentum, in kilogram metre per second (kg m s^{-1})
m = mass (kg)
$\vec{v}$ = velocity (m s^{-1})

KEY FORMULA

$$\vec{p}_2 - \vec{p}_1 = m\vec{v} - m\vec{u}$$

where:
$\vec{p}_1$ = initial momentum (kg m s^{-1})
$\vec{p}_2$ = final momentum (kg m s^{-1})
m = mass (kg)
$\vec{u}$ = initial velocity (m s^{-1})
$\vec{v}$ = final velocity (m s^{-1})

KEY FORMULA

Impulse = change in momentum
$J = F\Delta t = m\Delta v$

Weblink
Conservation of momentum

Law of conservation of momentum

When two objects collide, they transfer momentum. For two objects A and B that collide along a straight line, the number line sign convention is used to represent the vector nature of impulse and momentum. The arrows on top of the vectors can then be ignored.

In a system in which only the forces applied by the objects are considered – there are no external forces – the total momentum remains the same. This is the conservation of momentum law:

The total momentum in an isolated system is always the same.

In an isolated system in which objects interact, the total initial momentum is equal to the total final momentum:

$$\begin{aligned}\Sigma\,\vec{p}_{\text{before}} &= \Sigma\,\vec{p}_{\text{after}}\\ \Sigma(m\vec{v})_{\text{before}} &= \Sigma(m\vec{v})_{\text{after}}\end{aligned}$$

where: $\Sigma\,\vec{p}_{\text{before}} = \Sigma(m\vec{v})_{\text{before}}$ = sum of momentum of system before objects interact
$\Sigma\,\vec{p}_{\text{after}} = \Sigma(m\vec{v})_{\text{after}}$ = sum of momentum of system after objects interact
m = mass (kg)
$\vec{v}$ = velocity of objects (m s^{-1})

The total momentum, p_t, does not change:

$$\vec{p}_{\text{t before}} - \vec{p}_{\text{t after}} = 0$$

where: $\vec{p}_{\text{t before}}$ = total momentum before interaction (kg m s^{-1})
$\vec{p}_{\text{t after}}$ = total momentum after interaction (kg m s^{-1})

Weblink
Simulation of impulse and momentum

For interactions along a straight line, the vector symbols can be ignored. Momentum change is then treated as positive and negative numbers.

Momentum conservation happens continuously throughout the interaction, because it is the impulse of the force that is exerted by each object on the other at any infinitesimally small instant of time that causes the change of momentum.

$$\begin{aligned}J(\text{by A on B}) &= F(\text{by A on B})t\\ J(\text{by B on A}) &= F(\text{by B on A})t\end{aligned}$$

The total momentum, p_t, in the system before the interaction is the sum of the initial momenta of A and B:

$$p_{\text{t}} = p_{\text{Ai}} + p_{\text{Bi}}$$

The total momentum, p_t, in the system after the interaction is the sum of the final momenta of A and B:

$$p_{\text{t}} = p_{\text{Af}} + p_{\text{Bf}}$$

Thus:

$$p_{\text{Ai}} + p_{\text{Bi}} = p_{\text{Af}} + p_{\text{Bf}}$$

By rearranging this equality, the change of momentum for A and for B can be demonstrated:

$$\begin{aligned}p_{\text{Af}} - p_{\text{Ai}} &= p_{\text{Bi}} - p_{\text{Bf}}\\ p_{\text{Af}} - p_{\text{Ai}} &= {}^{-}(p_{\text{Bf}} - p_{\text{Bi}})\end{aligned}$$

The negative sign indicates that the change in momentum for object A is the opposite of the change in momentum for object B.

These momentum changes are produced by the impulse of the forces on each object. Thus:

$$F(\text{by B on A})t = {}^{-}F(\text{by A on B})t$$

This is just another way to state Newton's third law. Indeed, by dividing out the time interval, *t*, Newton's third law appears in either of the standard forms:

$$F(\text{by B on A}) = {}^{-}F(\text{by A on B})$$

or

$$F(\text{by B on A}) + F(\text{by A on B}) = 0$$

These are statements of Newton's third law, and we have already noted that the action–reaction pair cannot be added to form a net force. What is meant by this way of writing Newton's third law is that, through the impulse of the forces applied in the closed system, momentum is conserved. The division out of the time interval hides that fact.

PRACTICAL ACTIVITY 13.5.1

LAW OF CONSERVATION OF MOMENTUM AND NEWTON'S THIRD LAW

Introduction

Consider the following scenarios. A moving skateboard will slow down when a rider jumps sideways onto it. Further, a stationary skateboard rider, A, will start to move, and a moving skateboard rider, B, will slow down if they were to collide and move off together.

Research question

What happens when two objects collide in regards to momentum and forces?

Aim

To demonstrate:

- the law of conservation of momentum
- Newton's third law quantitatively

Materials

- 2 skateboards or equivalent carriages
- appropriate safety gear: helmet, knee pads, wrist pads or dynamic trolleys
- motion sensors or video recording device
- electronic balance

Construct a table similar to the one below. Identify specific risks to a person's safety and ways to manage these risks.

RISK ASSESSMENT

What are the risks in doing this investigation?	How can you manage these risks to stay safe?

Procedure

1 Find and record the masses of the skateboards, rider A and rider B (or dynamic trolleys and masses).

Conservation of momentum

1 Launch one skateboard so that it travels in a straight line at constant speed. This will require some practice.

2 Measure and record the constant speed of the skateboard.

3 Calculate and record the momentum of the skateboard.

4 Arrange for rider A to jump sideways onto the skateboard.

5 Measure the speed of skateboard plus rider.

6 Repeat steps 4 and 5 with rider B.

Newton’s third law

1 Launch rider A on a skateboard towards stationary rider B on the second skateboard.
2 When A is alongside B, they take hold of each other so that both riders move off together.
3 Measure and record the velocities of A and B from just before to just after the collision.
4 Repeat by launching rider B towards stationary rider A.

Analysis

Conservation of momentum

1 Calculate and record the momentum of the skateboard plus rider.
2 Estimate any uncertainties in the data and their effect on the momentum calculation.

Newton’s third law

3 Use the velocity data to calculate and record the deceleration of rider A and acceleration of rider B.
4 Calculate the forces *F*(by A on B) and *F*(by B on A).
5 Estimate any uncertainties in the data and their effect on the force calculations.

Evaluation

6 Explain why it is an essential part of the practical activity to jump sideways onto the skateboard.
7 Identify difficulties in producing accurate and precise measurements in these experiments.
8 Suggest ways to improve the quality of the data.

LEARNING CHECK 13.5

DESCRIBING

1 **Describe** impulse and its relationship to force and motion. **Identify** the relevant equations.
2 Write an equation that links impulse and momentum.
3 State what causes the momentum of an object to change.
4 State the law of conservation of momentum.
5 **Describe** the conditions for which the law of conservation of momentum applies.
6 **Explain** why momentum is conserved at every moment in a collision.

APPLYING

7 The law of conservation of momentum relies on Newton’s third law. **Explain** this statement.
8 For one-dimensional motion, **describe** how the number line is used to represent force vectors.
9 a **Describe** how to use a force–time graph to find impulse and, hence, momentum change.
  b **Describe** how to use an acceleration–time graph to find momentum change and, hence, impulse.

ANALYSING

10 Objects A and B have initial momentums p_{Ai} and p_{Bi}, respectively, along a straight line. They collide, and move off with momentums p_{Af} and p_{Bf}, respectively. Show that A transfers momentum to B and B transfers momentum to A.

13.6 Solving problems involving collisions

Interactions between objects are frequently referred to as **collisions**. Billiard balls, rugby players and vehicles collide. Any two objects that are subject to mutual forces of interaction in a closed system can be analysed as a collision. In these cases, the conservation of momentum occurs at all times from the start of the collision to its end. Once the mutual forces of the collision have stopped applying, new collisions may occur. For example, a car crash can be considered as an isolated collision during impact. Then, a further collision occurs as the system comes to a stop due to friction between the colliding vehicles and the road.

collision an interaction between two objects subject to action–reaction pairs of forces

Using conservation of momentum to analyse collisions between objects

When using the conservation of momentum to analyse the collisions between objects:

- Read the question carefully.
- Visualise the situation described; sketches are essential.
- Divide the page into two columns.
- Label the columns ‘Before’ and ‘After’.
- Sketch a diagram in the ‘Before’ column to show:
  - the situation before the interaction
  - the data provided in the question
  - any missing data.
- Sketch a diagram in the ‘After’ column to show:
  - the situation after the interaction
  - the data provided in the question
  - any missing data (on the diagram show symbol = ?).
- In the ‘Before’ column:
  - write an equation for the total momentum before the interaction
  - use symbols for any missing data (on the diagram show symbol = ?)
  - complete any calculations that can be completed.
- In the ‘After’ column:
  - write an equation for the total momentum after the interaction
  - use symbols for any missing data
  - complete any calculations that can be completed.
- Equate the equations for the ‘Before’ and ‘After’ situations, then:
  - solve algebraically
  - substitute numerical values
  - calculate the answer.

Weblink
Simulation of collision

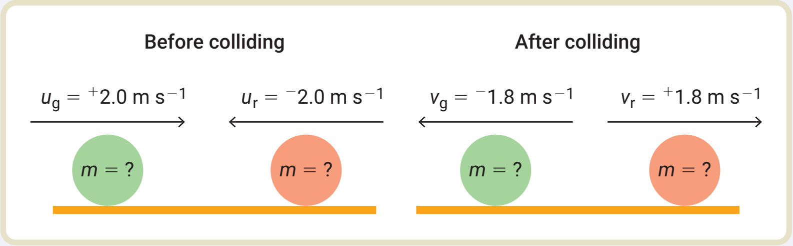
WORKED EXAMPLE 13.6.1

Two billiard balls of equal mass, one green, the other red, move towards each other from opposite directions at 2.0 m s^{-1}. They collide head-on and rebound, both at 1.8 m s^{-1} in directions opposite to their original velocities.

a Sketch the collision in Before and After columns.
b Show how momentum is conserved in this collision.

ANSWERS

a



b 1 **Identify the motions before and after collision.**

In the diagrams, motion to the right has been taken as positive.

$p_{\text{before}} = m \times u_g + m \times u_r$	$p_{\text{after}} = m \times v_g + m \times v_r$
$p_{\text{before}} = m \times {}^{+}2.0\ \text{m s}^{-1} + m \times {}^{-}2.0\ \text{m s}^{-1}$	$p_{\text{after}} = m \times {}^{-}1.8\ \text{m s}^{-1} + m \times {}^{+}1.8\ \text{m s}^{-1}$

2 **Apply the conservation of momentum.**

If conservation of momentum applies, the momentum before the collision should equal the momentum after the collision:

$p_{\text{before}} = p_{\text{after}}$

3 **Substitute known values.**

$m \times {}^{+}2.0\ \text{m s}^{-1} + m \times {}^{-}2.0\ \text{m s}^{-1} = m \times {}^{-}1.8\ \text{m s}^{-1} + m \times {}^{+}1.8\ \text{m s}^{-1}$

${}^{+}2.0\ \text{m s}^{-1} + {}^{-}2.0\ \text{m s}^{-1} = {}^{-}1.8\ \text{m s}^{-1} + {}^{+}1.8\ \text{m s}^{-1}$

4 **Calculate the conservation of momentum.**

$0 = 0$

WORKED EXAMPLE 13.6.2

A 1.5×10^3 kg car is moving to the right at 20 m s^{-1} while a 5.0×10^3 kg truck is moving to the left at 10 m s^{-1}. The car and truck collide and move off as one mass, stuck together.

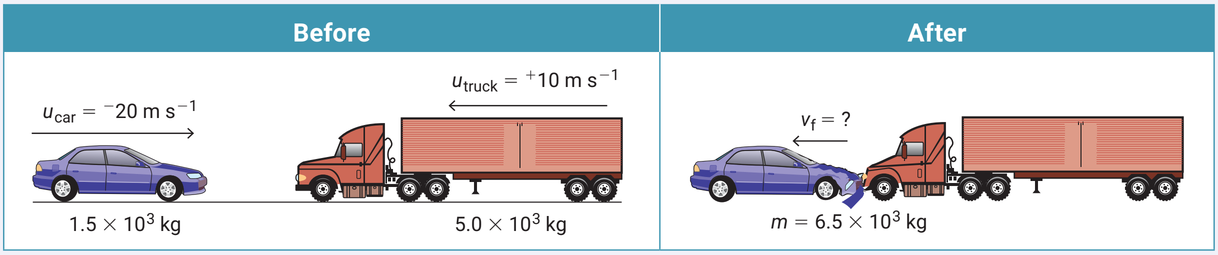
a Draw a diagram showing this situation.

b Calculate the change in the momentum of the truck.

c Find the velocity, v_f, of the wreckage immediately after the collision.

ANSWERS

a



b 1 **State the equation to calculate momentum before.**

$p_{\text{before}} = m \times u_{\text{car}} + m \times u_{\text{truck}}$

2 **Substitute known values.**

$p_{\text{before}} = 1.5 \times 10^3\ \text{kg} \times {}^{-}20\ \text{ms}^{-1} + 5.0 \times 10^3\ \text{kg} \times {}^{+}10\ \text{ms}^{-1}$

3 **Calculate the answer.**

$p_{\text{before}} = 2.0 \times 10^4\ \text{kg m s}^{-1}$

4 State the equation to calculate momentum after.

$p_{\text{after}} = (1.5 + 5.0) \times 10^3 \text{ kg} \times v_f$

5 Substitute the known values.

$p_{\text{after}} = 6.5 \times 10^3 \text{ kg} \times v_f$

c 1 State the equation.

$p_{\text{after}} = p_{\text{before}}$

2 Substitute the known values.

$6.5 \times 10^3 \text{ kg} \times v_f = {}^{+}2.0 \times 10^4 \text{ kg m s}^{-1}$

$$v_f = \frac{{}^{+}2.0 \times 10^4 \text{ kg m s}^{-1}}{6.5 \times 10^3 \text{ kg}}$$

3 Calculate the answer.

$v_f = {}^{+}3.1 \text{ m s}^{-1}$ (3.1 m s^{-1}, left)

Car collisions

Cars are designed to crumple on impact in a collision. This crumpling effect increases the time taken for the crash to be completed. Consequently, the forces applied are, on average, much less than if the cars came to an abrupt stop.

On impact, an unrestrained person inside the car will continue to travel at the original speed, even after the car comes to a stop. This is an example of Newton's first law. Consequently, the person will continue to move towards, and possibly collide with, the windscreen. At 60 km h⁻¹ that has a disastrous effect **(Figure 13.6.1)**. This is why seatbelts must be fitted and worn by all occupants in all Australian vehicles. Seatbelts allow the person to come to a stop with the vehicle.

a Normal driving with seatbelt, driver held in position

b No seatbelt

c Sudden stop – driver (or passenger) keeps moving and hits windscreen

FIGURE 13.6.1 (a) Seatbelts in vehicles enable the occupant to come to a stop with the vehicle. (b) Unrestrained occupants continue towards the windscreen at the speed of the car when the crash begins. (c) A collision when not wearing a seatbelt with the windscreen can be disastrous.

Worksheet
Seatbelts and air bags

WORKED EXAMPLE 13.6.3

A 60 kg person is in a car travelling at 90 km h⁻¹ (25 m s⁻¹) when the car collides with a stationary immovable object and comes to a stop in 0.08 s. The car decelerates at a constant rate because the force applied to the car is constant.

a Find the force applied to the person in the vehicle.

b Explain the advantage of crumple zones by considering what happens to the force on the person when the time over which deceleration occurs is doubled to 0.16 s

ANSWERS

a **1 State the equation.**

J(by car on person) = change of momentum of occupant

F(by car on person) × $t = mv - mu$

2 Substitute the known values.

$$F\text{(by car on person)} = \frac{60\text{ kg} \times 0\text{ m s}^{-1} - 60\text{ kg} \times 25\text{ m s}^{-1}}{0.08\text{ s}}$$

3 Calculate the answer.

F(by car on person) = $^{-}1.9 \times 10^4$ N

b **1 Identify the relationship between force and the change of momentum.**

For a given change of momentum, the equation shows:

$$F\text{(by car on person)} = \frac{mv - mu}{t}$$

$$F\text{(by car on person)} \propto \frac{1}{t}$$

2 Explain the impact of the relationship on the force experienced.

If $t \times 2$, then F(by car on person) $\times \frac{1}{2}$

Crumpling increases the time over which a force on the person is applied, so the force is reduced proportionately.

PRACTICAL ACTIVITY 13.6.1

MOMENTUM DURING A COLLISION

Research question

What happens to the momentum during a collision between two carts?

Aim

To analyse the momentum during a collision

Materials

- 2 dynamics trolley carts
- motion sensor and data logger (or ticker tape timing apparatus)
- spring
- string
- safety glasses

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The spring may flick back or flick an object into a person's eye.	Wear safety glasses when working with springs.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

1. Determine the mass of the two dynamics trolleys carts.
2. Tie the two trolleys together with string and with a compressed spring between them, as shown in **Figure 13.6.2**.
3. Release the trolleys by cutting or burning the string holding them together.

4 Measure and record data to find the velocities of each trolley after the simulated 'collision' (releasing or cutting of the string). Repeat this three times using the same spring and spring compression.

5 Calculate and record the momentum of the system of the two trolleys before and after each collision.

6 Find the change in the momentum for:

   a each trolley
   b the system.

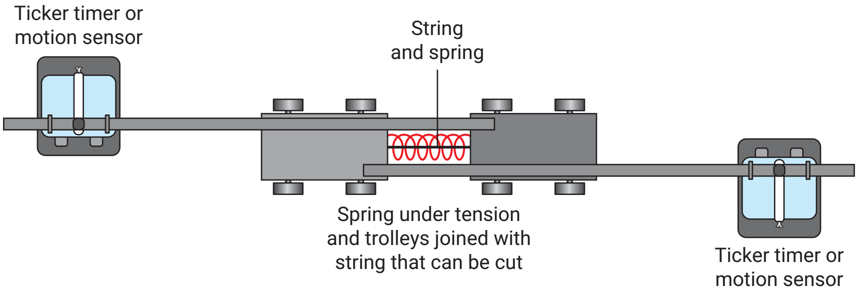


FIGURE 13.6.2 The apparatus for conservation of momentum experiment

Results

1 Record all relevant data collected in order to calculate the speeds of the trolleys.

2 Copy the following table and enter mass, speed and momentum data for each trolley.

	Mass of trolley (kg)	Speed of trolley after string is cut (m s^{-1})	Momentum of trolley (kg m s^{-1})	Change of momentum of trolley (kg m s^{-1})
Trial 1				
Trial 2				
Trial 3				
Average				

3 Estimate and record the uncertainty in the average momentum calculations by considering the effect of uncertainties on speed and mass measurements.

Analysis of results

1 Produce a data table that compares both the change of momentum of the two trolleys and the total momentum of the system before and after the collision. Include uncertainties in the table.

2 Decide whether, given the uncertainties in the experiment, the total momentum is conserved in this collision.

3 It is usual to regard a collision in terms of objects hitting each other. Explain how the situation of the trolleys flying apart can also be considered a collision.

4 Discuss improvements to the experimental design that would increase the precision of the measurements.

Interpretation

5 Within the limits of precision, decide whether the data confirms:

   a conservation of momentum
   b Newton's third law.

Evaluation

6 Identify difficulties in producing accurate and precise measurements in these experiments.

7 Suggest ways to improve the quality of the data.

Impulse

It is important to understand impulse because it helps you to understand concepts like collisions, where the change in momentum due to impulse determines the outcome of the collision, such as changes in velocity or direction of motion. Refer to section 13.5 for more information on impulse.

Impulse may be thought of as the area underneath a force–time graph, which is the integral of force with respect to time.

Interpreting *F*–*t* graphs

A constant force acting over a time interval is shown in **Figure 13.6.3**. The impulse of the force during the time interval from t_1 to t_2 is:

KEY FORMULA

$$\vec{J} = \Delta p = \vec{F}t$$
$$\vec{J} = \vec{F}(t_2 - t_1)$$
$$\vec{J} = \text{area under } F\text{–}t \text{ graph}$$

where:
$\vec{J} = \Delta p$ = impulse (kg m s^{-1})
$\vec{F}$ = force (N)
t = time interval between instantaneous times t_1 and t_2 (s)

$$\vec{J} = \Delta p = \vec{F}t$$
$$\vec{J} = \vec{F}(t_2 - t_1)$$
$$\vec{J} = \text{area under } F\text{–}t \text{ graph}$$

where: $\vec{J} = \Delta p$ = impulse (kg m s^{-1})
$\vec{F}$ = force (N)
t = time interval between instantaneous times t_1 and t_2 (s)

Similar to the way in which areas under *v*–*t* and *a*–*t* graphs in Chapter 12 were analysed, the area under any *F*–*t* graph can be shown to be the impulse of the force **(Figure 13.6.4)**.

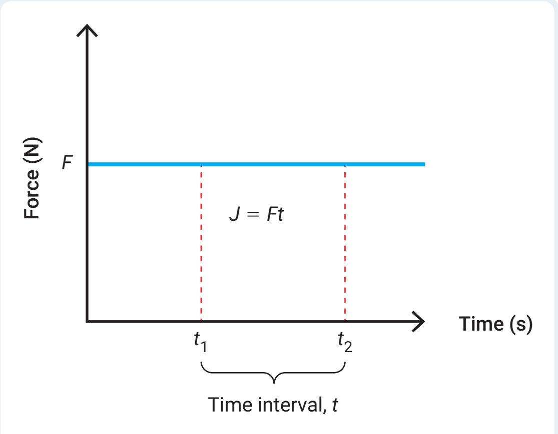


FIGURE 13.6.3 Impulse is the area under the *F*–*t* graph. The area also represents the change of momentum caused by the impulse.

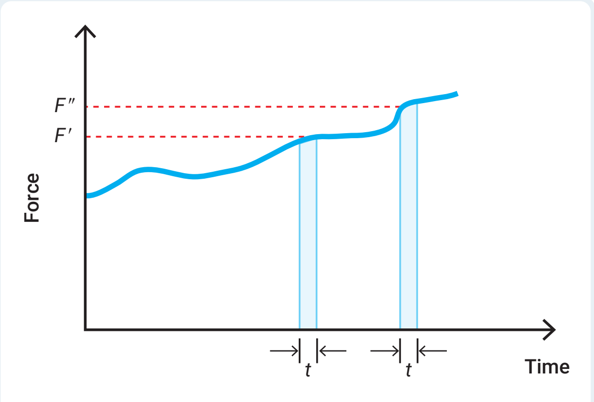


FIGURE 13.6.4 For a force that varies with time, the impulse, hence momentum change, is the area represented by the sum of all the small areas similar to those shown between small time intervals, *t*: $J = \Sigma(Ft)$.

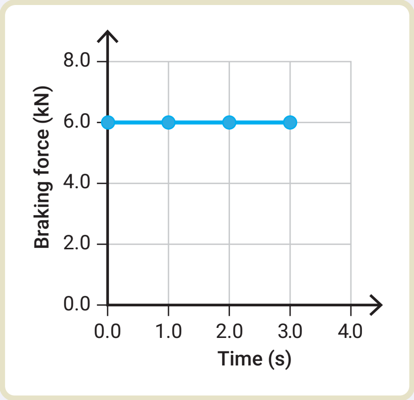
Worksheet
Force versus time

$$\text{Impulse} = \text{change in momentum}$$
$$= \text{area under } F\text{–}t \text{ graph}$$

Since the impulse causes the momentum to change, the area also represents the change in momentum.

WORKED EXAMPLE 13.6.4

The following graph shows the average force applied to a 1000 kg car while braking.



For the first 2.0 s, calculate the:

a impulse of the force applied by the brakes
b change in momentum of the car
c change in speed of the car.

ANSWERS

a **1 State the equation.**

Impulse = area under *F*–*t* graph

2 Substitute the known values.

$J = 6.0 \times 10^3\ \text{N} \times 2.0\ \text{s}$

3 Calculate the answer.

$J = 1.2 \times 10^4\ \text{N s}$

b **1 State the equation.**

Change of momentum = area under *F*–*t* graph

2 Substitute the known values.

$p_{2.0\ \text{s}} - p_{0\ \text{s}} = 1.2 \times 10^4\ \text{kg m s}^{-1}$

$p_{2.0\ \text{s}} - p_{0\ \text{s}} = 1.2 \times 10^4\ \text{kg m s}^{-1}$

$mv_{2.0\ \text{s}} - mv_{0\ \text{s}} = 1.2 \times 10^4\ \text{kg m s}^{-1}$

3 Calculate the answer.

$m(v_{2.0\ \text{s}} - v_{0\ \text{s}}) = 1.2 \times 10^4\ \text{kg m s}^{-1}$

c **1 Substitute values into the equation identified above.**

$1.0 \times 10^3\ \text{kg} \times (v_{2.0\ \text{s}} - v_{0\ \text{s}}) = 1.2 \times 10^4\ \text{kg m s}^{-1}$

$$v_{2.0\ \text{s}} - v_{0\ \text{s}} = \frac{1.2 \times 10^4\ \text{kg m s}^{-1}}{1.0 \times 10^3\ \text{kg}}$$

2 Calculate the answer.

$v_{2.0\ \text{s}} - v_{0\ \text{s}} = 12\ \text{m s}^{-1}$

Determining impulse

Worked examples 13.6.5 and 13.6.6 demonstrate where force–time graphs are used to determine the impulse and subsequently the change in momentum of a mass.

WORKED EXAMPLE 13.6.5

CONSTANT FORCE APPLIED

A 1.0 kg mass at rest experiences a constant force of 10 N to the east for 5 s.

Determine the:

a impulse applied
b change in momentum
c change in velocity of the mass.

ANSWERS

a **1 State the equation.**
Impulse, $J = F \times \Delta t$
2 Substitute the known values.
$J = 10\text{ N} \times 5$
3 Calculate the answer.
$J = 50\text{ N s}$

b **1 State the equation.**
Change in momentum $\Delta p = m \times \Delta v$, and $\Delta p = J$.
2 Substitute known values.
$\Delta p = J = 50\text{ kg m s}^{-1}$

c **1 State the equation.**
The change in momentum $\Delta p = m \times \Delta v$
2 Substitute known values.
$\Delta p = 50\text{ kg m s}^{-1} = 1.0\text{ kg} \times \Delta v$

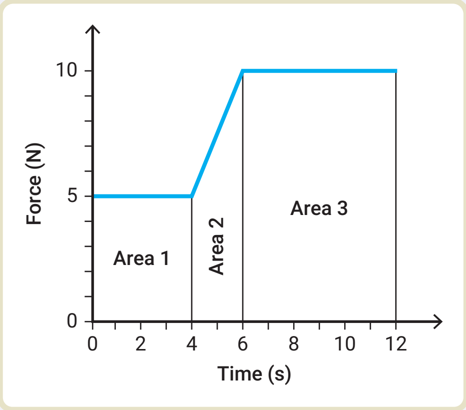
$$\Delta v = \frac{50\text{ kg m s}^{-1}}{1.0\text{ kg}}$$

3 Calculate the answer.
$\Delta v = 50\text{ m s}^{-1}$

WORKED EXAMPLE 13.6.6

VARYING FORCE OVER TIME

A 2.0 kg object experiences a force that varies according to the graph below.



A force of 5 N is applied for 4 s, then increases consistently for 2 s to a force of 10 N applied for a further 6 s. Determine over the entire period of 12 s the:

- **a** total impulse applied
- **b** change in momentum of the 2.0 kg object
- **c** total change in velocity of the mass.

ANSWERS

a **1 State the equation.**

For this, we would need to calculate each impulse individually.

Impulse, $J = F \times \Delta t$

$J_t = J_1 + J_2 + J_3$

2 Substitute known values.

$J_1 = 5\text{ N} \times 4 = 20\text{ N s}$

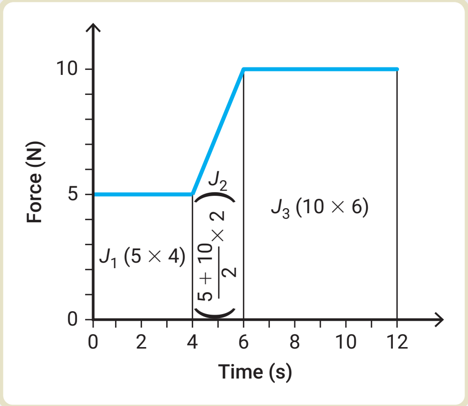
$J_2 = \frac{(5 + 10)\text{ N}}{2} \times 2 = 15\text{ N s}$

$J_3 = 10\text{ N} \times 6\text{ s} = 60\text{ N s}$

$J_t = 20\text{ N s} + 15\text{ N s} + 60\text{ N s}$

3 Calculate the answer.

$J_t = 95\text{ N s}$



b **1 State the equation.**

The change in momentum $\Delta p = m \times \Delta v$, and $\Delta p = J$.

2 Substitute known values.

$\Delta p = J$

$= 95\text{ N s} = 95\text{ kg m s}^{-1}$

This is also the sum of the areas underneath the graph.

c **1 State the equation.**

The change in momentum $\Delta p = m \times \Delta v$

2 Substitute the known values.

$95\text{ kg m s}^{-1} = 2.0\text{ kg} \times \Delta v$

$\Delta v = \frac{95\text{ kg m s}^{-1}}{2.0\text{ kg}}$

3 Calculate the answer.

$\Delta v = 47.5\text{ m s}^{-1}$

The total impulse is the sum of the different areas underneath the graph. In this case, it is the sum of the three separate areas (rectangle, trapezoid and rectangle) and is 95 N s. The change in momentum is equal to 95 kg m s^{-1} and this may be used to determine the change in velocity using $\Delta p = m \times \Delta v$.

LEARNING CHECK 13.6

DESCRIBING

1 **Summarise** the steps needed to solve collision-style questions.

2 In collision problems, **explain** why it is useful to:

   - **a** visualise and sketch the situations described
   - **b** set out the answer in Before and After columns.

3 The law of conservation of momentum relies on Newton's third law. **Explain** why this is the case.

APPLYING

4 In a crash test, a 1-tonne vehicle travelling at 20 m s^{-1} hits a crash barrier and crumples by 1.0 m in 2.0 s before coming to a stop.

  a **Calculate** the change in momentum.
  b **Calculate** the impulse exerted by the barrier.
  c What is the force applied by the car on the barrier?

5 A car travelling at 100 km h^{-1} comes rapidly to a stop. A small toy of mass 100 g strikes the windscreen and comes to a stop in 150 ms.

  a Use Newton's laws to **explain** why the toy hits the windscreen and comes to a stop.
  b **Calculate** the force applied by the windscreen on the toy.

6 A novice ice skater of mass 50 kg travelling at 3.0 m s^{-1} bumps into a stationary instructor of mass 80 kg. The instructor holds on to the novice so that they move off together. **Calculate** the speed with which they move off after collision.

ANALYSING

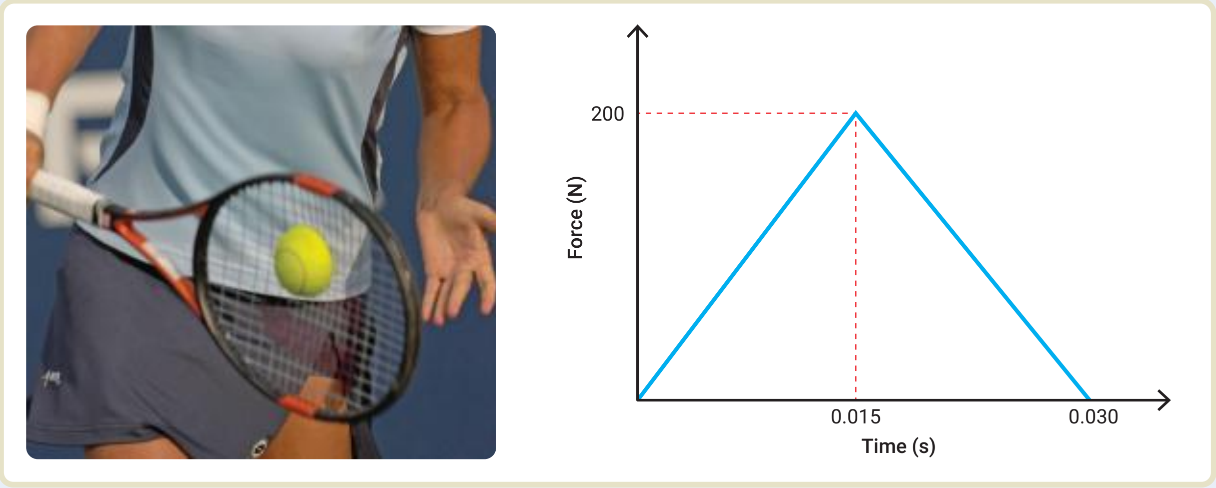
7 Two billiard balls, P and Q, of equal mass move towards each other from opposite directions at 1.5 m s^{-1}. They collide head-on and rebound, both at 0.5 m s^{-1} in directions opposite to their original velocities. Show that the sum of the momentum change of P and Q is zero.

8 Two balls, K and L, move towards each other, collide and rebound. Ball K is travelling in the positive direction initially. Data was recorded in the following table.

Ball	Mass (g)	Initial speed (m s^{-1})	Final speed (m s^{-1})
K	6.0	5.0	10.0
L	12.0	8.0	0.5

Explain how the data could be, or could not possibly be, correct.

9 A 58 g tennis ball travels at 30 m s^{-1} to the right. It is returned along the same direction. The force applied to the ball rises to a maximum before falling to zero as the ball leaves the racquet, as shown in the graph.



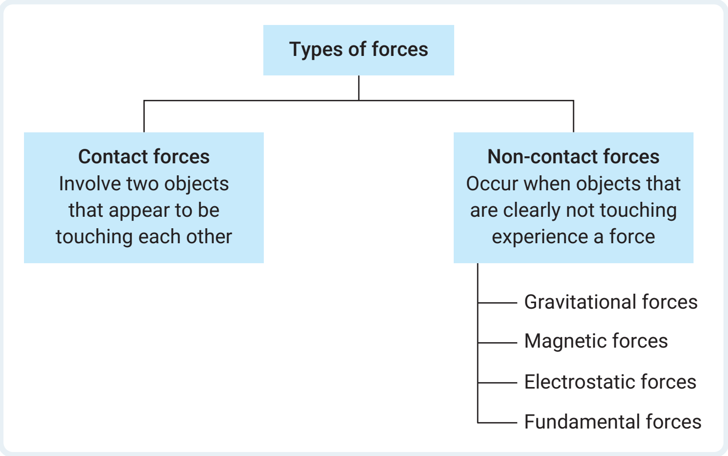
Blake Shaw/Alamy Stock Photo

  a **Calculate** the impulse of the force on the ball.
  b **Calculate** the change of momentum of the ball.
  c **Determine** the speed of the ball as it leaves the racquet.

CHAPTER SUMMARY

Expressing force

- Force can be represented as follows:
  - Object A exerts a force on object B: $\vec{F}(\text{by A on B})$
  - Object B exerts a force on A: $\vec{F}(\text{by B on A})$
- The two main types of forces are contact and non-contact forces.



Weight

- On Earth, the word 'weight' describes the gravitational force that is applied by the mass of Earth on a smaller mass, as shown by:

$$F_w = \vec{F}\,(\text{by mass of Earth on mass of object})$$

where: $F_w = \text{weight force (N)} = m \times g$

Newton's first law

- According to Newton's first law, the force applied on a mass causes the mass to change velocity. This is shown as:

$$\text{If } \sum \vec{F}(\text{on receiver}) = 0$$
$$\text{then } \vec{a} = 0$$

where: $\sum \vec{F}(\text{on receiver}) = \text{sum of forces on receiver}$

- From this, we can deduce that, if the acceleration of a mass is zero, the net force on that mass must be zero:

$$\text{If } \vec{a} = 0$$
$$\text{then } \sum \vec{F}(\text{on receiver}) = 0$$

where: $\sum \vec{F}(\text{on receiver})$ is the vector sum of all forces applied to the receiver object
$\vec{a}$ = the acceleration of the receiver (m s^{-2})

Newton's second law

- According to Newton's second law, the acceleration of a mass is impacted by the net force applied and its inertial mass. This is shown as:

$$\vec{a} = \frac{\sum \vec{F}}{m}$$

where: $\vec{a}$ = acceleration (m s^{-2})
$\sum \vec{F}$ = net force (N)
m = mass (kg)

- Given the acceleration due to gravity is constant, we can calculate the weight force by:

$$F_w = mg$$

where: F_w = weight force (N)
m = mass (kg)
g = acceleration due to gravity (m s^{-2})

Newton's third law

- According to Newton's third law:
  - For every action there is an equal and opposite reaction.

  When two objects A and B interact, the action–reaction pair of forces are:

$$F(\text{by } A \text{ on } B) \text{ and } F(\text{by } B \text{ on } A)$$

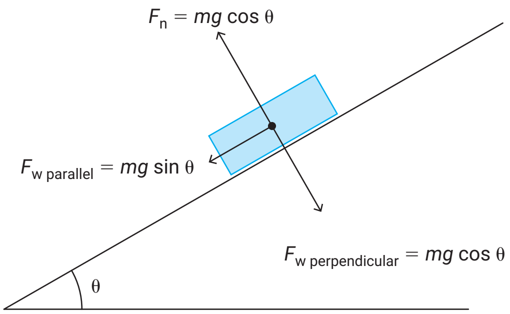
- Four conditions must be satisfied for these to be an action–reaction or Newton's third law pair of forces:
  - Same fundamental type
  - Equal in magnitude
  - Opposite in direction
  - Act on different objects
- Force on an athlete jumping:

$$\sum \vec{F}_{\text{net}}(\text{on athlete}) = \vec{F}_n + -\vec{F}_w > 0$$

where: $\sum \vec{F}_{\text{net}}(\text{on athlete})$ = net force on athlete (N)
F_n = force by surface on athlete perpendicular to the surface (N)
F_w = weight force on athlete (N)

Free-body diagrams

- Free-body diagrams identify and organise forces, simplifying complex physical situations by isolating the object and illustrating forces acting on it.



Impulse

- Impulse is the action of a force exerted over a time interval. It can be expressed as:

$$\vec{J} = \vec{F}t$$

where: $\vec{J}$ = impulse of the force, in newton seconds (N s)
$\vec{F}$ = force applied (N)
t = time interval (s)

Momentum

- Momentum is a quantity of motion, calculated as:

$$\vec{p} = m\vec{v}$$

where: $\vec{p}$ = momentum, in kilogram metre per second (kg m s^{-1})
m = mass (kg)
$\vec{v}$ = velocity (m s^{-1})

- According to the law of conservation of momentum, the total momentum in an isolated system is always the same. This can be shown as:

$$\vec{p}_2 - \vec{p}_1 = m\vec{v} - m\vec{u}$$

where: $\vec{p}_1$ = initial momentum (kg m s^{-1})
$\vec{p}_2$ = final momentum (kg m s^{-1})
m = mass (kg)
$\vec{u}$ = initial velocity (m s^{-1})
$\vec{v}$ = final velocity (m s^{-1})

$$\sum \vec{p}_{\text{before}} = \sum \vec{p}_{\text{after}}$$
$$\sum (m\vec{v})_{\text{before}} = \sum (m\vec{v})_{\text{after}}$$

where: $\sum \vec{p}_{\text{before}} = \sum (m\vec{v})_{\text{before}}$ = sum of momentum of system before objects interact
$\sum \vec{p}_{\text{after}} = \sum (m\vec{v})_{\text{after}}$ = sum of momentum of system after objects interact
m = mass (kg)
$\vec{v}$ = velocity of objects (m s^{-1})

- In other words, total momentum, p_t does not change:

$$\vec{p}_{\text{t before}} - \vec{p}_{\text{t after}} = 0$$

where: $\vec{p}_{\text{t before}}$ = total momentum before interaction (kg m s^{-1})
$\vec{p}_{\text{t after}}$ = total momentum after interaction (kg m s^{-1})

F–t graphs, momentum and impulse

- Impulse causes momentum to change. In *F–t* graphs, this means that the area under the graph represents the change in momentum:

Impulse = change in momentum
= area under *F–t* graph

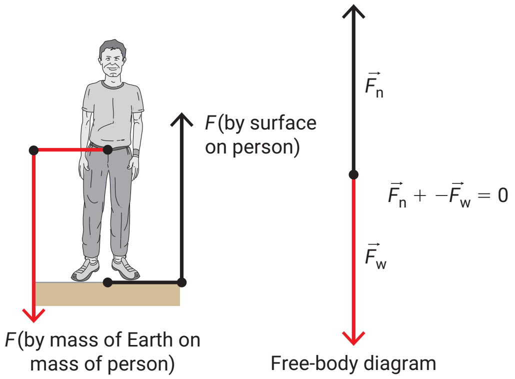
- With a constant force, the impulse of the force during the time interval is:

$$\vec{J} = \Delta p = \vec{F}t$$
$$\vec{J} = \vec{F}(t_2 - t_1)$$
$$\vec{J} = \text{area under } F\text{–}t \text{ graph}$$

where: $\vec{J} = \Delta p$ = impulse (kg m s^{-1})
$\vec{F}$ = force (N)
t = time interval between instantaneous times t_1 and t_2 (s)

Force on an object

- The forces applied to a person standing on a surface are the normal force and the weight force.
- The force perpendicular to the surface is the normal force.



CHAPTER EXAM

MULTIPLE CHOICE

1. A net force applied to a moving object can cause:

A speed to increase but not decrease.
B velocity to increase but not decrease.
C speed to remain the same but direction to change.
D velocity to remain the same but direction to change.

2. What is the change in momentum of a 50 kg ice skater who slows from 8.0 m s^{-1} to 3.0 m s^{-1}?

A $^{-}$400 kg m s^{-1}
B $^{-}$250 kg m s^{-1}
C $^{+}$250 kg m s^{-1}
D $^{+}$400 kg m s^{-1}

3. For a person standing on a platform, the normal and the weight force:

A apply to different objects.
B are similar types of forces.
C add up to a net force of zero.
D are an action–reaction pair of forces.

4. A person throws a ball directly downwards. While the ball is in flight, what is the action–reaction pair of forces?

A *F*(by hand on ball); weight of ball
B *F*(by hand on ball); *F*(by ball on hand)
C Weight; *F*(by mass of Earth on ball)
D Weight; *F*(by ball on mass of Earth)

5. The force that always acts at right angles to a surface is called the:

A weight.
B friction.
C normal force.
D gravitational force.

6. A 70 kg rower applies a force of 80 N on the water in order to move the boat along a river at 4.0 m s^{-1}. Which of the following is correct?

A The force on the rower and friction are in the same direction.
B The impulse by the rower and friction are in the same direction.
C The impulse by the rower and friction are in opposite directions.
D The force on the rower and the momentum of the rower are in opposite directions.

7. A car towing a trailer is accelerating on a level road. The car exerts a force on the trailer whose magnitude is:

A the same as that of the force the trailer exerts on the car.
B the same as that of the force the trailer exerts on the road.
C the same as that of the force the road exerts on the trailer.
D greater than that of the force the trailer exerts on the car.

8. A force of 1.0 N acts on a 10 kg object that can move freely. What is the object's acceleration?

A 0.102 m s^{-2}
B 0.5 m s^{-2}
C 1.0 m s^{-2}
D 9.8 m s^{-2}

9. A 5.0 kg object, initially at rest, is acted on by a net force of 3.0 N for 3.0 s. During that time how far does the object move?

- **A** 0.3 m
- **B** 0.9 m
- **C** 1.8 m
- **D** 2.7 m

10. A 300 g ball at rest is struck with a bat with a force of 150 N. If the bat was in contact with the ball for 0.020 s, what is the ball's velocity?

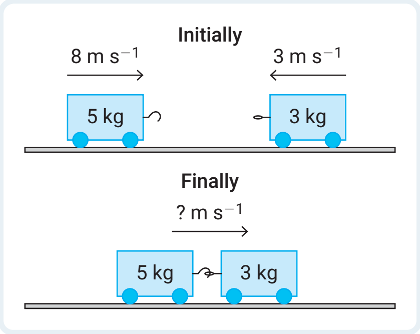
- **A** 0.01 m s^{-1}
- **B** 0.1 m s^{-1}
- **C** 2.5 m s^{-1}
- **D** 10 m s^{-1}

SHORT RESPONSE

11. A baseball travelling horizontally at 32 m s^{-1} is in contact with a baseball bat of mass 0.15 kg for 0.75 ms. It returns along the same path at 38 m s^{-1}.

- **a** Find the change in the momentum of the baseball.
- **b** **Calculate** the force applied by the ball on the baseball bat.

12. Two carts are moving towards each other as shown in the diagram. After the collision, they stick together and move off together.



Calculate the final velocity of the carts.

13. A shopping trolley of groceries in a supermarket car park has a total mass of 67 kg and is rolling east at a constant velocity. It then strikes another shopping trolley, which is at rest and contains groceries with an overall mass of 80 kg. The two trolleys remain connected after the collision. Using principles of physics and mathematics, **justify** why both trolleys must move in the same direction after the collision.

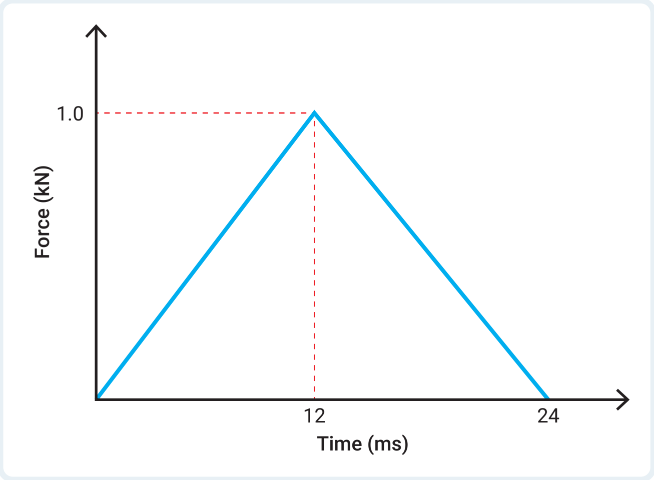
CROSS-CHAPTER QUESTION

14. A 100 g rubber ball is dropped on the ground from a height of 5 m. If the ball rises to 60% of its original height on rebounding, **calculate** the impulse imparted to the ball when it hit the ground.

DATA ANALYSIS

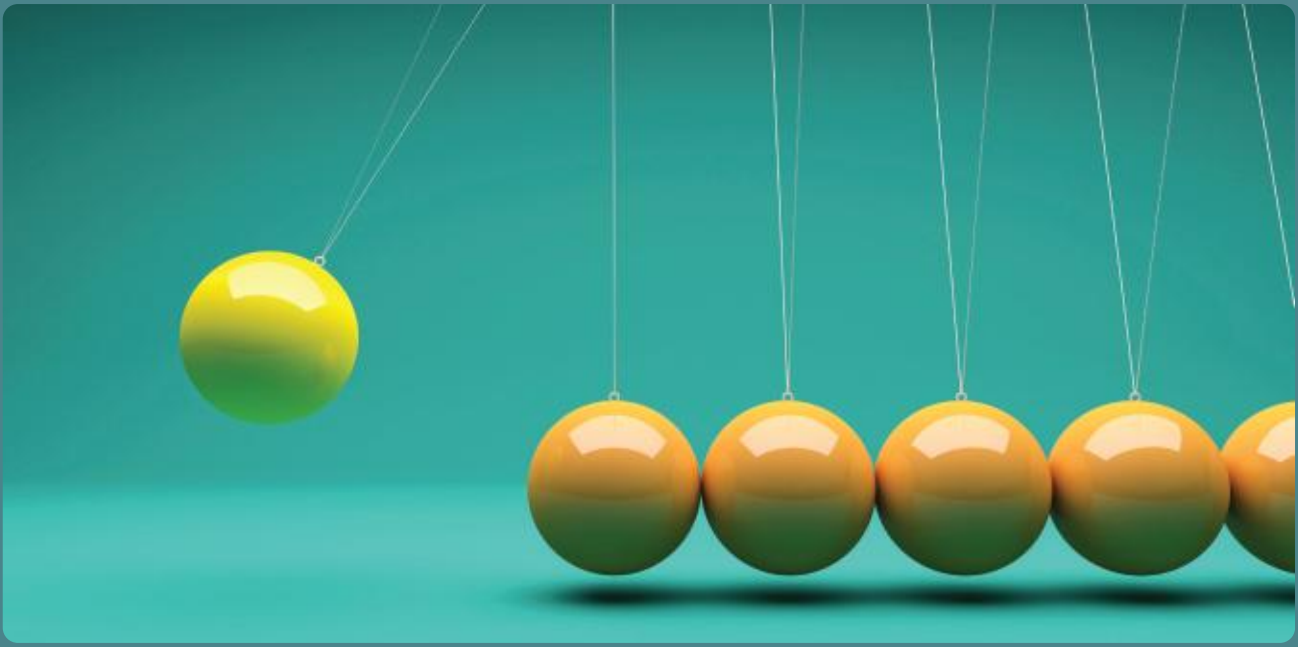
15. Analyse data

A cricket ball of mass 0.15 kg travels at 35 m s^{-1} horizontally towards the bat. It is struck directly back. The horizontal force applied by the cricket bat on the ball is shown in the graph. Find the return speed of the ball. Show all working.



CHAPTER 14

Newton's laws of motion



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SYLLABUS DOT POINTS

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 $\sum \frac{1}{2}mv^2_{\text{before}} = \sum \frac{1}{2}mv^2_{\text{after}}$.

SCIENCE INQUIRY

- Investigate a linear elastic collision between two objects.

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Introduction

In this chapter, we look at the explanation of motion in terms of work and energy. In order to complete a full analysis of motion, we will use the concepts and related equations of both impulse–momentum and work–energy.

Practicals

- Force applied in a model car crash
- Potential energy in springs
- Newton’s cradle

Worksheets

- Work–energy for a spring
- Work and energy

Nelson MindTap

To access resources above, visit
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ASSUMED KNOWLEDGE

- ✓ The SI unit for energy is the joule (J).
- ✓ Kinetic energy is the energy of movement.
- ✓ Potential energy is the energy ready to do work in a system.
- ✓ The law of conservation of energy states that energy cannot be created or destroyed, only transferred or transformed.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ recall the concepts of energy, work and the law of conservation of energy
- ✓ describe and explain energy changes and energy transformations
- ✓ describe and explain potential energy and kinetic energy
- ✓ calculate the kinetic energy and/or potential energy of an object
- ✓ perform experiments to investigate energy transformations
- ✓ categorise potential energy as gravitational or elastic
- ✓ solve problems involving force, work and acceleration in one and two dimensions
- ✓ describe and explain Hooke's law
- ✓ analyse and interpret force–distance or force–displacement graphs to quantify work and energy transformations
- ✓ solve problems involving transformations occurring between gravitational potential energy and kinetic energy
- ✓ compare elastic and inelastic collisions
- ✓ perform calculations to categorise collisions as elastic or inelastic
- ✓ interpret energy–time graphs
- ✓ explore how physical theory pertaining to forces, momentum, energy and collisions has contributed to the safety design features of vehicles as well as ergonomics/biomechanics.

14.1 Work and energy

energy a fundamental quantity that can be transformed and transferred; it is defined by source or by the way it is measured

Displacement and time are the two fundamental measurements of motion. A force acting for a time interval (impulse) causes momentum change. Similarly, a force acting over a distance interval (work) causes energy change.

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FIGURE 14.1.1 Food is stored chemical energy that is released for use by metabolic processes.

Energy

Energy is one of the fundamental ideas in physics. According to the Big Bang theory, the universe started as energy. All the energy in the universe is still in the universe. No more energy can be made – it cannot be made to disappear either. Nor can any energy appear from some other universe. The universe is all there is. And the energy in the universe is all the energy there is.

Energy is everywhere, yet it has no clear description. Thermal energy is the kinetic energy associated with particle motion. Atomic and nuclear energy relate to the storage and release of energy from atoms and atomic nuclei. Light energy comes from accelerations of charged particles or atomic energy level transitions. Sound energy is produced by vibrations and measured with a sound meter. Chemical energy is stored between atoms and is released; for example, in foods by metabolic processes. Springs store and release elastic potential energy. Mass can be converted to and from energy, as Einstein showed in his famous equation: $\Delta E = \Delta mc^2$.

Conservation of energy

The universe is an example of an **isolated system**. In fact, it is the only truly isolated system; inside the universe no energy has been created and none has been destroyed. However, energy has been transferred and transformed so that it appears in many different locations and forms. Other systems can be made to approximate an isolated system.

Since energy cannot be transferred or transformed, **energy change** is what can be measured. Measurement of change, or difference, in energy from some initial state to some final state is represented by the symbol ΔE. ΔE is the difference between two energies or the change in the amount of energy. Note that the symbol ΔE cannot be separated into Δ and E. It is a single symbol, not two symbols multiplied together. The Greek letter delta, Δ, represents 'difference' or 'change in'.

For a system in which energy changes from an initial value E_i to a final value E_f, the difference in energy or change in energy is:

$$\Delta E = E_f - E_i$$

Weblinks
Types of energy
Simulation: energy forms and changes

isolated system a system that no matter or energy transfers into or out of and in which no energy is created or destroyed

energy change (ΔE) energy transfer or transformation; quantity of energy that can be measured

Law of conservation of energy

In an isolated system, the energy in the system remains constant and no energy comes in or goes out. Nor is energy created or destroyed in an isolated system. Thus, in an isolated system, the total energy, E_t, remains constant and there is no change of total energy, ΔE_t, in the system.

In an isolated system:

- the total energy, E_t, is constant: E_t = constant
- there is no change of total energy: $\Delta E_t = 0$.

KEY FORMULA

$$W = F_{||}s$$

where:
W = work done (J)
$F_{||}$ = force parallel to the distance interval (N)
s = distance interval parallel to the force (m)

KEY FORMULA

$$W = \Delta E$$

where:
W = work done on the object (J)
ΔE = change in the energy of the object (J)

Work–energy change

When a force acts on an object through a distance, work is done on the object. **Work (W)**, is defined as force multiplied by the distance moved, where the force, $F_{||}$, and the distance interval, s, are in the same direction; that is, parallel to each other **(Figure 14.1.2)**:

$$W = F_{||}s$$

where:
W = work done (J)
$F_{||}$ = force parallel to the distance interval (N)
s = distance interval parallel to the force (m)

Work is measured in newton metres, N m, = kg m^2 s^{-2} = joule (J).

The force and the distance interval must be in the same direction.

When work is done, energy, ΔE, is transferred. This is the work–energy equation:

$$W = \Delta E$$

where:
W = work done on the object (J)
ΔE = change in the energy of the object (J)

Energy may be transferred as kinetic energy or potential energy.

work (W) the energy transferred due to the action of a force over a distance

FORMULA AND DATA BOOK

Types of energy change

kinetic energy (E_k) the energy of an object resulting from its motion

potential energy (E_p) the energy available to do work

When work is done, energy changes in one of two ways: the **kinetic energy (E_k)** of a system can be increased or decreased, or energy may be stored in a system as **potential energy (E_p)**. For example, energy is stored in a spring by applying a force to one or both ends of the spring to compress or stretch it. When the spring is released, the energy can be returned. For example, this will be seen as kinetic energy of a projectile.

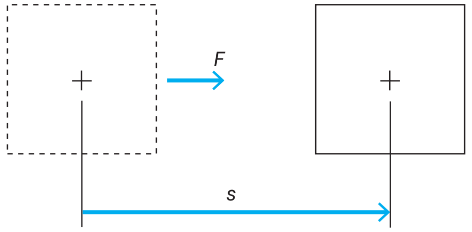


FIGURE 14.1.2 Work is done on an object by a force that is parallel to the direction of the distance interval, *s*.

Kinetic energy

The work–energy equation can be applied to kinematic equations to produce a quantitative definition of kinetic energy. The kinematic equations for constantly accelerated motion can be used to derive this definition:

Weblink
Kinetic and potential energy

FORMULA AND DATA BOOK

$$W = F_{\parallel}s \qquad \text{(equation 1: work – force – distance equation)}$$

$$F_{\parallel} = ma \qquad \text{(equation 2: Newton's second law)}$$

$$W = ma \times s \qquad \text{(equation 1 in equation 2)}$$

$$as = \frac{W}{m}$$

$$2as = 2\frac{W}{m} \qquad \text{(equation 3)}$$

$$v^2 = u^2 + 2as \qquad \text{(equation 4: } suvat\text{)}$$

$$2as = v^2 - u^2 \qquad \text{(equation 5)}$$

$$2\frac{W}{m} = v^2 - u^2 \qquad \text{(equation 3 in equation 5)}$$

$$\frac{W}{m} = \frac{1}{2}v^2 - \frac{1}{2}u^2$$

$$W = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

This equation shows that the work has changed the value of the quantity $\frac{1}{2}$ × mass × speed². This generalised quantity is called kinetic energy, E_k.

$$E_k = \frac{1}{2}mv^2$$

where:
E_k = kinetic energy (J)
m = mass (kg)
v = speed (m s^{-1})

KEY FORMULA

$$E_k = \frac{1}{2}mv^2$$

where:
E_k = kinetic energy (J)
m = mass (kg)
v = speed (m s^{-1})

PRACTICAL ACTIVITY 14.1.1

FORCE APPLIED IN A MODEL CAR CRASH

Introduction

When a vehicle crashes into a solid wall, it loses all kinetic energy. The vehicle also crumples. The change of kinetic energy and the crumple distance can be used to find the force applied to the car by the wall. In this experiment, the speed of a trolley is used to find its kinetic energy. The work done on the trolley by the wall, *W*, causes the kinetic energy to be reduced to zero. *W* is related to the force applied by the wall, *F*(by wall on trolley), and the crumple distance, *s*:

$$W = Fs = \Delta E_k$$

$$Fs = \frac{1}{2}mv^2$$

$$F = \frac{mv^2}{2s}$$

Research question

How does the magnitude of kinetic energy in a collision affect the degree of compression of a vehicle's crumple zone?

Aims

- To simulate a car collision
- To compare the forces applied when the crash occurs at different energies

Materials

- data logger or motion-sensing app
- dynamics trolley or toy car
- mass scales
- plasticine or aluminium foil
- ruler
- long plank, minimum 1 m
- solid wall or block

Procedure

Trial run

1 Set up the plank near the wall as shown in Figure 14.1.3.

2 Set up the data logger to measure the speed of the trolley as close as possible to the wall.

3 Attach plasticine to the front of the trolley.

4 Release the trolley from the highest point. Measure the height, *h*.

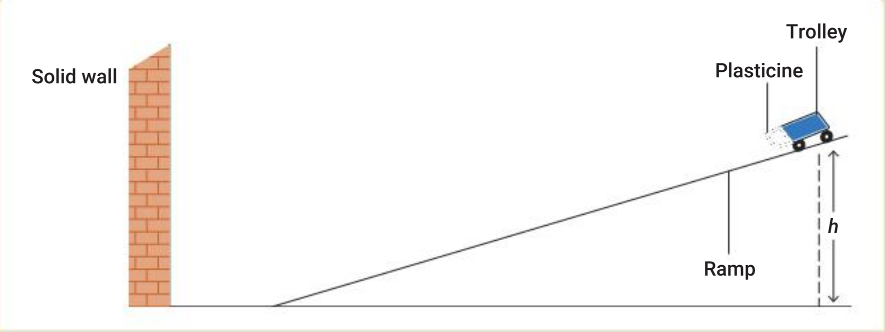


FIGURE 14.1.3 The experimental set-up for a simulated collision

5 Observe the crash.
   a If the trolley bounces back, add more plasticine or aluminium foil and repeat until the trolley does not rebound.
   b If it is difficult to measure the crumple distance, gently heat the plasticine or use less foil so it can deform more readily.

6 Roll the trolley from at least five different heights with two runs for each height. Release the trolley at the same height for each run to ensure that the speed can be measured consistently.

Results

1 Weigh the mass of the trolley and record it.

2 Measure the amount the plasticine or foil crumples in millimetres.

3 Record the data in a data table like the one below.

Run number	Release height, h ± uncertainty (cm)	Speed at wall, v ± uncertainty (cm s^{-1})	Crumple distance, s ± uncertainty (mm)

Analysis of results

1 Plot the graph of speed, v, versus release height, h.
Use the graph to determine any relationship between v and h.

2 Construct a data table showing the speed (in m s^{-1}) and kinetic energy, E_k (in J) at the wall, as well as the crumple distance (in m). Include uncertainties in each value.

3 Plot the graph of crumple distance, s, versus the change in kinetic energy, ΔE_k.

4 Calculate the force applied for each height using $Fs = \frac{1}{2} mv^2$ values.

Interpretation

5 Explain whether the height of release, h, can be used as a measure of the kinetic energy, E_k, at the wall.

6 Discuss what would happen to the force in this experiment if the speed was kept constant but the plasticine or foil was made firmer or softer.

Evaluation

7 Provide a justified answer to the research question.

8 Describe limitations to the validity and reliability of the raw and derived data.

9 Discuss how this practical activity could be used to understand and inform car design.

10 Indicate what might be done better to show the relationship between the kinetic energy of the trolley and the crumple distance.

Potential energy

Energy may also be added to or removed from a system without the system gaining or losing kinetic energy. In these cases, the energy is stored in the system as potential energy. Potential energy is not associated with a particular object but with the system in which the object exists. For example, energy from an external source can be stored as potential energy in a spring by stretching or compressing the spring. The spring system can return this **elastic potential energy** as kinetic energy when released.

Similarly, when energy is used to lift a mass up against the gravitational force, the energy is stored in the system of the two masses (Earth and object). When the object is released, this **gravitational potential energy** stored in the system can be returned as kinetic energy. This kinetic energy is usually observed as the kinetic energy of a mass. But it is actually the kinetic energy of the system that has increased at the expense of the potential energy that has decreased. The total of potential energy and kinetic energy remains constant.

elastic potential energy the energy stored in a spring or elastic system

gravitational potential energy the energy stored in a system consisting of masses subject to gravitational force

LEARNING CHECK 14.1

DESCRIBING

1 **Describe** and **explain** each of the following terms.

a	energy	**b**	energy change
c	work	**d**	kinetic energy
e	potential energy	**f**	elastic potential energy
g	gravitational potential energy.		

2 **Recall** the law of conservation of energy.

3 'The law of conservation of energy only applies to isolated systems.' **Explain** this statement.

4 **a** Write the work–energy equation in words and symbols.

  b **Explain** each term in the work–energy equation.

APPLYING

5 **Explain** why it is only possible to measure changes of energy.

6 Use examples from two different forms of energy to **explain** how potential energy is stored.

7 **Calculate** the kinetic energy of a 3.0 kg mass that is travelling at the following speeds.

  a 8.0 m s^{-1}

  b 60 km h^{-1}

8 A force of 20 N is applied over a distance of 5.0 m to an 8.0 kg object travelling at 10 m s^{-1}. The force and the distance are in the same direction.

  a **Calculate** the change in kinetic energy of the object.

  b **Determine** the final speed of the object.

ANALYSING

9 A force is continuously applied to a moving object at right angles to the motion of the object. This causes the object to change direction. **Describe** the change in motion of the object.

10 Draw a mindmap to connect the ideas and formulas about work and energy.

14.2 Solving problems involving work done by forces

Work may be done by forces that are constant, are uniformly increasing or decreasing or vary continuously in an irregular way. Force–distance graphs can be used to help determine the work done. In these graphs, the force that is doing the work is parallel to the distance.

Work done by a constant force

Figure 14.2.1 shows a constant force, F(by A on B), acting to move object B over a distance interval, s. The work done on B is:

$$W(\text{by A on B}) = F(\text{by A on B}) \times s = \text{area under } F\text{–}s \text{ graph}$$

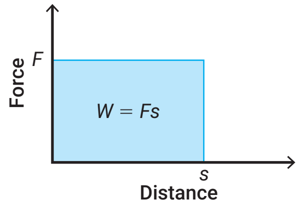


FIGURE 14.2.1 Work done is the area under the *F*–*s* graph.

Work done by the component of a force parallel to the direction of motion

Some forces are applied at an angle to the direction of motion. For example, a suitcase is pulled horizontally while the person is applying a force that is somewhat directed upwards. A lawnmower or vacuum cleaner is pushed in a downwards direction while moving horizontally. In these cases, it is only the component of the force parallel to the direction of motion that does work.

If the force is directed at an angle, θ, to the distance travelled, then the component of the force, $F_{||}$, is:

$$F_{||} = F\cos\theta$$

Thus, the work done is:

$$W = F_{||}s = Fs\cos\theta$$

where:
W = work done on the object (J)
F = force applied on the object (N)
$F_{||}$ = force applied on the object parallel to the direction of the distance travelled (N)
s = distance travelled by the object (m)
θ = angle between the force and the direction of the distance travelled (degrees)

This is shown in **Figure 14.2.2**

KEY FORMULA

$$W = F_{||}s = Fs\cos\theta$$

where:
W = work done on the object (J)
F = force applied on the object (N)
$F_{||}$ = force applied on the object parallel to the direction of the distance travelled (N)
s = distance travelled by the object (m)
θ = angle between the force and the direction of the distance travelled (degrees)

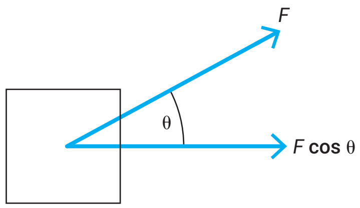


FIGURE 14.2.2 Only the component of a force parallel to the distance travelled does work: $F_{||} = F\cos\theta$.

Work done by a stepwise force

If the force by A on B changes from one constant force to another constant force, then the total work done is the sum of the areas under each section of an *F*–*s* graph, as shown in **Figure 14.2.3**.

$$\begin{aligned} W(\text{on B}) &= \text{area under } F\text{–}s \text{ graph} \\ &= \sum\left[F(\text{by A on B}) \times s\right] \\ &= \left[F_1(\text{by A on B}) \times s_1\right] + \left[F_2(\text{by B on A}) \times (s_2 - s_1)\right] \end{aligned}$$

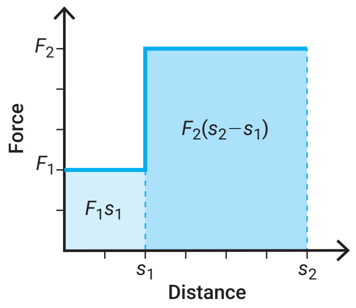


FIGURE 14.2.3 Work done by forces on B is the sum of all the areas under the F–s graph.

Any force that varies with distance

The area under any F–s graph is the work done, and hence the energy transferred, by the force. The work, W' done by a force, F', over a small distance interval, s', is $W' = F' s'$. Similarly, the work, W'', done in distance interval s'' by force F'' is $F''s''$.

Therefore, the total work done, is the sum of all the W' **(Figure 14.2.4)**. Hence:

$$W = \sum(F's')$$

Weblink
Hooke's law

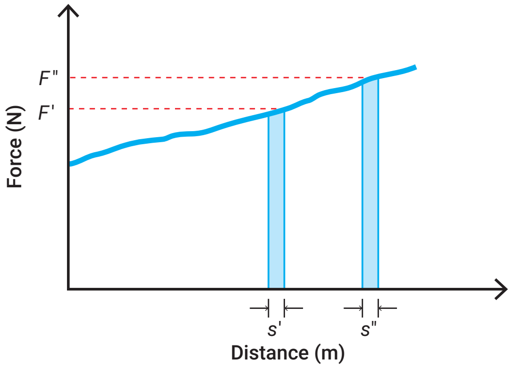


FIGURE 14.2.4 Work done is the sum of all the small areas similar to $F's'$ and $F"s"$. The area is also the energy transfer to or from a system.

Work done by a constantly increasing force

Spring-like forces are a very significant group of forces. They apply for everyday springs as well as large-scale building materials. The force applied by a spring is a function of the spring system. By Newton's third law, the force applied *by* a spring is equal to the force applied *to* a spring. When a force is applied to a spring to cause it to change length, the spring system applies the same magnitude of force but in the opposite direction. Therefore, the change in length is always in the opposite direction to the force applied by the spring. The spring applies a restoring force. For a significant group of elastic materials, the restoring force applied by the spring is proportional to the change of length of the spring, This is known as Hooke's law:

$$F(\text{by spring}) \propto -x$$

$$F(\text{by spring}) = k(-x)$$

$F(\text{by spring})$ = force applied to or by a spring (N)
x = change of length of spring (m)
k = constant of proportionality (stiffness) (N m^{-1})

KEY FORMULA

Hooke's law

$$F(\text{by spring}) = k(-x)$$

where:
$F(\text{by spring})$ = force applied to or by a spring (N)
x = change of length of spring (m)
k = constant of proportionality (stiffness) (N m^{-1})

Hooke's law refers to a property of the spring. That is, it relates to the force applied by the spring, not the force applied on the spring.

The constant of proportionality, k, has physical meaning. It is the stiffness (resistance to compression) of the spring. The larger the value of k, the stiffer the spring.

Potential energy stored in spring systems

In most cases, the analysis of springs involves the potential energy stored in the spring. The energy stored in the spring comes from the work done on the spring by an external force. By Newton's third law, the force applied by the spring to store the energy is equal in magnitude to the external force applied on the spring.

For springs that obey Hooke's law, it is usual to draw F–x graphs in the first quadrant, where the force axis actually represents the magnitude of the force applied by the spring: F(by spring). The force applied on the spring, F(on spring), is responsible for the extension of the spring, x. This means that the extension is dependent on the force (independent variable) applied on the spring and the graph should be an x–F(on spring) graph. However, it is the extension that causes the spring to apply a force, so the graph should be F(by spring)–x. The F(by spring)–x graph looks like **Figure 14.2.5** because F(by spring) and the extension, x, that causes it are in opposite directions.

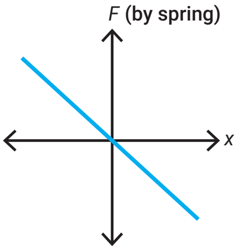


FIGURE 14.2.5 Hooke's law: the force by the spring and the extension are oppositely directed.

The usual presentation of Hooke's law is shown in **Figure 14.2.6**. The graph is simplified by graphing the magnitude of the force applied by the spring against the extension that caused it: F(by spring)–x.

The potential energy taken up by the spring system is the area under the F–x graph:

$$W = \text{area} = \frac{1}{2}Fx$$

$$= \frac{1}{2}(kx) \times x$$

$$= \frac{1}{2}kx^2$$

where:

W = potential energy stored in a spring (J)
k = spring constant or stiffness (N m^{-1})
x = extension (or compression) of the spring (m)

Worksheet
Work–energy for a spring

KEY FORMULA

$$W = \frac{1}{2}kx^2$$

where:
W = potential energy stored in a spring (J)
k = spring constant or stiffness (N m^{-1})
x = extension (or compression) of the spring (m)

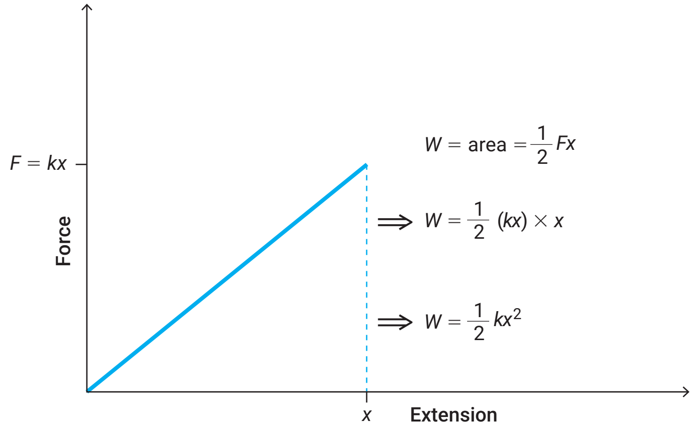


FIGURE 14.2.6 The magnitude of the force applied by the spring is a function of the magnitude of the extension that causes this force.

PRACTICAL ACTIVITY 14.2.1

POTENTIAL ENERGY IN SPRINGS

Introduction

Extension and compression can be used to measure the stiffness of, and the potential energy stored in, a spring. When a spring is extended, it is said to be ‘in tension’. When it is compressed, it is ‘in compression’. Both forces are ‘restorative forces’ because they have the direction that would restore the spring to its original length.

Research question

Does the experimentally determined value of the spring constant, k, correlate with the qualitative stiffness of a spring?

Aim

To find, for a variety of springs, the:

- spring constant, k, or stiffness
- potential energy in the spring system

Materials

- 3 open springs that can be compressed and extended
- force measurer: a data logger or mechanical spring balance
- ruler
- clamp

RISK ASSESSMENT

What are the risks in doing this experiment?	How can you manage these risks to stay safe?
The spring may flick back or flick an object into a person’s eye.	Wear safety glasses when working with springs.

Copy and complete the risk assessment table in your write-up. Add any more risks you can think of, and ways to manage them. Ask your teacher to check your table before you proceed.

Procedure

1 Measure extension as a function of force applied for each spring. The maximum extension should be the same for each spring.

2 For each spring in tension, construct a data table that includes the following data.

Spring	Extension of spring, *x* (m)	Uncertainty in extension (m)	Force applied by spring, *F*(by spring) (n)	Uncertainty in *F*(by spring) (N)

3 Measure five values for extension and force applied.

4 Repeat steps 1–3 for the springs in compression.

Analysis of results

1 For each spring under both tension and compression:

- **a** plot a graph of *F*(by spring) versus *x*, including uncertainty bars (Do not assume the line includes the origin.)
- **b** find the value of the stiffness, *k*, for each spring (gradient)
- **c** find the amount of potential energy stored in the spring, E_p.

2 Report this derived data in a properly constructed data table.

Interpretation

3 For each spring, compare the spring constant, or stiffness under extension and under compression.

4 Compare the springs in both tension and compression with respect to:

- **a** stiffness or spring constant
- **b** maximum potential energy measured.

5 Explain why the comparisons of stiffness and stored energy rely on the springs being the same length and the same diameter.

6 Explain why the graph line may not include (0, 0).

Evaluation

7 Provide a justified answer to the research question.

8 Describe limitations to the validity and reliability of the raw and derived data.

9 Indicate what might be done better to make fair comparisons between springs.

LEARNING CHECK 14.2

DESCRIBING

1 **Explain** what work is.

2 **Describe** the relationship between work and energy.

3 Given a force–distance graph, **recall** how to calculate the work done.

4 Use a diagram to help **define** the work done by a force that is acting at an angle to the direction of motion. On the diagram, show the definition of each symbol used.

5 Consider springs that obey Hooke's law.

- **a** Write Hooke's law in symbols.
- **b** **Explain** what each symbol represents.
- **c** On an appropriate graph show:
  - **i** stiffness or spring constant
  - **ii** energy stored in the spring.

APPLYING

6 In a test crash, a force of 1.5×10^5 N is applied over 5.0 cm to a dummy head. **Determine** the work done on the dummy head.

7 A force of 30 N is applied at an angle of 30° to the horizontal on a box in order to drag the box 20 m across a horizontal surface. **Calculate** the work done by the force on the box.

8 A winch applies a 400 N force to pull a 250 kg boat across a 15 m long horizontal surface. For the last 6.0 m, a second winch is attached to assist. It applies an additional force of 200 N. **Calculate** the combined work done by the winches in order to pull the boat across the surface.

ANALYSING

9 A 30 cm length of spring obeys Hooke's law. It has a stiffness of 50 N m^{-1}. It can be extended to a maximum length of 50 cm.

- **a** Draw a graph to show how the spring extension and force applied by the spring are related. Provide numerical values for the axes.
- **b** **Calculate** the energy stored in the spring when it is 50 cm long.

14.3 Solving problems involving kinetic energy and gravitational potential energy

Near Earth's surface, a constant force, $F = mg$, is applied to every mass. When a mass, m, falls from a position above Earth towards Earth, the gravitational force, mg, is applied over a distance Δh, which increases as the mass falls. This force does work, W, on the mass. The greater the distance of the fall, the greater the work done. All of this work transfers an amount of kinetic energy, ΔE_k, so that the mass moves at increasing speed from initial speed, u, to final speed, v. The gravitational force applied on the mass works to impart a change in the kinetic energy of the system. This change is all associated with the mass, as long as air resistance is regarded as negligible. Work and gain in kinetic energy are equivalent:

$$W = \Delta E_k$$

$$mg\Delta h = \Delta E_k$$

$$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

where:

m = mass (kg)

g = acceleration due to gravity (9.8 m s^{-2})

Δh = distance travelled (m)

v = final speed (m s^{-1})

u = initial speed (m s^{-1})

KEY FORMULA

$$\Delta E_k = mg\Delta h$$

$$mg\Delta h = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

where:

m = mass (kg)

g = acceleration due to gravity (9.8 m s^{-2})

Δh = distance travelled (m)

v = final speed (m s^{-1})

u = initial speed (m s^{-1})

KEY FORMULA

$$W = \Delta E_p$$

$$\Delta E_p = mg \times \Delta h \text{ (J)}$$

It is important to consider the mass before it began to descend. If the mass is to gain kinetic energy, the energy needs to be available in the first place. In order to be at its position, the mass must have been lifted up against the gravitational force. The energy need to lift the mass by a distance, Δh, is the work done to raise it by this amount.

This is equal to the energy added into the system as potential energy, ΔE_p:

$$W = \Delta E_p$$

$$\Delta E_p = mg \times \Delta h$$

KEY FORMULA

Near Earth, where air resistance is negligible:

$$+\Delta E_k = -\Delta E_p$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)
'+' sign means 'gain'; '–' sign means 'loss'

KEY FORMULA

$$\Delta E_k + \Delta E_p = 0$$
$$+\Delta E_k = -\Delta E_p \text{ (falling mass)}$$
$$-\Delta E_k = +\Delta E_p \text{ (rising mass)}$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)

The change of total energy, ΔE_t in this system is zero:

$$\Delta E_t = \Delta E_k + \Delta E_p = 0$$
$$\Delta E_k = -\Delta E_p$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)
'+' sign means 'gain'; '–' sign means 'loss'

Since the total change in energy in the system is zero, the positive gain in kinetic energy as the mass falls is provided by a consequent negative gain (a loss) in potential energy of the system. Similarly, as a mass rises against the gravitational force, the negative change in kinetic energy is transformed into a positive gain in potential energy of the system:

$$-\Delta E_k = +\Delta E_p$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)

Whether the mass is rising or falling, the total change in energy of the system is zero.

Zero of gravitational potential energy

For objects that move vertically near Earth, it is useful to define a position where the gravitational potential energy of the Earth–mass system is zero. This is usually taken as the point of projection. The potential energy of the system then increases as the height above the zero point increases. Consequently, there is an equal decrease in kinetic energy of the system that is usually associated with the projectile. This coincides with experience. A ball thrown up at speed v_{max} loses speed, hence kinetic energy. It momentarily stops at the top of its flight, h_{max}. On the way down, the speed, hence the kinetic energy, increases until all the potential energy has been expended back at the zero point. At the top point, the kinetic energy at launch has all been converted to potential energy. The two values are equal:

$$mgh_{max} = \frac{1}{2}mv^2_{max}$$

KEY FORMULA

For vertical projection from $h = 0$:

$$mgh_{max} = \frac{1}{2}mv^2_{max}$$

$$v_{max} = \sqrt{2gh_{max}} \quad \text{or} \quad h_{max} = \frac{v^2_{max}}{2g}$$

where:
v_{max} = maximum launch speed (m s^{-1})
h_{max} = maximum height reached above zero of potential energy (m)
m = mass (kg)
g = acceleration due to gravity (9.8 m s^{-2})

- The maximum launch speed can be deduced by measuring the maximum height above the zero of potential energy:

$$v_{max} = \sqrt{2gh_{max}}$$

- The maximum height can be deduced by measuring the launch speed at the zero of potential energy:

$$h_{max} = \frac{v^2_{max}}{2g}$$

where:
h_{max} = maximum height reached above zero of potential energy (m)
v_{max} = maximum launch speed (m s^{-1})
m = mass (kg)
g = acceleration due to gravity (9.8 m s^{-2})

Solving problems involving vertical displacements

Worksheet
Work and energy

To solve problems in which objects move vertically near Earth, a work–energy analysis is usually useful.

For changes in potential energy, $\Delta E_p = mg\Delta h = mg(h_f - h_i)$.

- Identify the initial height, h_i.
- Identify the final height, h_f.
- Substitute values into the equation.
- Calculate the answer.

For changes in kinetic energy:

$$\begin{aligned}\Delta E_k &= \frac{1}{2}mv_f^{\,2} - \frac{1}{2}mv_i^{\,2}\\ &= \frac{1}{2}m(v_f^{\,2} - v_i^{\,2}) \text{ or } \frac{1}{2}m(v_f - v_i)^2\end{aligned}$$

- Identify the initial speed, v_i.
- Identify the final speed, v_f.
- Substitute values into the equation.
- Calculate the answer.

It is frequently necessary to equate kinetic energy changes with potential energy changes in order to find height changes or speed changes. If measurements are made relative to the zero of potential energy, then at the:

- bottom of the flight, $h_i = 0$ and $E_p = 0$
- top of the flight, $v_f = 0$ and $E_k = 0$.

In these cases, substitute values into either:

$$v_{max} = \sqrt{2gh_{max}} \quad \text{or} \quad h_{max} = \frac{v^2{}_{max}}{2g}$$

WORKED EXAMPLE 14.3.1

A rhythmic gymnast throws a 420 g ball vertically upwards to a height of 8.0 m.

a Calculate the potential energy gain at the top of the ball's flight.

b Determine the initial speed of the ball as it leaves the gymnast's hand.

ANSWERS

a **1 State the formula.**

$\Delta E_p = mg\Delta h$

2 Substitute the known values into the formula.

$\Delta E_p = 0.42\text{ kg} \times 9.8\text{ m s}^{-2} \times (8.0\text{ m} - 0\text{ m})$

3 Calculate the answer.

$\Delta E_p = 33\text{ J}$

b **1 State the formula for potential energy.**

$\Delta E_k = -\Delta E_p$

$\frac{1}{2}mv_f^{\,2} - \frac{1}{2}mv_i^{\,2} = -33\text{ J}$

2 Substitute the known values into the formula.

Since the initial speed = 0 m s^{-1}:

$$\frac{1}{2}m(0)^2 - \frac{1}{2}mv_i^{\ 2} = -33\text{ J}$$

$$\frac{1}{2}mv_i^{\ 2} = 33\text{ J}$$

3 Rearrange to find the unknown.

$$v_i = \sqrt{\frac{2 \times 33\text{ J}}{0.42\text{ kg}}}$$

4 Calculate the answer.

$$v_i = 12.5\text{ m s}^{-1} = 13\text{ m s}^{-1}$$

When objects move at right angles to Earth's gravitational force, there is no gravitational force component in the direction of motion; therefore, no work is done by the gravitational force. Thus, a body that is simultaneously moving vertically and horizontally, such as a ball thrown from one person to another, is only worked on by the gravitational force as it moves vertically up or down but not as it moves sideways.

WORKED EXAMPLE 14.3.2

A waterslide starts from a height of 15 m above the ground. A 40 kg person sits at the top of the waterslide.

a Calculate the potential energy associated with the person at the top of the slide.

b Find the maximum kinetic energy the person will gain when sliding to the bottom of the slide.

c Calculate the maximum speed of the person.

d Will a 60 kg person go down the slide faster than the 40 kg person? Give reasons for your answer.

ANSWERS

a **1 State the formula.**

$$E_p = mg\Delta h$$

2 Substitute known values into the formula.

$$E_p = 40\text{ kg} \times 9.8\text{ m s}^{-2} \times (15\text{ m} - 0\text{ m})$$

3 Calculate the answer.

$$E_p = 5.9 \times 10^3\text{ J}$$

b **1 Identify the relationship between the change in kinetic energy and potential energy.**

$$+\Delta E_k = -\Delta E_p$$

2 Substitute known values into the formula.

$$+\Delta E_k = -[40\text{ kg} \times 9.8\text{ m s}^{-2} \times (0\text{ m} - 15\text{ m})]$$

3 Calculate the answer.

$$+\Delta E_k = 5.9 \times 10^3\text{ J}$$

c **1 State the formula.**

$$\Delta E_k = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

$$= \frac{1}{2}mv^2 - 0$$

2 Rearrange to find the unknown.

$$v = \sqrt{\frac{2\Delta E_k}{m}}$$

3 Substitute the known values.

$$v = \sqrt{\frac{2 \times 5.9 \times 10^3 \text{ J}}{40 \text{ kg}}}$$

4 Calculate the answer.

$v = 17 \text{ m s}^{-1}$

d **1 Identify the relationship between speed and mass.**

$$v = \sqrt{\frac{2\Delta E_k}{m}}$$

$$= \sqrt{\frac{2 \times mg\Delta h}{m}}$$

$$= \sqrt{2g\Delta h}$$

This is independent of the mass.

2 Compare the speeds of both masses

No. The speed at the bottom will be the same, no matter the mass (so long as friction is negligible).

LEARNING CHECK 14.3

DESCRIBING

1 Write the equation that connects *change* in total energy, *change* in kinetic energy and *change* in potential energy.

2 Write the equation that connects work done by Earth's gravitational force on a mass that:

  a is lifted by a distance Δh

  b falls by a distance Δh.

3 A mass, m, is projected upwards with an initial speed, v_i, and reaches a maximum height, h, above the ground. Write the equation that:

  a links the maximum kinetic energy with the maximum potential energy in the Earth–mass system

  b enables calculation of v_i from measurements of h

  c enables calculation of h from measurements of v_i.

APPLYING

4 For masses 'near Earth', it is usual to define the zero of potential energy at Earth's surface. **Explain** why this is useful.

5 **Explain** why gravitational potential energy is transferred only when a mass moves vertically but not horizontally.

6 A cricketer throws a 160 g ball vertically upwards to a height of 20.0 m.

  a **Calculate** the potential energy gain at the top of the ball's flight.

  b **Determine** the speed of the ball as it leaves the cricketer's hand.

7 A 50 kg person slips down a funpark slide that is 20 m high. **Calculate** the changes in potential energy and kinetic energy of the system at:

  a the top of the slide

  b the bottom of the slide

  c halfway down the slide.

ANALYSING

8 A 2.0 kg projectile is launched from the ground vertically upwards at 20 m s^{-1}. Use comparative calculations to show that it does not matter whether the initial potential energy of the system is zero or 100 J at Earth's surface.

14.4 Interpreting energy–time graphs

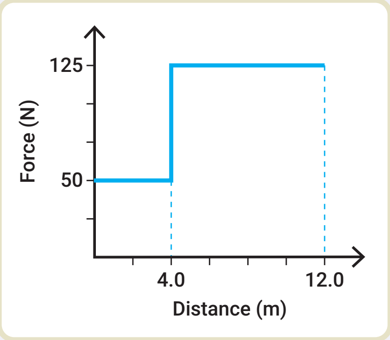
Graphs are frequently drawn to show aspects of motion. A force–time graph relates to an analysis of impulse or change in momentum. Force–distance graphs are used for work–energy analyses. For movement that is subject to the gravitational force near Earth, the force–distance graph shows a constant force as distance changes. Frequently, force–extension graphs are drawn for springs. In both of these cases, the area under the force–distance graph is the work done, hence energy change, in the system.

You can solve problems involving force–distance graphs by following these steps.

- Read the question carefully.
- Visualise the situation.
- Check the scales on both axes.
- Convert all scale readings to appropriate SI units.
- Identify the area required as:
  - work done on or by the system
  - kinetic energy increase or decrease
  - potential energy increase or decrease.
- Set up appropriate equations.
- Equate energy changes with areas.
- Substitute values.
- Calculate the answers.
- Check to ensure the results answer the question.

WORKED EXAMPLE 14.4.1

The graph shows the force applied by one and then two people pulling a 50 kg box, initially at rest, over a frictionless floor.



a Calculate the work done by the:

  i first person before the second person starts to pull

  ii second person, assuming the first person continues to pull with the same force as before.

b Calculate the kinetic energy gained by the box after it has been pulled 12 m.

c Calculate the speed of the box at 12 m.

ANSWERS

a i 1 State the formula.

W = area under graph

2 Substitute the known values into the formula.

$W = 50\text{ N} \times 4.0\text{ m}$

3 Calculate the answer.

$W = 200\text{ J}$

ii **1 State the formula.**

W = area under graph

2 Substitute the known values into the formula.

$$W = (125\text{ N} - 50\text{ N}) \times (12.0\text{ m} - 4.0\text{ m})$$
$$= 75\text{ N} \times 8.0\text{ m}$$

3 Calculate the answer.

$W = 600$ J

b **1 State the formula.**

W = total area under the curve

2 Substitute the known values.

$$W = (50\text{ N} \times 12.0\text{ m}) + (75\text{ N} \times 8.0\text{ m})$$
$$= 600\text{ J} + 600\text{ J}$$

3 Calculate the answer.

$W = 1.2 \times 10^3$ J

c **1 State the equation.**

$$W = \Delta E_k$$

$$W = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

2 Substitute the known values into the formula.

$$\frac{1}{2}mv^2 = 1200\text{ J}\,(u = 0\text{ m s}^{-1})$$

$$v = \sqrt{\frac{2 \times 1200\text{ J}}{50\text{ kg}}}$$

3 Calculate the answer.

$v = 6.9\text{ m s}^{-1}$

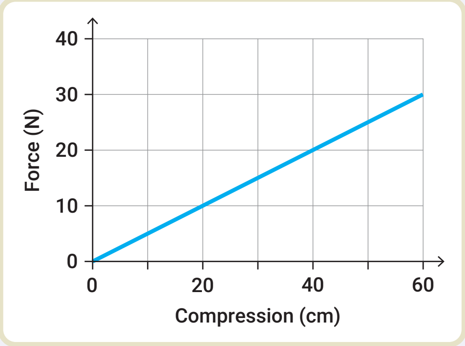
WORKED EXAMPLE 14.4.2

The graph shows the magnitude of a force applied by a spring as a function of the compression of the spring. A 40.0 g ball bearing is placed at the end of the spring ready to be launched horizontally.

a Calculate the spring constant or stiffness of the spring in N m^{-1}.

b Find the energy stored in the spring when it is compressed by 40 cm.

c Calculate the speed of the ball bearing when the spring is released from a compression of 40 cm.



ANSWERS

a **1 State the formula.**

k = gradient of F–x graph

2 Substitute known values into the formula.

Note that the x-axis scale is in centimetres; therefore, convert to metres.

$$k = \frac{30\text{ N}}{0.60\text{ m}}$$

3 Calculate the answer.

$k = 50\ \text{N m}^{-1}$

b **1 State the formula.**

ΔE_p = area under F–x graph

2 Substitute the known values into the formula.

$$\Delta E_p = \frac{1}{2} \times 20\ \text{N} \times 0.40\ \text{m}$$

3 Calculate the answer.

$\Delta E_p = 4.0\ \text{J}$

c **1 Identify the kinetic energy of the spring.**

$$\Delta E_k = \Delta E_p$$
$$= 4.0\ \text{J}$$

2 Substitute the known values into the formula.

Note that we need to convert the mass to kg.

$$\frac{1}{2}m(v_f^{\,2} - v_i^{\,2}) = 4.0\ \text{J}$$

$$\frac{1}{2} \times 4.0 \times 10^{-2}\ \text{kg} \times [v_f^{\,2} - (0\ \text{m s}^{-1})^2] = 4.0\ \text{J}$$

$$2.0 \times 10^{-2}\ \text{kg} \times v_f^{\,2} = 4.0\ \text{J}$$

3 Rearrange to find the unknown.

$$v_f = \sqrt{\frac{4.0\ \text{J}}{2.0 \times 10^{-2}\ \text{kg}}}$$

4 Calculate the answer.

$v_f = 14\ \text{m s}^{-1}$

LEARNING CHECK 14.4

DESCRIBING

1 Write down the steps needed in order to solve problems involving force–distance graphs.

2 **Explain** why the area under a force–distance graph can be used to measure energy change.

3 Show that the energy stored in a spring that obeys Hooke's law, $F = k(^-x)$, is $\frac{1}{2}kx^2$ when the spring is extended by an amount x.

APPLYING

4 The force–distance graph in **Figure 14.4.1** is for a particle of mass 1.5 kg.

Calculate the work done:

- **a** in the first 10 m
- **b** between 3.0 m and 17 m.

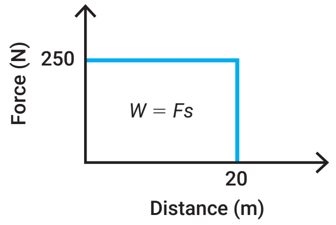


FIGURE 14.4.1 Force–distance graph

5 Person A pulls a heavy load across a floor (**Figure 14.4.2**). Later, person B comes to assist. The friction force is a constant 28 N.

- a **Calculate** the work done by person A after the load has travelled:
  - i 4.0 m
  - ii 16 m.
- b **Calculate** the work done by person B after the load has travelled:
  - i 12 m
  - ii 20 m.
- c **Calculate** the work done by the friction force after 24 m.

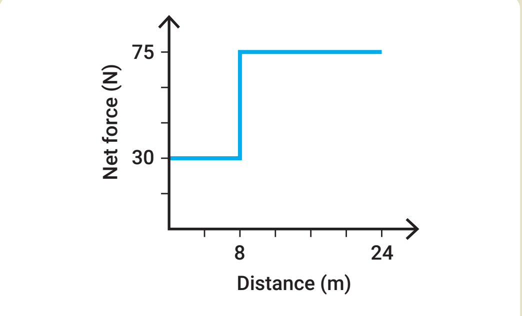


FIGURE 14.4.2 Force–distance graph

6 The speed–time graph for a goods train is shown in Figure 14.4.3. The mass of the train is 5500 tonnes. The total frictional forces on the train are 1.0×10^4 N.

Calculate the work done by the train:

- a in the first 600 s
- b between 1200 s and 1800 s.

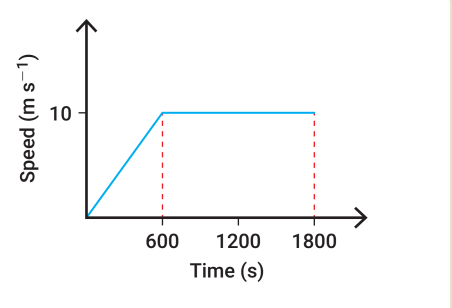


FIGURE 14.4.3 Speed–distance graph

ANALYSING

7 A spring of stiffness k and natural length ℓ is compressed so that its length becomes L. Express Hooke's law for this spring in terms of L and ℓ. Rewrite this expression for the case when the spring is extended to a length L.

8 A spring lies on a horizontal table. It has a natural length of 45 cm and a spring constant of 200 N m^{-1}. It is compressed to a length of 20 cm and a projectile of mass 200 g is placed on the end. The spring is then released.

- a **Sketch** the situation.
- b Draw the force–extension graph for this spring.
- c On the graph, indicate how to measure the energy stored in the spring.
- d **Calculate** the speed at which the projectile is released.

14.5 Elastic and inelastic collisions

The total kinetic energy immediately before a collision is sometimes equal to the total kinetic energy immediately after the collision. If the kinetic energies of all the particles in a collision are added up immediately before and immediately after a collision, they can be compared. If they are the same before and after the collision, then the kinetic energy has been conserved because it has all been returned. For example, a spring can be compressed by a moving object until it stops. All this energy can be stored, then released.

Solving problems: elastic and inelastic collisions

To solve collision questions involving energy and momentum, use the Before and After column arrangement shown in Worked example 14.5.1.

The total kinetic energy before and after can then be added into the columns and compared. Then a decision can be made as to whether the collision is:

- elastic – both values are the same and kinetic energy is conserved
- inelastic – the values are different and kinetic energy is not conserved.

In all collisions, momentum is conserved, whereas kinetic energy is not necessarily conserved.

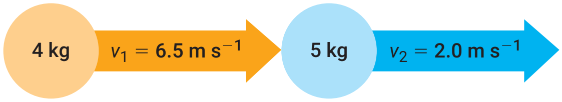
WORKED EXAMPLE 14.5.1

A 4.0 kg mass travelling to the right at 6.5 m s⁻¹ collides with a 5.0 kg mass moving to the right at 2.0 m s⁻¹. They stick together and move off at a speed of 4.0 m s⁻¹.

Determine whether the collision is elastic or inelastic.

ANSWER

Before

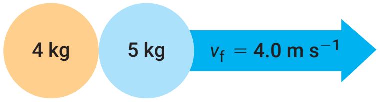


$$\sum E_k(\text{before}) = \frac{1}{2}\left[4.0\text{ kg}\times(6.5\text{ m s}^{-1})^2\right] + \frac{1}{2}\left[5.0\text{ kg}\times(2.0\text{ m s}^{-1})^2\right]$$

$$\sum E_k(\text{before}) = 84.5\text{ J} + 10\text{ J}$$

$$\sum E_k(\text{before}) = 94.5\text{ J}$$

After



$$\sum E_k(\text{after}) = \frac{1}{2}\left[9.0\text{ kg}\times(4.0\text{ m s}^{-1})^2\right]$$

$$\sum E_k(\text{after}) = 72.0\text{ J}$$

$$\sum E_k(\text{before}) \neq \sum E_k(\text{after})$$

The collision is inelastic.

Weblink
Collision lab

Combining energy and momentum analyses

Impulse–momentum or work–energy concepts and equations can be used together to analyse a collision. This is because these two ways of analysing motion relate to the same situation. A complete analysis of a collision includes finding values for force, distance, time and velocity. Impulse–momentum analysis is used when the data involves force, time and velocity. Work–energy analysis is used when the data involves force, distance and velocity. The analyses can be combined to completely investigate the motion. Two important points need to be emphasised.

- The total momentum immediately before a collision is always equal to the total momentum immediately after the collision (law of conservation of momentum).
- The total kinetic energy immediately before a collision is sometimes but not always equal to the total kinetic energy immediately after the collision.

  Elastic collision:

$$\sum E_k(\text{before}) = \sum E_k(\text{after})$$

$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} = \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

  Inelastic collision:

$$\sum E_k(\text{before}) \neq \sum E_k(\text{after})$$

$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} \neq \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

These analytical techniques are used to understand car collisions. The longer it takes, in terms of time and distance, for a car to come to a stop, the smaller the average force that is applied to the occupants.

KEY FORMULA

Elastic collision:

$$\sum E_k(\text{before}) = \sum E_k(\text{after})$$

$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} = \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

Kinetic energy is conserved.

KEY FORMULA

Inelastic collision:

$$\sum E_k(\text{before}) \neq \sum E_k(\text{after})$$

$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} \neq \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

Kinetic energy is not conserved.

Interpreting energy–time graphs

Analysing energy–time graphs serves to understand energy transformations and transfers within systems, and particularly collisions. These graphs depict the variation in energy over time, aiding in identifying conservation principles and efficiency of energy conversions. Manufacturers leverage this fact when designing cars.

Conservation of energy for collisions

In both elastic and inelastic collisions, the total mechanical energy (kinetic energy plus potential energy) of the system remains constant if external forces, such as friction, are negligible. In an elastic collision, kinetic energy is conserved, meaning the total kinetic energy before the collision equals the total kinetic energy after the collision. In contrast, in an inelastic collision, some kinetic energy is transformed into other forms (such as thermal or potential energy), so the total kinetic energy decreases, but total mechanical energy remains conserved.

Conservation of momentum for collisions

In elastic and inelastic collisions, momentum is conserved. The total momentum of the system before the collision equals the total momentum after the collision, regardless of whether the collision is elastic or inelastic. This principle holds true as long as no external forces (such as friction or external impulses) act on the system. The conservation of momentum allows you to predict final velocities or masses involved in the collision based on initial conditions and the principle of momentum conservation.

WORKED EXAMPLE 14.5.2

ELASTIC COLLISION (KINETIC ENERGY CONSERVED)

Two objects with masses $m_1 = 2.0$ kg and $m_2 = 3.0$ kg collide elastically. Mass m_1 is moving east initially with a velocity of 5 m s^{-1}. Mass m_2 is initially at rest. After the collision mass m_1 is moving east with a velocity of 3 m s^{-1}.

a Apply the law of conservation of energy to determine the final velocity of the 3.0 kg mass, m_2.

b Draw an energy–time graph for this scenario.

ANSWERS

a **1 State the formula.**

The law of conservation of energy dictates that for an elastic collision, the sum of kinetic energy of the objects before the collision will equal the sum of the kinetic energy of the objects after the collision; that is:

$$E_k(\text{before}) = E_k(\text{after})$$

$$= \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 = E_k(\text{after}) = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2$$

2 Substitute the known values into the formula.

$$E_k = \frac{1}{2}2.0 \times 5^2 + \frac{1}{2}3.0 \times 0^2 = E_k(\text{after}) = \frac{1}{2}2.0 \times 3^2 + \frac{1}{2}3.0 \times v_2^2$$

3 Calculate the answer.

Use the conservation of energy statements and kinetic energy formula to determine the final velocity of mass m_2.

$$E_k(\text{before}) = 25 + 0 = E_k(\text{after}) = 9 + \frac{1}{2}3.0 \times v_2^2$$

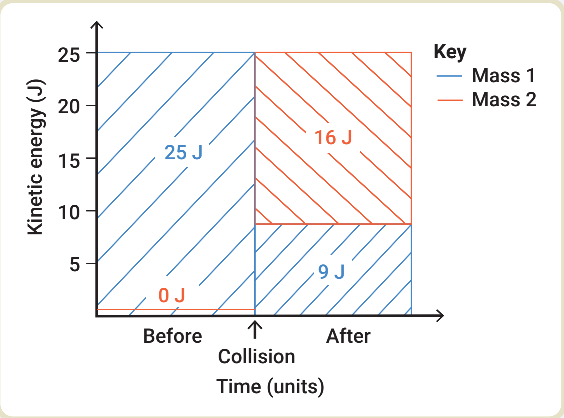
$$25 = 9 + 1.5\,v_2^2$$

Hence $v_2 = \sqrt{\dfrac{25-9}{1.5}}$

And $v = 3.26$ m s^{-1} to the east.

b In an elastic collision, kinetic energy is conserved. Therefore, on the energy–time graph, the total kinetic energy before the collision should be equal to the total kinetic energy after the collision. The energy–time graph before and after the collision shows how the sum of the areas before (25 J + 0 J) is equal to the sum of the areas after (16 J + 9 J).

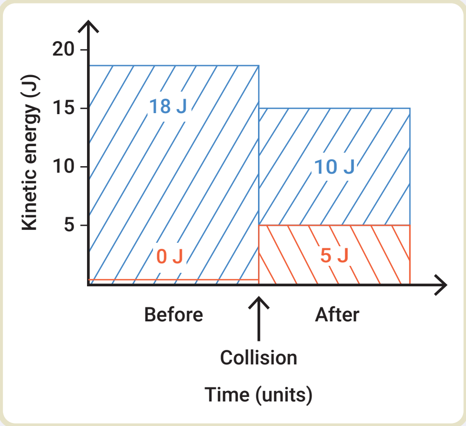
The energy–time graph shows a constant total kinetic energy before and after the collision, indicating that kinetic energy is conserved.



WORKED EXAMPLE 14.5.3

INELASTIC COLLISION (KINETIC ENERGY NOT CONSERVED)

A 4.0 kg object moving with a velocity of 3 m s^{-1} to the right collides with a stationary 2.0 kg object. Interpret the energy–time graph to determine whether the collision was elastic or inelastic.



ANSWERS

1 State the formula.

Determine the kinetic energy before the collision based on the values provided.

$$E_k(\text{before}) = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2$$

2 Substitute the known values into the formula.

$$E_k = \frac{1}{2}4.0\times 3^2 + \frac{1}{2}2.0\times 0^2$$

$$= 18\text{ J} + 0\text{ J}$$

3 Calculate the kinetic energy.

$$E_k = 18\text{ J}$$

4 Interpret the energy–time graph.

In an elastic collision, kinetic energy is conserved. In an inelastic collision, kinetic energy is not conserved.

Therefore, we need to use the energy–time graph to compare the total kinetic energy before the collision to the total kinetic energy after the collision. (10 J + 5 J) ≠ (18 J + 0 J)

5 Draw a conclusion.

The energy–time graph shows a decrease in total kinetic energy after the collision, indicating that kinetic energy is not conserved and that the collision is inelastic.

When solving problems involving a combination of work–energy and impulse–momentum analyses, it is useful to first identify the data available.

- If displacement (*s*) data is initially provided, use work–energy, then impulse–momentum.
- If time (*t*) data is initially provided, use impulse–momentum then work–energy.

WORKED EXAMPLE 14.5.4

A 75 kg person in a 2.0×10^3 kg vehicle is travelling at 14 m s^{-1} when it crashes into a wall. The vehicle crumples by 0.50 m before coming to a stop on the wall.

a Calculate the total change in kinetic energy for the vehicle.

b Calculate the average force applied by the wall on the car.

c Calculate the time taken for the car to come to a stop.

d Determine the force applied by the seatbelt on the person.

ANSWERS

a **1 State the formula.**

$$\Delta E_k = \frac{1}{2}m(v_f - v_i)^2$$

2 Substitute the known values into the formula.

$$\Delta E_k = \frac{1}{2} \times (2000 + 75) \times (0 - 14)^2$$

3 Calculate the answer.

$$\Delta E_k = 2.0 \times 10^5 \text{ J}$$

b **1 State the formula.**

Use work–energy analysis because the data includes force, displacement and velocity.

$$W(\text{by wall on car}) = F(\text{by wall on car}) \times s$$

2 Rearrange to find the unknown.

$$F(\text{by wall on car}) = \frac{W(\text{by wall on car})}{s}$$

3 Substitute the known values into the formula.

$$F(\text{by wall on car}) = \frac{-2.0 \times 10^5 \text{ J}}{0.5 \text{ m}}$$

4 Calculate the answer.

$$F(\text{by wall on car}) = -4.0 \times 10^5 \text{ N}$$

c **1 State the formula.**

Use impulse–momentum analysis to find the time interval, *t*.

$$J = Ft = mv_f - mv_i$$

$$F(\text{by wall on car}) \times t = m(v_f - v_i)$$

2 Rearrange the formula to find the unknown.

$$t = \frac{m(v_f - v_i)}{F(\text{by wall on car})}$$

3 Substitute the known values into the formula.

$$t = \frac{2.0 \times 10^3 \text{ kg} \times (0 \text{ m s}^{-1} - 14 \text{ m s}^{-1})}{-4.0 \times 10^5 \text{ N}}$$

4 Calculate the answer.

$$t = 7.0 \times 10^{-2} \text{ s}$$

d **1 State the formula.**

The person stops at the same rate as the vehicle. Impulse–momentum or work–energy can be used to find the force, *F*, applied by the seatbelt on the person.

Impulse–momentum:

$$\begin{aligned} Ft &= mv_f - mv_i \\ &= m(v_f - v_i) \end{aligned}$$

2 Rearrange the formula to find the unknown.

$$F = \frac{m(v_f - v_i)}{t}$$

3 Substitute the known values into the formula.

$$F = \frac{75\ \text{kg} \times (0\ \text{m s}^{-1} - 14\ \text{m s}^{-1})}{7.0 \times 10^{-2}\ \text{s}}$$

4 Calculate the answer.

$$F = -1.5 \times 10^4\ \text{N}$$

Work–energy:

1 State the formula.

$$\begin{aligned} Fs &= \frac{1}{2}mv_f^{\,2} - \frac{1}{2}mv_i^{\,2} \\ &= \frac{1}{2}m(v_f^{\,2} - v_i^{\,2}) \end{aligned}$$

2 Rearrange the formula to find the unknown.

$$F = \frac{\frac{1}{2}m(v_f^{\,2} - v_i^{\,2})}{s}$$

3 Substitute the known values into the formula.

$$F = \frac{\frac{1}{2} \times 75\ \text{kg} \times \left[(0\ \text{m s}^{-1})^2 - (14\ \text{m s}^{-1})^2\right]}{0.5\ \text{m}}$$

4 Calculate the answer.

$$F = -1.5 \times 10^4\ \text{N}$$

PRACTICAL ACTIVITY 14.5.1

NEWTON'S CRADLE

Introduction

Elastic collisions are characterised by equal kinetic energies before and after the collision. A Newton's cradle consists of several hard metal balls independently hung and just touching each other. When one or more balls are released to collide with the remainder, a nearly elastic collision may be observed.

Research question

How does a Newton's cradle demonstrate conservation of energy and momentum in collisions?

O.V.D./Shutterstock.com

FIGURE 14.5.1 Newton's cradle

Aim

To demonstrate:

- conservation of energy
- elastic collisions
- conservation of momentum

Materials

- Newton's cradle consisting of at least five balls of equal mass (mass, *m*, of 1 ball = 1 unit)
- ruler
- motion-measuring device such as a motion sensor or video camera

Procedure

1. Set up the cradle and motion-measuring device.
2. Draw back one ball to a measured height, Δh.
3. Release the ball (incoming ball).
4. Record the interaction.
5. Measure the height to which the ball (outgoing ball) at the other end rises.
6. Repeat by drawing back two, three and four balls.
7. Record all data in a correctly constructed data table.

Analysis of results

1. From the height data, calculate the velocity of the:
   - **a** incoming ball(s) at impact
   - **b** outgoing ball(s) as they start to rise.
2. From the kinetic energy data, calculate the:
   - **a** velocity of the:
     - **i** incoming ball(s) at impact
     - **ii** outgoing ball(s) at the moment they start to rise
   - **b** momentum of the:
     - **i** incoming ball(s) at impact
     - **ii** outgoing ball(s) at the moment they start to rise.
3. Estimate the uncertainty in the measurements of height and the effect of the uncertainties in the calculated velocities.

Interpretation and evaluation

4. Answer the research question by indicating the extent to which the following were, or were not, demonstrated:
   - conservation of energy
   - elastic collisions
   - conservation of momentum.
5. Explain how conservation of energy was assumed in order to calculate the velocities of the incoming balls.
6. Explain why there was no need to measure the mass of the balls in grams.
7. Identify any energy losses and ways to reduce these.
8. Explain what you would need to do to measure the energy of a 'click' produced when two balls collide using this apparatus and method.

LEARNING CHECK 14.5

DESCRIBING

1 **Describe** and **explain:**
  - **a** elastic collision
  - **b** inelastic collision.

2 In analysing a collision, **identify** the quantity that is:
  - **a** always conserved
  - **b** only conserved for elastic collisions.

3 **Identify** the starting concepts for analysis of collisions involving:
  - **a** time–interval data
  - **b** displacement data.

4 **Compare** the conservation of momentum and energy transfers from the start to the end of an elastic collision.

APPLYING

5 A 4.0 kg mass, P, sliding to the right at 3.0 m s^{-1} collides with a 5.0 kg mass, Q, moving to the left at 2.0 m s^{-1}. P moves off at 1.0 m s^{-1} to the left. The collision takes 0.4 s.
  - **a** **Calculate** the velocity of Q after the collision.
  - **b** **Calculate** the force applied by P on Q.
  - **c** State whether the collision is elastic or inelastic.

6 A vehicle travelling at 10 m s^{-1} comes to a sudden stop. It crumples by a distance of 1.0 m. For a 100 kg passenger wearing a seatbelt, **calculate** the:
  - **a** force applied by the seatbelt on the person
  - **b** time taken for the person to come to a stop.

ANALYSING

7 **Explain** how a Newton's cradle can be used to demonstrate elastic collisions.

Conservation of energy

- All the energy in the universe is all the energy there is; no additional energy can be made nor lost.

$$\Delta E = E_f - E_i$$

where:
E_i = initial energy state (J)
E_f = final energy state (J)

- Law of conservation of energy in an isolated system:

E_t = constant and $\Delta E_t = 0$ (J)
E_t = total energy (J)

Work and energy

- Work is calculated by multiplying the force applied to the object and the distance moved. The force and distance need to be parallel to each other.

$$W = F_{\|}s$$

where:
W = work done (J)
$F_{\|}$ = force parallel to the distance interval (N)
s = distance interval parallel to the force (m)

- When work is done on an object, energy is transferred to the object.

$$W = \Delta E$$

where:
W = work done on the object (J)
ΔE = change in the energy of the object (J)

- Kinetic energy can be determined by the mass and velocity of an object.

$$E_k = \frac{1}{2}mv^2$$

where:
E_k = kinetic energy (J)
m = mass (kg)
v = speed (m s^{-1})

- When a force is applied at an angle, work can also be calculated, given the angle of the force.

$$W = F_{\|}s = Fs\cos\theta$$

where:
W = work done on the object (J)
F = force applied to the object (N)
$F_{\|}$ = force applied on the object parallel to the direction of the distance travelled (N)
s = distance travelled by the object (m)
θ = angle between the force and the direction of the distance travelled (degrees)

Potential energy and springs

- The force applied by a spring is equal to the force applied to the spring.
- A spring applies the same magnitude of force as the force applied to change the length of the spring; however, it does so in the opposite direction.
- Hooke's law

  $$F(\text{by spring}) = k(-x)$$

  where:
  F(by spring) = force applied to or by a spring to an external cause (N)
  x = change of length of spring (m)
  k = constant of proportionality = stiffness (N m^{-1})
- The potential energy stored in a spring system can be calculated given the stiffness and the length at which the spring has been extended or compressed.

  $$W = \frac{1}{2}kx^2$$

  where:
  W = potential energy stored in a spring (J)
  k = spring constant or stiffness (N m^{-1})
  x = extension (or compression) of the spring (m)

Work and energy changes

- The work done on an object is the same as the change in kinetic energy; for example, when pushing an object.
- The work done on an object is also the equivalent to the change in the object's potential energy; for example, when lifting an object.

  $$W = \Delta E_p$$
  $$\Delta E_p = mg \times \Delta h$$

- The gain in kinetic energy is equivalent to the loss in potential energy. As a result, the total change in energy of the system is 0.
- The relationship between the kinetic and potential energy of an object can be used to calculate the maximum height for vertical projection.

  $$\Delta E_k = mg\Delta h$$
  $$mg\Delta h = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

  where:
  m = mass (kg)
  g = acceleration due to gravity ($9.8\ \text{m s}^{-2}$)
  Δh = distance travelled (m)
  v = final speed (m s^{-1})
  u = initial speed (m s^{-1})

- Near Earth, where air resistance is negligible:

$$+\Delta E_k = -\Delta E_p$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)
'+' sign means 'gain'; the '–' sign means 'loss'

$$\Delta E_k + \Delta E_p = 0$$
$$+\Delta E_k = -\Delta E_p \text{ (falling mass)}$$
$$-\Delta E_k = +\Delta E_p \text{ (rising mass)}$$

where:
ΔE_k = change in kinetic energy (J)
ΔE_p = change in potential energy (J)

- For vertical projection from $h = 0$:

$$mgh_{max} = \frac{1}{2}mv^2{}_{max}$$

$$v_{max} = \sqrt{2gh_{max}} \text{ or } h_{max} = \frac{v^2{}_{max}}{2g}$$

where:
v_{max} = maximum launch speed (m s^{-1})
h_{max} = maximum height reached above zero of potential energy (m)
m = mass (kg)
g = acceleration due to gravity (m s^{-2})

Elastic and inelastic collisions

- For elastic collisions, the kinetic energy before and after is the same.
- Elastic collision:

$$\sum E_k\text{(before)} = \sum E_k\text{(after)}$$
$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} = \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

Kinetic energy is conserved.

- For inelastic collisions, the kinetic energy before and after are different.
- Inelastic collision:

$$\sum E_k\text{(before)} \neq \sum E_k\text{(after)}$$
$$\sum\left(\frac{1}{2}mv^2\right)_{\text{before}} \neq \sum\left(\frac{1}{2}mv^2\right)_{\text{after}}$$

Kinetic energy is not conserved.

CHAPTER EXAM

MULTIPLE CHOICE

1. A ball is thrown upwards. The gravitational potential is stored in:

A the ball.
B Earth.
C the ball–Earth system.
D the loss of kinetic energy of the ball.

2. How much kinetic energy is gained by a 4.5 kg mass when it is thrown downwards at 2.0 m s^{-1} from a height of 12.3 m to the ground?

A 4.5 J
B 9.0 J
C 551 J
D 560 J

3. How much work is done on a car of mass 800 kg when it accelerates uniformly from 14 m s^{-1} to 30 m s^{-1} in 3.0 s?

A 1.0×10^5 J
B 2.0×10^5 J
C 2.8×10^5 J
D 3.6×10^5 J

4. At any time in a collision between two objects:

A momentum but not kinetic energy is conserved.
B kinetic energy but not momentum is conserved.
C kinetic energy and momentum are both conserved.
D neither kinetic energy nor momentum are conserved.

5. A 150 kg yak has an average power output of 120 W. Recall that power = energy ÷ time. The time it takes for the yak to climb a 1.2 km high mountain is:

A 25 minutes.
B 4.1 hours.
C 13.3 hours.
D 14.7 hours.

6. A total of 20 340 J of work is used to lift a load of bricks to a height of 15.25 m. What is the weight of the bricks?

A 136 N
B 418 N
C 1334 N
D 13 077 N

7. What is the kinetic energy of a 900 kg car that is travelling with a velocity of 60 km h^{-1}?

A 12.8 kJ
B 125 kJ
C 1.23 MJ
D 1.62 MJ

8. What is the velocity of a 5000 kg truck with a kinetic energy of 360 kJ?

A 2 km h^{-1}
B 31 km h^{-1}
C 43 km h^{-1}
D 144 km h^{-1}

9. When a 16 g mass is lifted 10 m, by how much does the potential energy of the mass increase?

A 1.6 J
B 16 J
C 160 J
D 1.6 kJ

10. A girl on a swing varies in height above the ground from 60 cm to 180 cm. The girl's maximum velocity is:

A 1.5 m s^{-1}.
B 4.8 m s^{-1}.
C 24 m s^{-1}.
D dependent on the girl's mass.

SHORT RESPONSE

11. During a competition, the centre of mass of a 60 kg high jumper rises from 0.63 m to 1.8 m above the ground. The top of the landing mat is 0.42 m above the ground.

a **Calculate** the change in potential energy of the system.
b Find the vertical speed with which the high jumper left the ground.
c **Calculate** the kinetic energy of the high jumper when landing on the mat.

12. A man uses a rope and system of pulleys to raise a 20 kg box to a height of 10 m. He exerts a force of 85 N on the rope and pulls a total of 25 m of rope through the pulleys.

a **Calculate** the amount of work performed.
b **Determine** how much the potential energy of the box increases by.
c If the answers for parts **a** and **b** are different, justify why this may be.

13. A 800 kg car moving at 6 m s^{-1} begins to coast down a hill 40 m high with its engine off. The driver applies the brakes so that the car's speed at the bottom of the hill is 20 m s^{-1}. **Calculate** how much energy was lost to friction when braking.

CROSS-CHAPTER QUESTION

14. In a test crash at 20 m s^{-1}, the head of an 8.0 kg unrestrained crash-test dummy is smashed in by 5.0 cm by the windscreen.

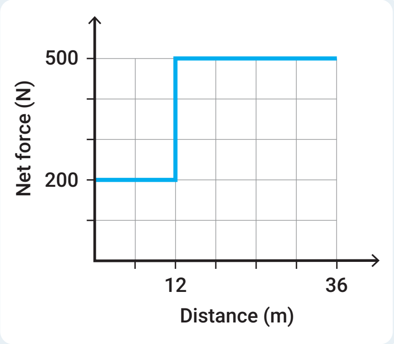
a **Calculate** the average force applied to the head of the crash-test dummy.
b Find the time taken for the crash-test dummy to be damaged by the windscreen.

DATA ANALYSIS

15. **Analyse data**

The following graph shows how the net force applied to a boat being winched towards a boat ramp varies with distance. The boat travels at 2.0 m s^{-1}. There is a constant friction force of 30 N.

a **Calculate** the work done by the net force during the first 12 m.
b Find the total work done by the winch after 36 m of effort.



SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- 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.

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Playing it safe: applying the physics of forces and motion

Our understanding of forces and motion has significantly enhanced car safety through the implementation of critical technologies such as seatbelts, crumple zones and airbags. This has revolutionised vehicle safety and saved countless lives on the road.

Newton's laws in action

Newton's laws of motion provide the foundation for understanding car safety.

- The law of inertia: An object in motion tends to stay in motion unless acted upon by an external force. Conversely, an object at rest remains at rest unless an external force compels it to move. This law underscores the importance of seatbelts, which prevent passengers from continuing forward during a collision.
- The second law: The force acting on an object is directly proportional to its mass and acceleration. Airbags and crumple zones use this principle. By increasing the time over which the force is applied, they reduce the peak force experienced by passengers during impact **(Figure 1)**.

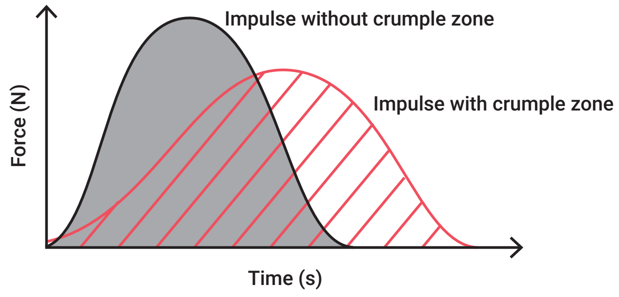


FIGURE 1 Comparative impulse graphs for a collision – with and without crumple zones. Note the decrease in maximum force applied to achieve the same change in momentum (impulse).

Seatbelts: taming inertia

Seatbelts exemplify Newton's first law. When a collision occurs, seatbelts lock in place, preventing passengers from continuing their motion due to their own momentum and inertia. As the car decelerates, passengers exert a force on the seatbelt, which then exerts an equal and opposite force back on them. This controlled deceleration minimises injuries.

Airbags: slowing down safely

Airbags extend the time it takes for a car occupant's head to decelerate from maximum speed to zero. Rapid deceleration would result in a large force, increasing the risk of head injuries. By slowing down the process, airbags reduce the maximum force acting on passengers' heads.

Crumple zones: controlled deformation

Crumple zones are strategically designed areas of a vehicle that crush in a controlled manner during a collision. They serve two critical purposes:

- Increased time for deceleration: Like airbags, crumple zones extend the time it takes for the vehicle to slow down upon impact. This reduces the maximum force exerted on passengers.
- Energy absorption: The deformation (crumpling) of the car absorbs energy from the collision, minimising the transfer of energy to passengers. Modern cars are engineered to crumple in specific zones, protecting the passenger compartment.

ANCAP safety ratings

The Australasian New Car Assessment Program (ANCAP) evaluates vehicle safety and assigns star ratings based on crash tests and safety features.

Five-star ratings are assigned to cars with advanced safety features, including seatbelts, airbags and well-designed crumple zones. These features reduce the risk of injury during collisions.

The widespread adoption of ANCAP ratings encourages manufacturers to prioritise safety enhancements for the betterment of society.

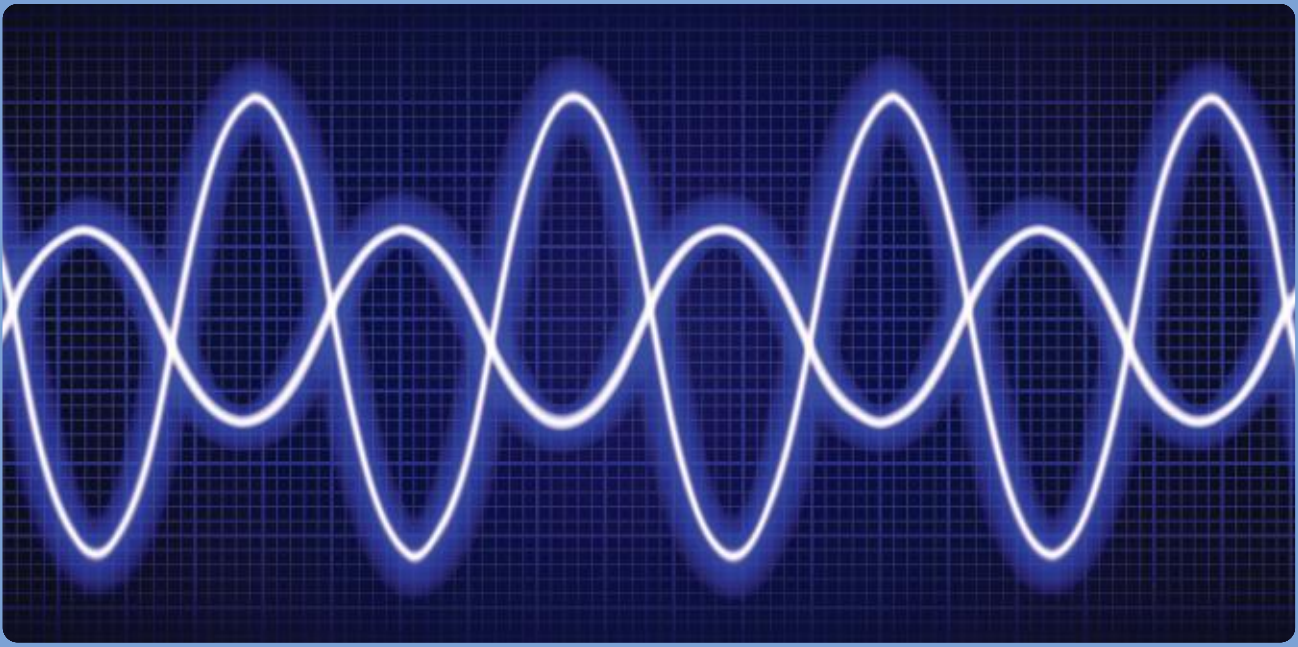
Reference

BBC Bitesize, Newton’s laws. https://www.bbc.co.uk/bitesize/guides/zgn82hv/revision/11.

CHAPTER

15

Wave properties



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SYLLABUS DOT POINTS

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 the significant contributions of scientists such as Laura Bassi, Willebrord Snellius, Albert A. Michelson and Edward W. Morley.
- 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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Introduction

Our investigations into the movement of objects up to this point has focused entirely upon motion in straight lines. It turns out, however, that almost all motion is more correctly described, at least at a fundamental level, by movement in a periodic form, also known as wave motion.

Sound waves, seismic waves, light and even particles all have wave properties that cannot be entirely described with the classical Newtonian laws of motion. In this chapter, we will investigate the features of waves that require a medium to travel through, and their behaviour when they interact with everyday objects.

Worksheets

- Graphing a wave in Excel
- Wave characteristics
- Reflection of waves
- Superposition of waves

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Waves can be used to transfer energy through different mediums.
- ✓ Mediums are made up of interconnected particles that are disturbed by travelling waves.
- ✓ The SI unit for velocity is metres per second ($m\ s^{-1}$).
- ✓ Some examples of waves are sound waves, ocean waves and light.
- ✓ Velocity can be calculated using the equation $v = \frac{s}{t}$.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain a wave and how it can transfer energy
- ✓ categorise wave types
- ✓ describe and explain mechanical waves and electromagnetic waves
- ✓ describe and explain transverse waves and longitudinal waves
- ✓ compare and contrast mechanical waves, electromagnetic waves, transverse waves, longitudinal waves, pulses and continuous waves
- ✓ describe the different mediums of mechanical waves such as water, strings and air
- ✓ describe and explain sound waves and seismic waves
- ✓ describe and explain the quantitative and qualitative aspects of a wave, including sinusoidal form, crests, troughs, amplitude, frequency, wavelength, velocity and period
- ✓ analyse and interpret displacement–time graphs of wave forms
- ✓ analyse and interpret displacement–distance graphs of wave forms
- ✓ solve problems involving wave form quantities
- ✓ describe how wave velocities can be dependent on their medium
- ✓ describe and explain what happens to a wave or pulse when it is reflected
- ✓ explain the law of reflection
- ✓ identify the normal, incident wave, reflected wave, incident angle, and angle of reflection on a diagram
- ✓ describe and explain total internal reflection, reverberation, decay and echoes
- ✓ describe and explain wave refraction
- ✓ compare and contrast real and apparent position
- ✓ identify the normal, incident wave, refracted wave, angle of incidence and angle of refraction on a diagram
- ✓ describe and explain diffraction
- ✓ interpret diagrams representing diffraction
- ✓ describe and explain the principle of superposition
- ✓ interpret or construct diagrams representing wave superposition
- ✓ categorise superposition as constructive or destructive interference
- ✓ describe and explain the Doppler effect and sonic boom
- ✓ link wave theory to the design of devices such as noise cancelling headphones and its contribution to seismic studies
- ✓ describe and explain standing waves.

15.1 Waves transfer energy

FIGURE 15.1.1 Concentric circular waves formed when a stone is dropped into water

Africa Studio/Shutterstock.com

There are many types of waves. A stone dropped into a pond of water creates a circular wave that will spread out in a circle **(Figure 15.1.1)**. A string held taut and vibrated at one end will form waves that travel through the string from one end to the other. Sound energy can be carried to our ears through any medium by sound waves. Seismic waves from explosions and earthquakes travel through Earth, and can give scientists an insight into what lies beneath its surface. Light waves can travel through the vacuum of space and tell us about the content of distant stars.

Despite the many differences between different kinds of waves, they all have one feature in common: all individual waves transfer energy from one place to another.

Since a wave is a travelling phenomenon that causes multiple points to move simultaneously, it is difficult to calculate the energy of a wave. Instead, we define the **intensity** of the wave as the rate at which energy is carried by the wave. It has units of watts per square metre ($\mathrm{W\,m^{-2}}$) and is known to be proportional to the square of the **amplitude** (A) or maximum displacement of a particle in a wave.

A wave will travel out in all directions from its source in a three-dimensional sphere. As the wave moves outwards, the energy that was emitted from the source becomes spread over a larger spherical surface **(Figure 15.1.2)**. As a result, the intensity of the wave decreases as the wave gets further from the source.

intensity a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel

amplitude the maximum displacement of a particle in a wave from its mean position; units: m

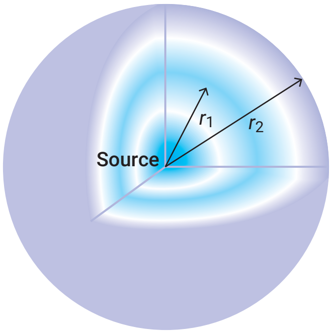

FIGURE 15.1.2 A wave travelling outwards from a source in three dimensions forms a sphere.

Types of waves

The transfer of energy through waves involves the propagation of disturbances or oscillations through a medium or space. Waves can be classified into two main types: mechanical waves and electromagnetic waves.

Mechanical waves

Mechanical waves require a medium to travel through, such as water or air. These waves transfer energy by causing particles in the medium to oscillate or vibrate as the wave passes through. Examples include sound waves, water waves and seismic waves. In a mechanical wave, energy is transferred from one point to another without the actual transfer of matter.

Electromagnetic waves

Electromagnetic waves do not require a medium and can travel through a vacuum. These waves consist of oscillating electric and magnetic fields that propagate through space. Examples include light waves, radio waves, microwaves and X-rays. In electromagnetic waves, energy is carried by the oscillating fields themselves.

Regardless of the type of wave, energy transfer occurs as the wave travels from its source to a receiver. This transfer of energy can take various forms depending on the wave's characteristics. For example, in a sound wave, energy is transferred as compression and rarefaction of air molecules longitudinally, while in an electromagnetic wave, energy is carried by changing transverse electric and magnetic fields at 90 degrees to each other.

LEARNING CHECK 15.1

DESCRIBING

1 **Identify** what feature all waves have in common.

2 **Describe** 'intensity' as it applies to travelling waves.

3 **Explain** what happens to the intensity of a wave when its amplitude is doubled.

ANALYSING

4 **Examine** Figures 15.1.1 and 15.1.2 and establish a reason why waves on a pond surface appear as circles if waves are known to travel as spheres.

15.2 Mechanical waves

If an ocean wave is observed moving towards the shore, it would be easy to make the incorrect assumption that it was carrying water from far out at sea towards the land (Figure 15.2.1). Water waves, together with sound waves, seismic waves and waves on a string are termed **mechanical waves**, and all require a **medium** to travel through. They

mechanical wave a wave that requires a physical substance to be able to propagate

medium a substance that allows the transfer of energy from one place to another

KC Hunter/Alamy Stock Photo

FIGURE 15.2.1 Ocean waves may appear to bring water from out at sea, but this is not so.

do not transport the whole medium from place to place but, rather, the particles of the medium oscillate around their rest position (Figure 15.2.2).

Mechanical waves travel in a material medium made of interconnected particles that are progressively disturbed. Energy, but not particles, is transferred through the medium.

We can describe a wave using the ideas of wavefronts and rays. A **wavefront** is a surface joining all points in space that are reached at the same instant by a wave propagating through a medium. A **ray** is a line drawn at right angles to the wavefront in the direction of propagation. This description is called the **ray model** (Figure 15.2.3).

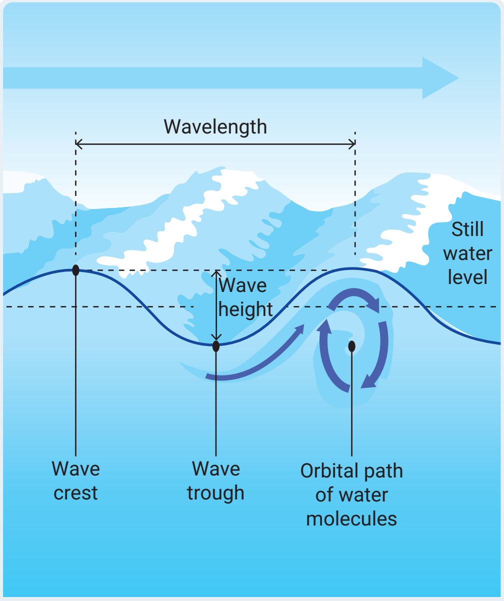

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FIGURE 15.2.2 Ocean waves are caused by the movement of water particles below the surface of the wave. The particles stay in orbits and do not travel forwards with the wave.

wavefront an imaginary surface joining all points in space that are reached at the same instant by a wave propagating through a medium

ray a line drawn at right angles to a wavefront and in the direction of travel

ray model a model that describes light as travelling in rays that change direction during interactions with matter

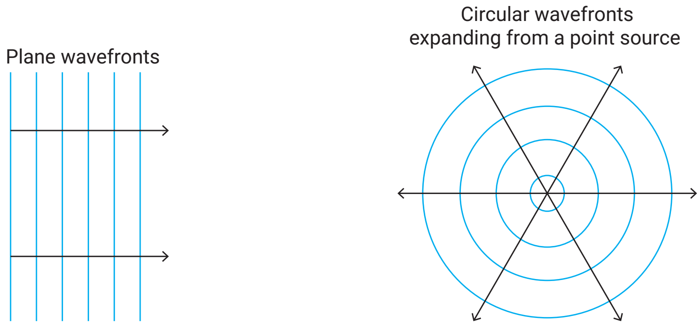


FIGURE 15.2.3 Wavefront models of waves. In the ray model, the arrows represent the direction of propagation of the wavefronts.

LEARNING CHECK 15.2

DESCRIBING

1 **Describe** 'mechanical wave'.

2 **Describe** 'wavefront'.

3 **Recall** the importance of a medium to the propagation of mechanical waves.

4 **Describe** the motion of a medium as a mechanical wave passes through it.

5 **Classify** the ocean waves shown in Figure 15.2.1 as plane wavefronts or circular wavefronts and explain your answer.

15.3 Wave types

Pulses

pulse a single wavefront travelling through a medium

Figure 15.1.1 shows that a stone that drops into a body of water creates surface disturbances that radiate from the point where the stone broke the water. The leading edge of the entire wave forms a circle that is the wavefront. If only a single wavefront passes through a medium, it is called a **pulse**.

A single pulse on a rope can be created by quickly moving your hand up and down (Figure 15.3.1). When the hand pulls up on the end of the rope, the section of the rope that is immediately next to the end section feels a force and begins to move up as well. This continues for each adjacent section as the wave pulse moves along the rope. When the hand moves back down to the original position, the section next to the hand experiences a force back down and begins to move downwards, and so forth. The original source of the wave was therefore a disturbance and the forces holding the rope together cause the pulse to travel.

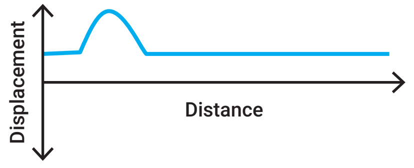


FIGURE 15.3.1 A representation of a wave pulse in a stretched string or spring

Continuous waves

continuous wave repeating waves passing through a medium

If stones are dropped in water in a regular pattern, wavefronts are produced continuously. A **continuous wave** moves outwards at a constant speed in all directions. The source of such waves must be a disturbance that is continuous and oscillating, in other words, a vibration. As can be seen in Figure 15.3.2, a hand oscillates one end of a rope up and down repeatedly and results in a continuous wave travelling to the right along the rope.

Weblink
Simulation of waves on a string

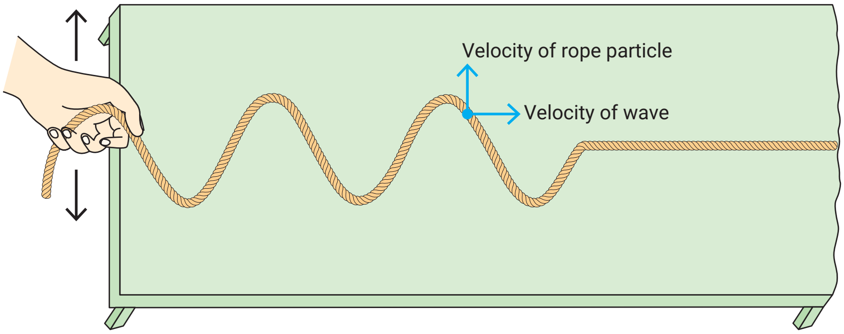


FIGURE 15.3.2 Representation of a continuous wave on a rope arising from a vibrating disturbance

Transverse waves

transverse wave a wave whose particles oscillate about a mean position perpendicular to the direction of travel by the wave

If the end of a stretched slinky spring is moved up and down relative to the length of the slinky, a wave will move down its length. The particles of the slinky vibrate up and down in a direction that is transverse (at right angles) to the motion of the wave. This type of wave is called a **transverse wave** (Figure 15.3.3).

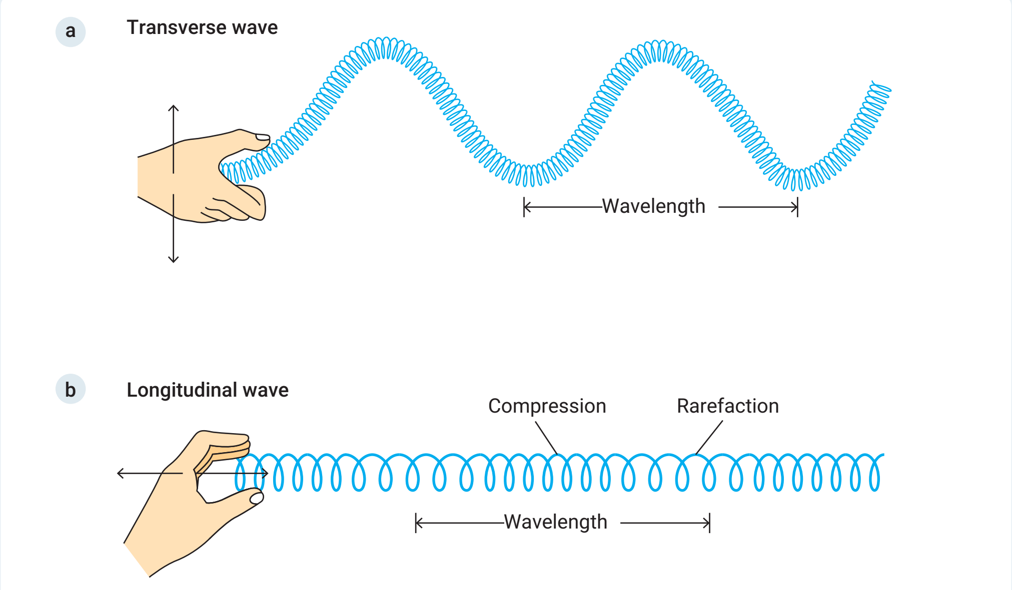


FIGURE 15.3.3 (**a**) In a transverse wave, particles oscillate about a mean position perpendicular to the direction of travel by the wave. (**b**) In a longitudinal wave, particles oscillate around a mean position in the same line as the direction of travel of the wave.

In a transverse wave, individual particles of the medium move up and down about their rest position. A series of wave **crests** and wave **troughs** moves through the medium. A graph of the position of particles along the medium at one particular time looks like a sine graph (Figure 15.3.4).

crest the positive peak of a wave; unit: m

trough the negative peak of a wave; unit: m

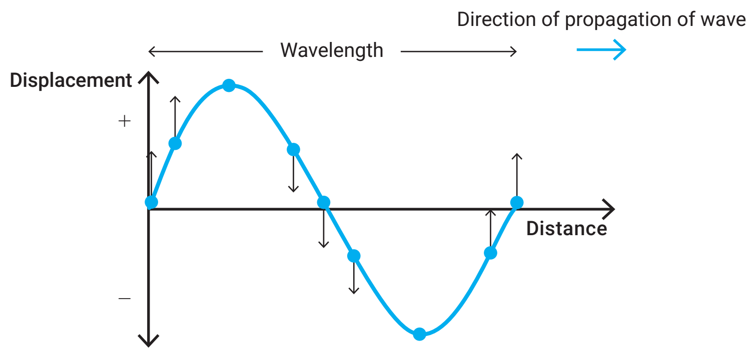


FIGURE 15.3.4 A displacement–distance graph of a transverse mechanical wave showing the position of the particles at an instant in time

Weblink
Transverse and longitudinal waves

At a crest or a trough, particles are stationary and about to move towards the mean position. Particles on either side of the crest or trough are moving away from or towards the mean position.

Longitudinal waves

Longitudinal waves can be created by quickly pushing and pulling on the end of a stretched slinky. In a longitudinal wave the motion of the particles of the medium is along the line of the direction of travel by the wave. In this type of wave, there is a series of **compressions** and **rarefactions**, as shown in Figure 15.3.3b.

longitudinal wave a wave whose particles oscillate about a mean position in the same line as the direction of travel of the wave

compression a region of high pressure in a mechanical wave

rarefaction a region of low pressure in a mechanical wave

Particles move back and forth in the same line as the direction of the transfer of energy. The further away from the mean position a particle moves before returning, the greater the amplitude of the disturbance.

When the particles around a point are all moving towards the point, there is a local compression. If they are all moving away from the point, there is a local rarefaction. A particular point in the medium through which the wave disturbance is travelling experiences a series of compressions and rarefactions (changes to the undisturbed pressure) as the energy passes through it. **Figure 15.3.5** shows a snapshot at an instant in time of where the particles along the top have been displaced to as a sound wave in air passes.

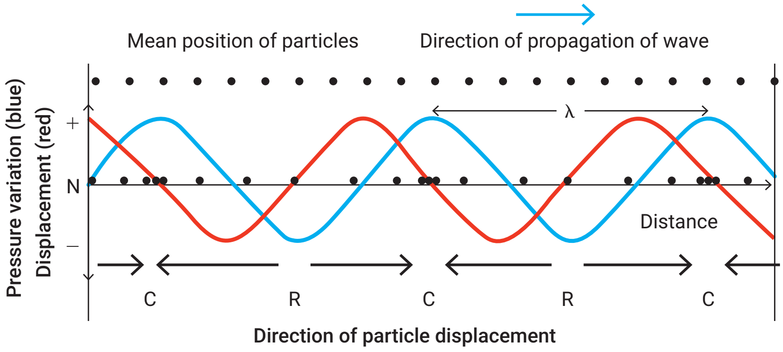


FIGURE 15.3.5 Longitudinal wave showing rarefactions (R) and compressions (C) in a medium at the same time

Figure 15.3.5 also shows how the air pressure varies. Maximum pressure occurs when the particles are most constrained (blue), hence displaced little. The pressure is lowest when the displacement of particles from their mean positions (red) is greatest.

LEARNING CHECK 15.3

DESCRIBING

1 **Describe**:
   - **a** pulse
   - **b** continuous wave
   - **c** compression
   - **d** rarefaction.

2 **Compare** the motion of a particle in a medium that is transmitting a transverse wave with that of a medium transmitting a longitudinal wave.

3 **Compare** the nature of a disturbance that will form a pulse on a string with that which will form a continuous wave.

15.4 Examples of waves

Transverse waves occur when the particles of the medium through which a wave is travelling oscillate about a mean position in a direction that is perpendicular to the direction of the wave itself. There are many examples of this in nature, including vibrations on stringed instruments, surface waves on water (or at least, they can be modelled like this) and seismic (earthquake) S waves.

Longitudinal waves are caused by the transfer of energy in the form of compressions and rarefactions through a medium in line with the direction of wave travel. Examples of longitudinal waves include sound waves and seismic P waves.

Vibrations on stringed instruments

Whenever the strings of a musical instrument are plucked (guitar and harp), bowed (violin, cello or double bass) or struck (piano), the initial disturbance results in a portion of the string being displaced in a direction that is transverse to the string itself.

The particles in this position of initial displacement will cause their adjacent particles to feel a force and will displace them as well. These will then cause the displacement of their adjacent particles and so on. In this way, a wave will travel along the string.

Zoulou_55/Shutterstock.com

FIGURE 15.4.1 Transverse waves travelling on a guitar string can be seen to be oscillating in a direction perpendicular to the string itself.

Surface waves on water

As previously mentioned, waves travelling on the ocean do not transport large volumes of water towards the shore. Instead, as can be seen in Figure 15.2.2 (page 421), the water particles essentially oscillate in a direction that is perpendicular to the direction of travel of the wave. In actual fact, they move in circles below the surface, but are still considered to move as transverse waves.

Sound waves

In a sound wave, particle oscillations are always parallel to the direction of energy flow; therefore, sound waves are longitudinal waves. When sound travels through a medium, the particles form a series of compressions and rarefactions **(Figure 15.4.2a)**. At compressions, the pressure of the medium is higher than the normal pressure. At rarefactions, the pressure is lower than normal. This can be seen in a graph of pressure variation against the distance from the source **(Figure 15.4.2b)**.

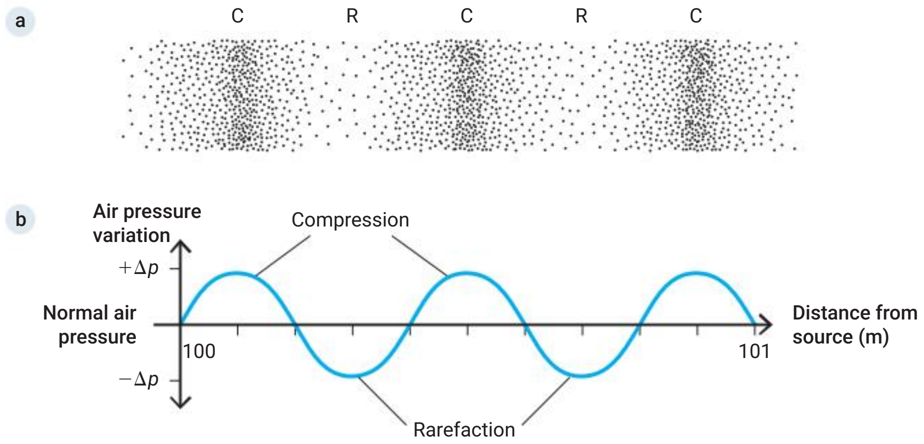


FIGURE 15.4.2 (**a**) When sound travels through a medium, the particles form a series of compressions and rarefactions. (**b**) The graph shows pressure variation with distance.

When a sound wave strikes the ear (**Figure 15.4.3**), the pressure changes between the compressions and rarefactions cause the ear drum to move in and out. This motion is then transferred to the three bones of the middle ear and on to the fluid of the cochlea in the inner ear. The movement of this fluid causes small hairs on the surface of the cochlear to vibrate, which ultimately creates the nerve pulses that our brain recognises as sound.

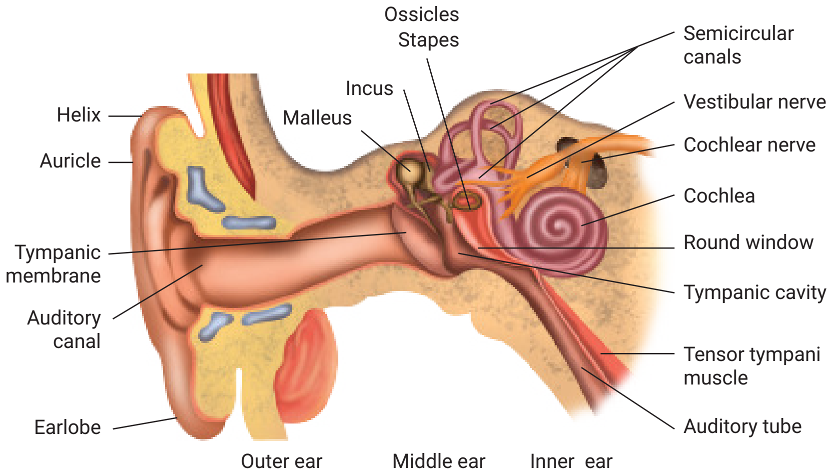


FIGURE 15.4.3 The anatomy of the ear. Vibrations are passed on from air entering the ear canal, through the middle ear and into the inner ear. From here, nerve pulses are passed on to the brain.

Seismic waves

The outer layer of Earth is made up of tectonic plates. Earthquakes happen as these plates catch when slipping past one another. The pressure builds up at the catch points as the plates continue to press on each other. When the pressure gets too great, the rock gives way and the plates suddenly slip past each other with a jolt. The stored energy is released abruptly. Vibrations travel as shockwaves (seismic waves) through Earth's interior.

These seismic waves radiate in all directions from the point underground where the energy was released. This point is known as the **seismic focus**. Directly above this is the earthquake's **epicentre** – the point on Earth's surface where the earthquake will be experienced most strongly. If this is in an inhabited area, it is the point at which the most damage is done.

Waves that propagate within the ground are called **body waves.** There are two types of body waves: the primary or **P waves** and the secondary or **S waves** (**Figure 15.4.4**). Primary (P) waves are longitudinal compression waves (sound waves). Secondary (S) waves

seismic focus the underground point from which earthquake energy is released

epicentre the point on Earth's surface directly above the seismic focus

body wave a seismic wave that travels through the body of Earth

P wave (or primary) a longitudinal earthquake compression wave that passes through the body of Earth

S (or secondary) wave a transverse earthquake waves that shakes Earth in directions which are perpendicular to the direction that the wave is travelling; also known as shear waves

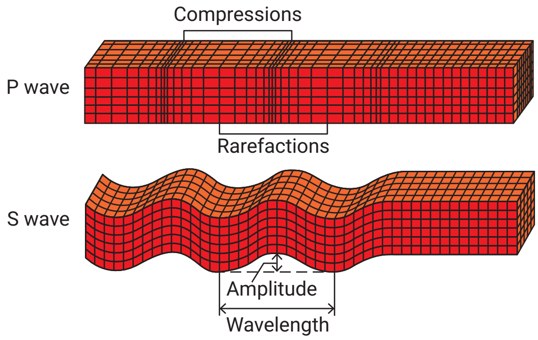


FIGURE 15.4.4 Propagation of longitudinal primary (P) and transverse secondary (S) shear waves

are transverse waves; they are also called shear waves. Their velocities vary with the density of the rock they pass through. The density of rock increases with depth due to the pressure of the rock above. This means the speed of the waves increases with depth. Different rock composition also affects the speed of the waves. This density gradient refracts the waves back up to the surface in a curved concave path, where they can be recorded on a **seismograph**.

seismograph a device that records the amplitude and frequency of seismic waves and yields information about Earth and its subsurface structure

LEARNING CHECK 15.4

DESCRIBING

1 **Classify** each of the following waves as transverse or longitudinal.
  a Sound waves
  b Seismic S waves
  c Seismic P waves
  d Waves on a stringed instrument
  e Surface water waves

2 **Describe:**
  a compression
  b rarefaction.

3 Outline how waves are produced in a stringed instrument.

4 Outline how surface water waves are produced.

5 Outline the way in which sound is transported from the air into the ear so that it is received as the sensation of sound.

6 **Compare** the properties of seismic S and P waves. What causes their formation?

ANALYSING

7 **Analyse** the structure of the ear presented in Figure 15.4.3 (page 422) to suggest some common causes of deafness.

8 **Analyse** the behaviour of waves in different types of rock to suggest a way in which a seismograph may be used to examine the inner composition of Earth.

15.5 Wave features

The behaviour of mechanical waves can be graphed on either a **displacement** versus time graph or on a displacement versus distance graph. Both graphs will give a **sinusoidal pattern**; however, each graph shows different features of the wave and gives slightly different information about the wave.

displacement the straight-line distance between the current position of a particle in a wave and its mean position

sinusoidal pattern a pattern that is similar in shape to that of a sine wave

Displacement versus time graph

A displacement–time graph (Figure 15.5.1) shows the displacement from the mean position of a single particle in the medium as it changes over time. It is very useful for finding the amplitude and period of a wave and can be extended to find the frequency.

Worksheet
Graphing a
wave in Excel

period (T) the time it takes before a wave repeats itself; units: s

frequency (f) the number of whole waves of cycles in one second; unit: Hz or s^{-1}

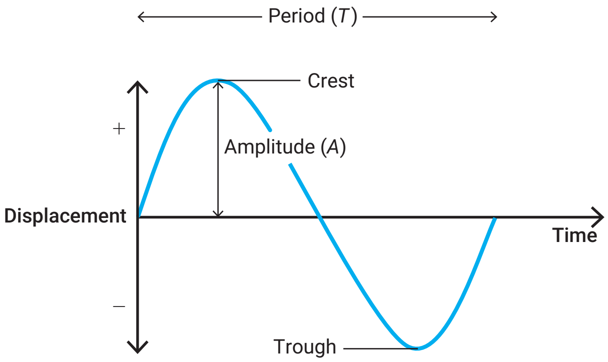


FIGURE 15.5.1 A displacement–time graph of a mechanical wave represents the displacement of one particle of the medium experiencing a wave disturbance over time. It also shows the amplitude of the wave.

KEY FORMULA

The frequency of a wave

$$f = \frac{1}{T}$$

where: f = frequency (Hz or s^{-1})
T = period (s)

The **period (T)** of a wave is the time it takes before a wave repeats itself and amplitude (A) is the largest distance of the particle from the mean position before returning. The top of the wave is called a crest and the bottom a trough.

The **frequency (f)** of a wave is the number of crests generated in a time interval. The unit of frequency is the hertz, Hz. As one period is the time it takes to complete one full wave, the inverse of the period is the number of full waves per second, the frequency.

$$f = \frac{1}{T}$$

where: f = frequency (Hz or s^{-1})
T = period (s)

WORKED EXAMPLE 15.5.1

It is observed that once the crest of one ocean wave passes a point, it takes 3.0 s for the next crest to arrive at the same point. Calculate the frequency (in Hz) of the waves.

ANSWER

1 **State the equation.**

$$f = \frac{1}{T}$$

2 **Substitute known values.**

$$f = \frac{1}{3\text{ s}}$$

3 **Calculate the answer.**

$f = 0.3333\ s^{-1}$

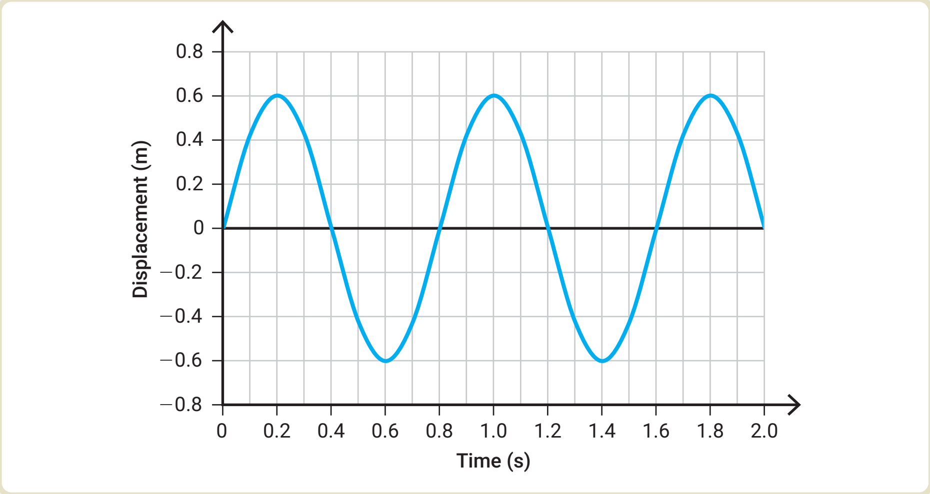
4 **Give the answer with the correct units and number of significant figures.**

$f = 0.33$ Hz

WORKED EXAMPLE 15.5.2

Analyse the wave features in the graph below and calculate the wave's:

a amplitude
b period
c frequency.



ANSWERS

a 1 **Determine the relationship between amplitude and information presented by the graph.**

The amplitude is the maximum displacement of the crest.

2 **Calculate the answer.**

$A = 0.6\text{ m} - 0.6\text{ m}$

b 1 **Determine the relationship between period and the information presented by the graph.**

The period is the time for one full wave to be completed.

2 **Use the graph to determine the answer.**

$T = 0.8\text{ s}$

c 1 **State the equation.**

$$f = \frac{1}{T}$$

2 **Substitute known values.**

$$f = \frac{1}{0.8\text{ s}}$$

3 **Calculate the answer.**

$f = 1.25\text{ Hz}$

Displacement versus distance graph

A displacement–distance graph shows the displacement of particles at different distances along the medium at a single instant in time. It can be very useful to calculate the amplitude, the wavelength and, together with the frequency, the wave velocity.

KEY FORMULA

$$v = \frac{\lambda}{T} = f\lambda$$

where: v = wave velocity (m s^{-1})
λ = wavelength (m)
T = period (s)
f = frequency (Hz)

wavelength (λ) the distance travelled by a wave before it repeats itself; units: m

wave velocity (v) the velocity at which a wave crest moves through a medium

The **wavelength (λ)** is the distance that one wave covers before it repeats itself.

The **wave velocity (*v*)** is the speed at which the crests of the wave travel through the medium. Wave velocity must be differentiated from the velocity of the particles in the medium itself.

The wave velocity can be calculated from the wavelength and the period or the wavelength and the frequency, as shown in Worked example 15.5.3.

$$v = \frac{\lambda}{T} = f\lambda$$

where: v = wave velocity (m s^{-1})
λ = wavelength (m)
T = period (s)
f = frequency (Hz)

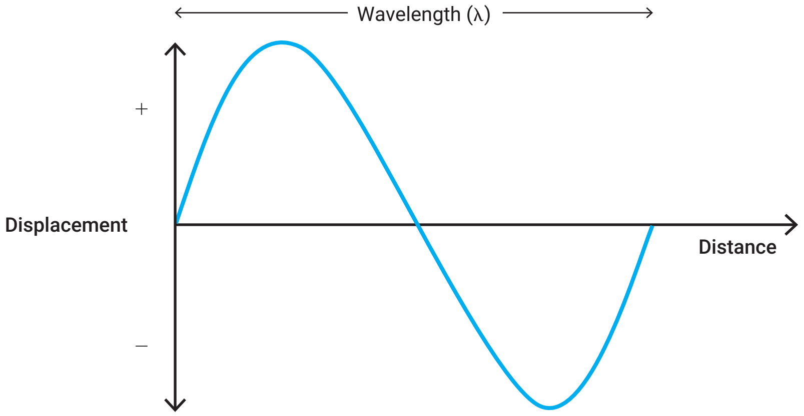


FIGURE 15.5.2 The displacement–distance graph of a mechanical wave shows the displacement of all the particles of the medium experiencing a wave disturbance at an instant in time.

WORKED EXAMPLE 15.5.3

A wave on a string is measured as having a wavelength of 2.6 cm and a period of 0.30 s. Calculate the wave velocity.

ANSWER

1 **State the equation.**

$$v = \frac{\lambda}{T}$$

2 **Substitute known values.**

$$v = \frac{0.026\ \text{m}}{0.30\ \text{s}}$$

3 **Calculate the answer.**

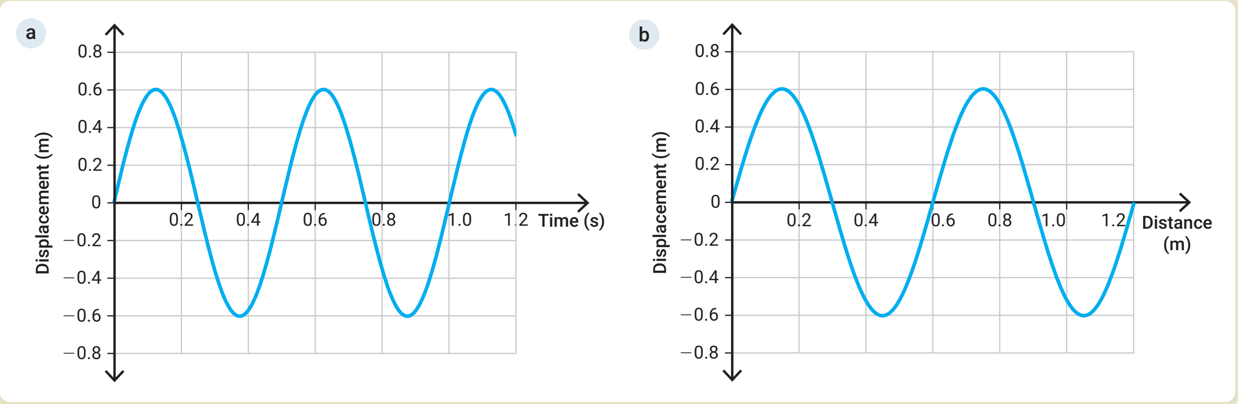
$v = 0.0866$ m s^{-1}

4 **Give the answer to the correct number of significant figures.**

$v = 8.7 \times 10^{-2}$ m s^{-1}

WORKED EXAMPLE 15.5.4

Analyse the following graphs and calculate the velocity of the wave.



ANSWER

1 Use the graphs to determine the period and wavelength.

From graph **a**: $T = 0.5$ s

From graph **b**: $\lambda = 0.6$ m

2 State the equation.

Use the wave velocity equation:

$$v = \frac{\lambda}{T}$$

3 Substitute the known values.

$$v = \frac{0.6\ \text{m}}{0.5\ \text{s}}$$

4 Give the answer to the correct number of significant figures.

$v = 1.2\ \text{m s}^{-1}$

WORKED EXAMPLE 15.5.5

A wave travels with a velocity of 340 m s^{-1} and has a frequency of 1000 Hz. Calculate its wavelength.

ANSWER

1 State the equation.

$v = f \times \lambda$

2 Rearrange to find the unknown.

$$\lambda = \frac{v}{f}$$

3 Substitute the known values.

$$\lambda = \frac{340\ \text{m s}^{-1}}{1000\ \text{Hz}}$$

4 Calculate the answer.

$\lambda = 0.34$ m

Therefore, the wavelength of the wave is $\lambda = 0.34$ m.

WORKED EXAMPLE 15.5.6

A wave travels with a velocity of 300 m s^{-1} and has a wavelength of 0.5 m. Calculate the frequency of the wave.

ANSWER

1 **State the equation.**

$v = f \times \lambda$

2 **Rearrange to find the unknown.**

$f = \frac{v}{\lambda}$

3 **Substitute known values.**

$f = \frac{300 \text{ m s}^{-1}}{0.5 \text{ m}}$

4 **Calculate the answer.**

$f = 600$ Hz

Therefore, the frequency of the wave is $f = 600$ Hz.

WORKED EXAMPLE 15.5.7

A wave travels with a velocity of 120 m s^{-1} and has a wavelength of 2.5 m. Calculate the:

a frequency of the wave

b period of the wave.

ANSWERS

Identify the variables

- Velocity $v = 120$ m s^{-1}
- Wavelength $\lambda = 2.5$ m

a 1 **State the equation.**

$v = f \times \lambda$

2 **Rearrange to find the unknown.**

$f = \frac{v}{\lambda}$

3 **Substitute known values.**

$f = \frac{120 \text{ m s}^{-1}}{2.5 \text{ m}}$

4 **Calculate the answer.**

$f = 48$ Hz

Therefore, the frequency of the wave is $f = 48$ Hz.

b 1 **State the equation.**

$f = \frac{1}{T}$

2 **Rearrange to find the unknown.**

$T = \frac{1}{f}$

3 Substitute the known values.

$$T = \frac{1}{48}$$

4 Calculate the answer.

$$T = 0.0208 \text{ s}$$

Therefore, the time period of the wave is $T = 0.0208$ s.

Wave velocity in different media

Wave speed depends on the material and its state – solid, liquid or gas. Speed differences between materials in the same state are affected most by density. The greater the density of the gas, the more sluggish the interactions between the neighbouring particles will be. This results in the wave travelling more slowly in denser gases. For example, a sound wave will travel nearly three times faster in helium than it will in air because helium is much less dense than air.

The speed of a sound wave in air depends on temperature and humidity. Temperature has the most effect because it affects density. Warm, dry air is less dense than cold air. Humidity is also important. Moist air is less dense than dry air because water vapour is less dense than both oxygen and nitrogen.

The speed of a wave travelling in a wire also depends on how much the wire is being stretched – the tension in the wire. The greater the tension, the greater the speed of the wave.

It is important to note that the speed of a wave depends on the properties of the medium through which the wave is travelling, not the frequency or wavelength of the wave.

TABLE 15.5.1 The speed of sound in different media at 25°C and 1 atmosphere pressure

State	Substance	Speed (m s^{-1})
Solid	Aluminium	6420
	Nickel	6040
	Steel	5960
	Iron	5950
	Brass	4700
	Glass (flint)	3980
Liquid	Water (sea)	1531
	Water (distilled)	1498
	Ethanol	1207
	Methanol	1103
Gas	Hydrogen	1284
	Helium	965
	Air	346
	Oxygen	316
	Sulfur dioxide	213

Worksheet
Wave characteristics

WORKED EXAMPLE 15.5.8

A wave has a frequency 10 Hz and a wavelength of 2.0 cm. How far will this wave travel in 1.5 minutes?

ANSWER

1 **State the equation.**

$$v = \frac{s}{t}$$

2 **Rearrange to find the unknown.**

$s = vt$ (1)

3 **State the second equation required.**

$v = \lambda f$ (2)

4 **Substitute equation (2) into equation (1).**

$s = \lambda ft$

5 **Substitute the known values.**

$s = 0.02\ \text{m} \times 10\ \text{Hz} \times 90\ \text{s}$

6 **Give the answer to the correct number of significant figures.**

$s = 18\ \text{m}$

TABLE 15.5.2 Wave terminology

Term	Definition	Symbol	Unit
Displacement	Distance between the position and the mean position of a particle	s	metre (m)
Amplitude	The largest distance away from the mean position that a particle moves before returning	A	metre (m)
Frequency	The number of crests generated in a time interval	f	hertz (Hz)
Wavelength	The distance between successive crests	l	metre (m)
Period	The time it takes before a wave repeats itself	T	second (s)
Wave velocity	The rate at which a wave covers distance	v	metres per second (m s^{-1})

LEARNING CHECK 15.5

DESCRIBING

1 **Describe** and **explain** the following terms.

- **a** Crest
- **b** Trough
- **c** Displacement
- **d** Amplitude
- **e** Period
- **f** Frequency
- **g** Wavelength
- **h** Wave velocity

2 Recall what information can be obtained directly from a displacement–time graph?

3 Recall what information can be found directly from a displacement–distance graph?

4 Identify what can affect the speed of a wave.

5 **Compare** the terms ‘displacement’ and ‘distance’ as they are used in this section.

APPLYING

6 If a wave has a frequency of 23 Hz, calculate its period.

7 A slinky spring is oscillated at a rate of one pulse every 0.50 s, and it is found that the distance between crests is 0.60 m.

- **a** **Calculate** the wave velocity.
- **b** **Calculate** the frequency.
- **c** Draw a displacement vs time graph of the wave.
- **d** Draw a displacement vs distance graph for the wave.

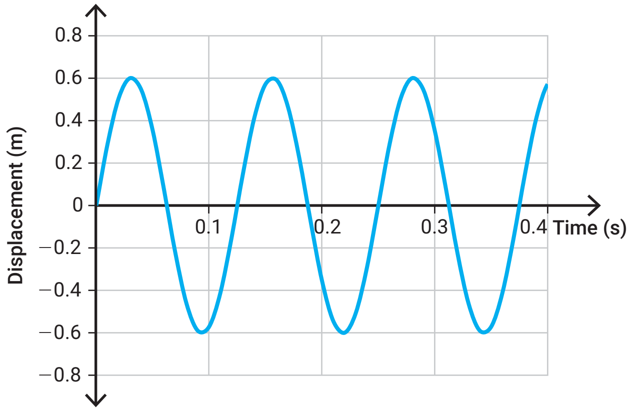
8 A tsunami travels at 800 km h^{-1} across the ocean. It has a wavelength of 150 km. **Calculate** the time interval between wave crests.

ANALYSING

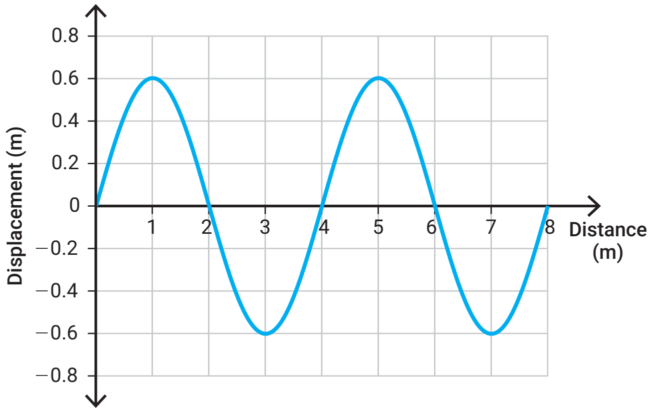
9 **Analyse** the following graphs to calculate the:

- **a** amplitude
- **b** period
- **c** frequency
- **d** wavelength
- **e** wave velocity.

i



ii



The wave velocity equation $v = \frac{\lambda}{T}$ is a reworking of the constant velocity formula of classical mechanics, $v = \frac{s}{t}$, with the wavelength taking the place of the displacement and the period taking the place of the time. Both equations can be used to calculate the wave velocity.

15.6 Reflection

Waves can interact with surfaces, edges and interfaces between different materials. These interactions include reflection, refraction and diffraction. When a wave strikes a surface or a boundary between two media, a part of the wave will always be reflected. Evidence of this can readily be seen in echoes, which are reflections of sound waves, and the reflection of waves off the seashore.

Worksheet
Reflection of waves

Reflection of transverse waves at a surface

When a wave pulse travels down a rope that is fixed at one end, a crest of a transverse wave is reflected as a trough **(Figure 15.6.1a)**. When the rope is free at one end, a crest of a transverse wave is reflected as a crest (Figure 15.6.1a).

If a wave pulse travelling on a light string meets the boundary with a heavy string, part of the pulse is reflected and part is transmitted, as shown in **Figure 15.6.2**.

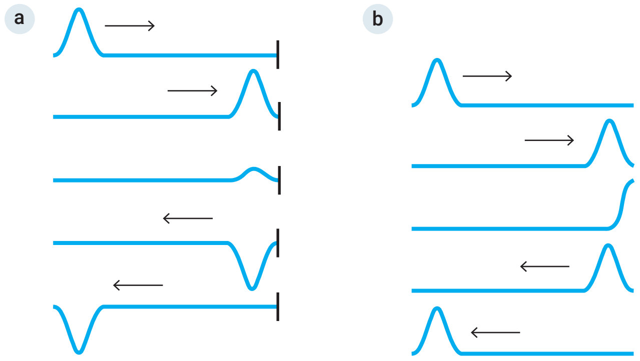


FIGURE 15.6.1 (**a**) A stretched string fixed at one end reflects waves (fixed-end reflection) upside down (out of phase). The wavelength and frequency are unchanged. (**b**) A stretched string free at one end reflects waves (free-end reflection) the same way up (in phase). The wavelength and frequency are unchanged.

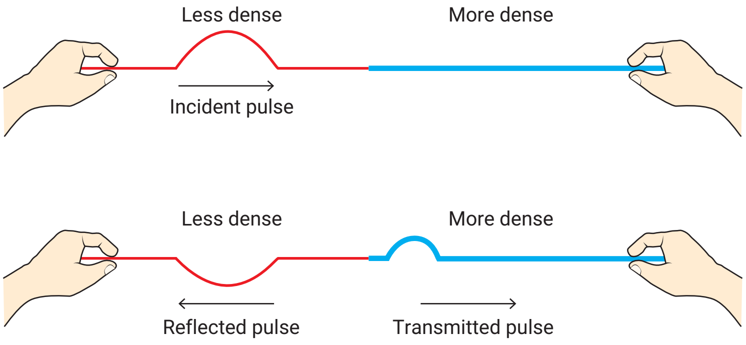


FIGURE 15.6.2 The transmission and reflection of a wave pulse at a boundary between two media of different densities. In this case, the wave travels from a less dense medium to a more dense medium. Note how the incident pulse is mostly reflected out of phase, with some energy transmitted in phase.

The part that is reflected returns in an inverted position as if it had struck a fixed boundary. The part that is transmitted into the heavier rope remains upright. The heavier the second material, the less energy is transmitted, and the more that is reflected.

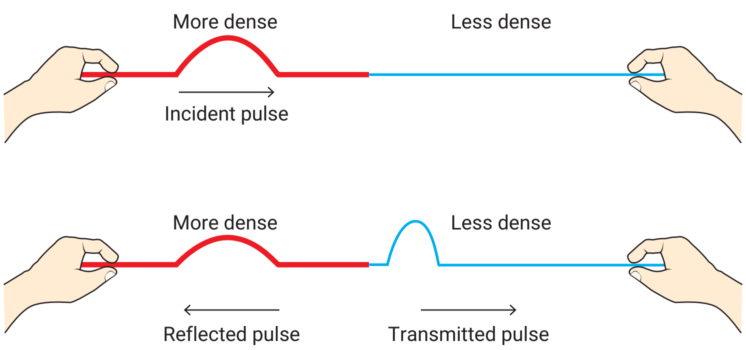


FIGURE 15.6.3 The transmission and reflection of a wave pulse at a boundary between two media of different densities. In this case, the wave travels from a more dense medium to a less dense medium. Note how the incident pulse is mostly transmitted in phase, with some energy reflected also in phase.

Reflection of two- or three-dimensional waves

When a two- or three-dimensional wave strikes a surface at an angle, the reflected wave bounces off the surface with an **angle of reflection** that is equal to the **angle of incidence**. This is known as the **law of reflection**.

$$i = r$$

where: i = angle of incidence (degrees)
r = angle of reflection (degrees)

The angle of incidence is defined as the angle that the **incident** (incoming) **wave** makes with a **normal** to the surface (i.e. a line perpendicular to the surface) at the point of contact with the surface. The angle of reflection is the angle between the same normal and the reflected wave. Figure 15.6.4 is a ray diagram of the law of reflection.

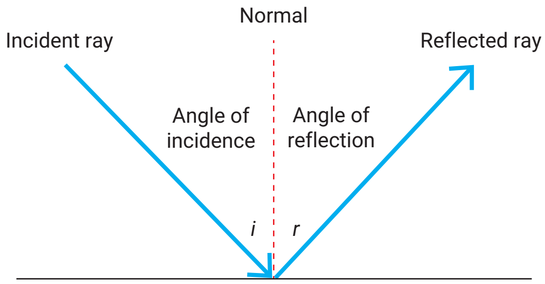


FIGURE 15.6.4 The law of reflection for waves states that the angle of incidence will equal the angle of reflection.

KEY LAW

Law of reflection

$$i = r$$

where: i = angle of incidence (degrees)
r = angle of reflection (degrees)

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

angle of incidence the angle made between an incident (incoming) wave and a normal drawn to the surface at the point of incidence

law of reflection when a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence

incident wave an incoming wave

normal a line drawn perpendicular to a surface

total internal reflection the transport and containment of a wave by coherently reflecting it back and forth often in a tube

Total internal reflection

Reflection of sound is used in stethoscopes and sonar depth sounders. In stethoscopes, sound waves reflect back and forth along the inner walls of a tube (Figure 15.6.5). This is known as **total internal reflection**.

iStock.com/Yobro10

FIGURE 15.6.5 Stethoscopes allow sound to travel to the ear by total internal reflection.

reverberation the effect that occurs when too many sound wave reflections arrive at your ear for you to distinguish between the sounds

decay the decrease in amplitude when the vibrating source of a wave is removed

Reverberation

When sound is produced in an enclosed space, a large number of echoes or **reverberations** build up and then slowly **decay** as the sound is absorbed by the walls and the air (Figure 15.6.6). When the sound source stops, the reflections continue, decreasing in amplitude, until they can no longer be heard. The longer the time of decay the greater the reverberation.

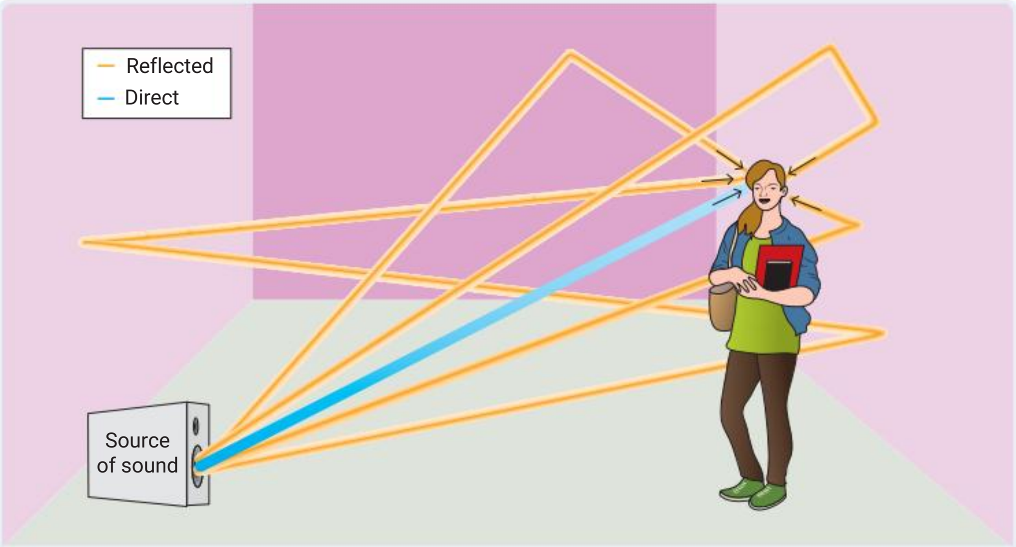


FIGURE 15.6.6 Multiple reflections and direct sound cause reverberation.

Echoes

If you clap your hands or make a loud sharp sound at a distance from a good sound-reflecting surface, you hear an echo. The human ear can distinguish sounds that are about one-fifteenth of a second apart. In air, the speed of sound is about 340 m s^{-1}, so the minimum distance the sound must travel for you to hear the echo is:

$$v = \frac{\text{distance}}{\text{time}}$$

$$\begin{aligned}\text{distance} &= v \times t \\ &= 340\,\text{m}\,\text{s}^{-1} \times 6.67 \times 10^{-2} \\ &= 22.7\,\text{m}\end{aligned}$$

The minimum distance between the clap (source) and the echo surface is:

$$\frac{22.7}{2} = 11.3\text{ m}$$

LEARNING CHECK 15.6

DESCRIBING

1 **Describe** and **explain** 'reflection' as it applies to waves.

2 **Describe** what happens to a pulse on a string with a fixed end when it is reflected.

3 **Describe** what happens to a pulse on a string with a free end when it is reflected.

4 **Describe** what happens to a pulse on a string when it meets a junction with a string of higher density.

5 State the law of reflection as it applies to a two-dimensional wave.

6 **Compare** the phenomena of reverberation and echo and explain the differences and similarities between them.

7 **Explain** why it is useful that waves can travel in a tube such as a stethoscope.

APPLYING

8 For total internal reflection to be a useful way to transport waves, as much energy as possible must be reflected back into the tube cavity and very little transferred to the tube walls. **Apply** your understanding of wave reflection at a boundary between two media to suggest how this might be achieved.

9 The audience at a concert hall or auditorium wishes to hear as clear a sound as possible, free from echoes and with as little reverberation as possible. Use your understanding of wave reflection to suggest how this might be achieved.

15.7 Refraction

The **refraction** of waves involves a change in the direction of the waves as they pass from one medium to another. Refraction, or the bending of the path of a wave, is accompanied by changes in the speed and wavelength of the wave. This is due to the new medium having a different elastic property and/or mass density, which affects the rate of transmission of the wave energy. If the medium (or its properties) is changed, the speed of the wave is changed. The frequency does not change; therefore, from the wave velocity equation, the wavelength must change.

If a wave meets the interface at right angles, it will not change direction, but its speed and wavelength will change. If it meets the interface at any other angle, its direction will also change, as shown in Figure 15.7.1a.

refraction the change in direction of a wave when it passes through a boundary between two media of different densities at an angle other than 90°; speed and wavelength also change, frequency remains constant

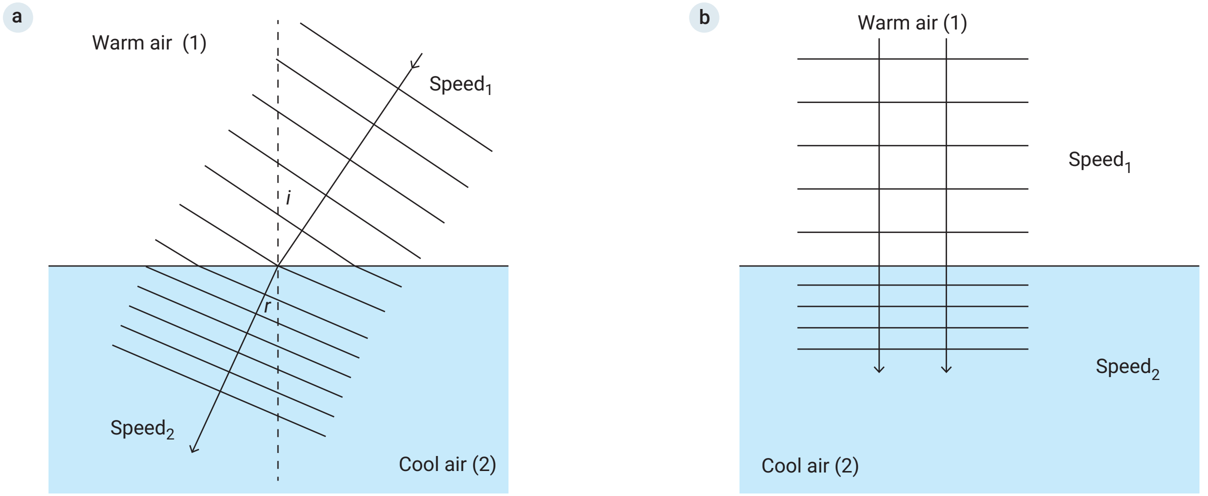


FIGURE 15.7.1 (a) A sound wave is refracted (changes direction) when it meets the boundary between two layers of different density at an angle other than a right angle. (b) At right angles, there is no change in direction, but speed and wavelength both change.

The apparent position of underwater objects

apparent position the position that an object appears to an observer, which may be different from its actual position due to the refraction of its light waves

Several optical illusions are caused by the refraction of light as it changes media, especially from water to air. As can be seen in Figure 15.7.2, the light rays travelling from the fish to the eye are refracted as they exit the water. As the human brain assumes that waves travel in straight lines, the observer believes the fish is at a position (its **apparent position**) which is higher than its actual position. People who spear fish from above the water's surface are aware of this phenomenon and know to aim lower than where the fish appears.

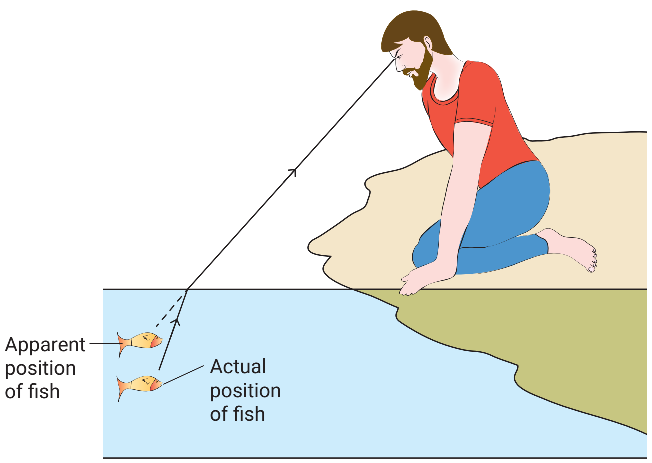


FIGURE 15.7.2 The apparent position of an underwater object is different from its actual position due to the refraction of light waves as they exit the water.

The setting sun

When the Sun gets close to the horizon, the different densities of the atmosphere cause refraction of the incoming light rays (Figure 15.7.3). This results in the Sun appearing higher in the sky than its actual position. When the lowest edge of the Sun appears to be just touching the horizon, the Sun has actually already set!

In addition, and as can also be seen in Figure 15.7.3, the incoming rays from the lower edge of the Sun are refracted to a greater degree than the rays from the upper edge. This causes the characteristic oval shape of the Sun at sunset. Because the Moon and stars all undergo the same phenomenon near the horizon, astronomical observations are always corrected for **atmospheric refraction**.

atmospheric refraction the refraction of light rays as they pass through Earth's atmosphere

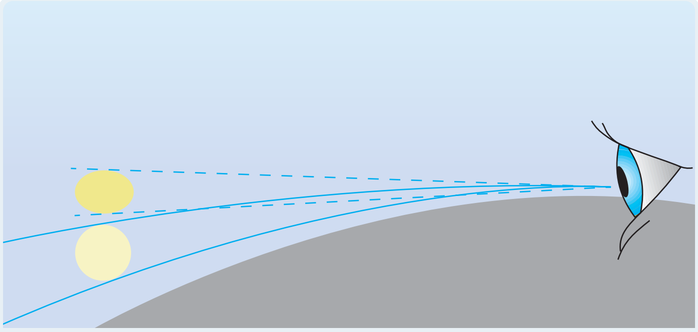


FIGURE 15.7.3 Incoming rays from the setting Sun (solid lines) are refracted by the atmosphere and make it appear higher in the sky.

LEARNING CHECK 15.7

DESCRIBING

1 **Describe** and **explain** 'refraction' as it applies to waves.
2 **Describe** and **explain** 'apparent position'.
3 **Describe** and **explain** 'atmospheric refraction'.
4 **Explain** under what circumstance refraction of waves will occur.
5 **Explain** what happens to the wavelength, frequency, period and velocity of a wave as it moves into a denser medium.

APPLYING

6 **Explain**, with the use of a diagram, why the legs of a person standing in water up to their waist appear shorter than they really are to a person outside of the water.

15.8 Diffraction

How is it that we can hear a sound even though its source is around a corner? Why is it that the sky is still light after the Sun has set below the horizon? Both of these phenomena and many others can be explained by the concept of **diffraction**, which explains that when waves encounter an obstacle or a gap in a boundary, they will bend around it and move into the region behind it to some degree.

diffraction the bending of waves around an obstacle

The amount of bending that occurs depends on the wavelength of the incident wave and the size of the obstacle it encounters (Figure 15.8.1). The amount of spread is greatest when the wavelength is greater than the width of the obstacle or gap.

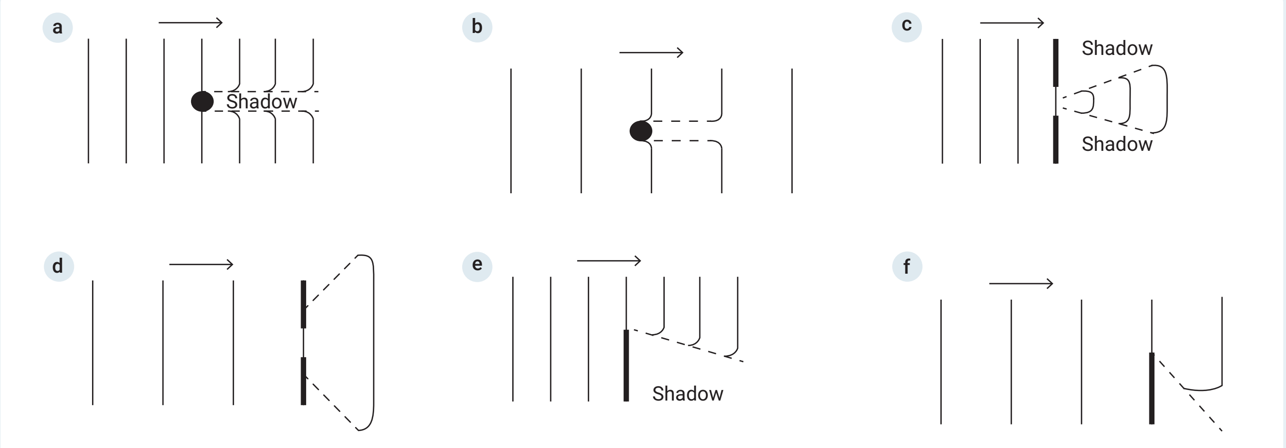


FIGURE 15.8.1 Diffraction of water waves: (**a**) short wavelength around an object, (**b**) long wavelength around an object, (**c**) short wavelength through a gap, (**d**) long wavelength through the same gap, (**e**) short wavelength around the edge of a barrier and (**f**) long wavelength around the edge of the same barrier

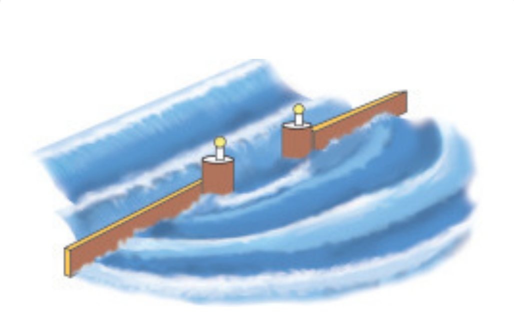


FIGURE 15.8.2 The diffraction of ocean waves at a gap in a harbour wall results in calmer waters.

Ocean waves at the entrance to a harbour

Diffraction is a very useful phenomenon when it comes to providing a safe harbour for boats. Many harbours and marinas are protected from the open ocean by an enclosing sea wall that contains a gap for the passage of boats.

The incoming waves diffract when they pass through the gap in the harbour wall and spread out as circular waves in the water of the harbour (Figure 15.8.2). In the process, the energy of the incoming section is dissipated into the whole of the circular wave and the amplitude decreased. This effect is increased by decreasing the size of the gap and ensures the calmness of the harbour regardless of conditions in the open ocean.

LEARNING CHECK 15.8

DESCRIBING

1 **Describe** 'diffraction' as it applies to the behaviour of waves.

2 **Explain** how the phenomenon of diffraction is used to create calm waters in a boat harbour.

3 **Compare** the properties of reflection, refraction and diffraction of waves.

4 Waves diffract around an obstacle. Suggest ways to increase the amount of diffraction.

APPLYING

5 Use the concept of diffraction of sound waves to **explain** why you would hear a loud whistle that is blown on the other side of a large tree trunk behind which you are hiding if the tree is in an open field.

15.9 The principle of superposition

If two waves of the same type (either longitudinal or transverse) are travelling through the same medium and are in the same place at the same time, **interference** or wave overlap occurs. Consider the two pulses shown in both images at the top of Figure 15.9.1 travelling towards each other. In each case, the pulses are of equal amplitude and velocity, but in Figure 15.9.1a, the pulses are **out of phase** (one is a crest and the other a trough) and in Figure 15.9.1b, the pulses are **in phase** (both are crests).

Even though in both cases shown in Figure 15.9.1 the pulses meet and pass through each other, in Figure 15.9.1a, the interference region has an amplitude of zero, whereas in Figure 15.9.1b, the interference region has an amplitude equal to twice the amplitude of a single pulse. This is the basis of the **principle of superposition**, which states that when two or more waves of the same nature travel past a point in a medium, the medium will undergo a resultant displacement at that point. The resultant displacement of the medium at that point is the sum of the individual particle displacements due to the waves at that point.

In Figure 15.9.1a, the waves are out of phase and therefore have opposite displacements at the instant they interfere with each other. Because of superposition, the resultant wave has a displacement of zero. This is called **destructive interference**. Conversely, in Figure 15.9.1b,

interference wave overlap

out of phase when the crests of a wave align with the troughs of another wave of equal wavelength

in phase when two waves of equal wavelength have their crests and troughs aligned

principle of superposition when two or more waves of the same nature travel past a point in a medium, the medium undergoes a resultant displacement at that point, which is the sum of the individual particle displacements due to the waves at that point

destructive interference the interference of out-of-phase waves resulting in a decreased displacement at the point of overlap the waves are in phase and, as such, the sum of the displacements makes a total greater than the displacement of either of the individual pulses. This is called **constructive interference**.

constructive interference the interference of in-phase waves resulting in an increased displacement at the point of overlap

Weblink
Superposition of waves

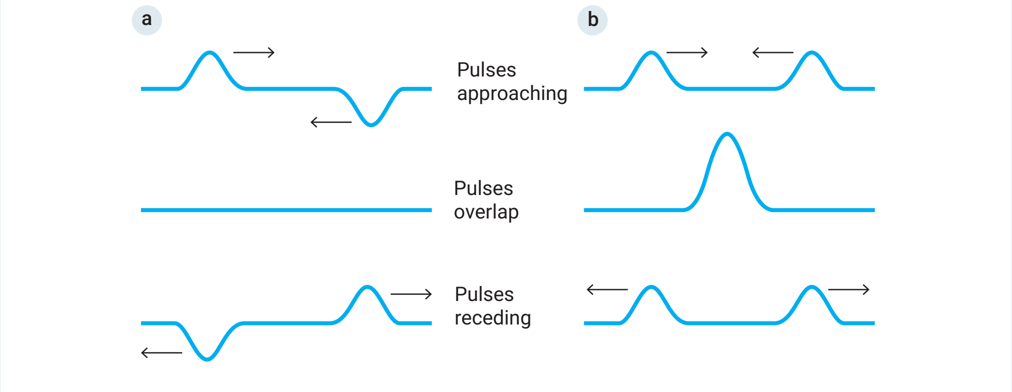


FIGURE 15.9.1 Two wave pulses approaching each other on a string. When they meet, they interfere (a) destructively or (b) constructively.

Superposition of waves

The superposition of waves refers to the combination of two or more waves overlapping in the same medium, resulting in a new wave pattern. When waves superpose, their displacements at any point in the medium add together vectorially.

Contributions of superposition

When waves with similar frequencies and are in phase (peaks align with peaks and troughs align with troughs) superpose, they reinforce each other, resulting in a wave with greater amplitude. This is referred to as constructive interference (Figure 15.9.2).

When waves with similar frequencies but are out of phase (peaks align with troughs) superpose, they partially or completely cancel each other out, resulting in a wave with reduced or zero amplitude. This is referred to as destructive interference (Figure 15.9.3).

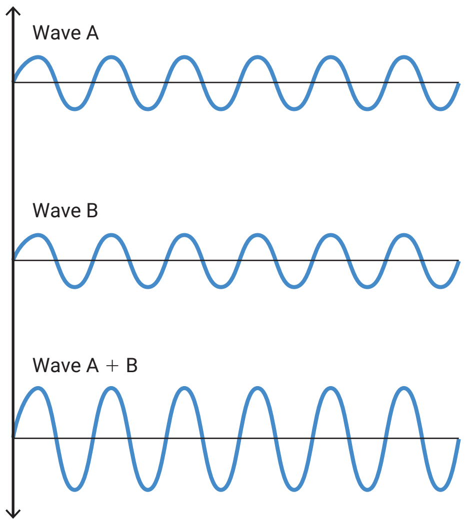


FIGURE 15.9.2 Constructive interference

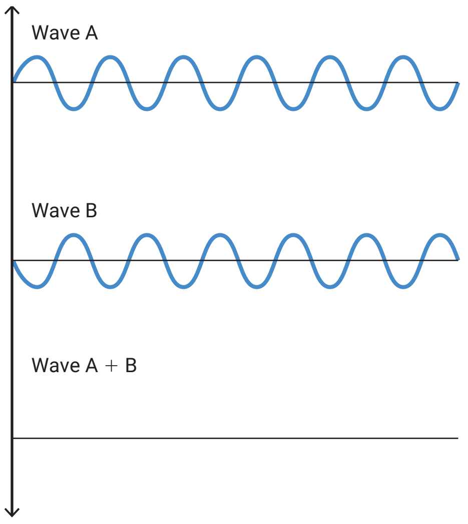


FIGURE 15.9.3 Destructive interference

Cancellation of superposition

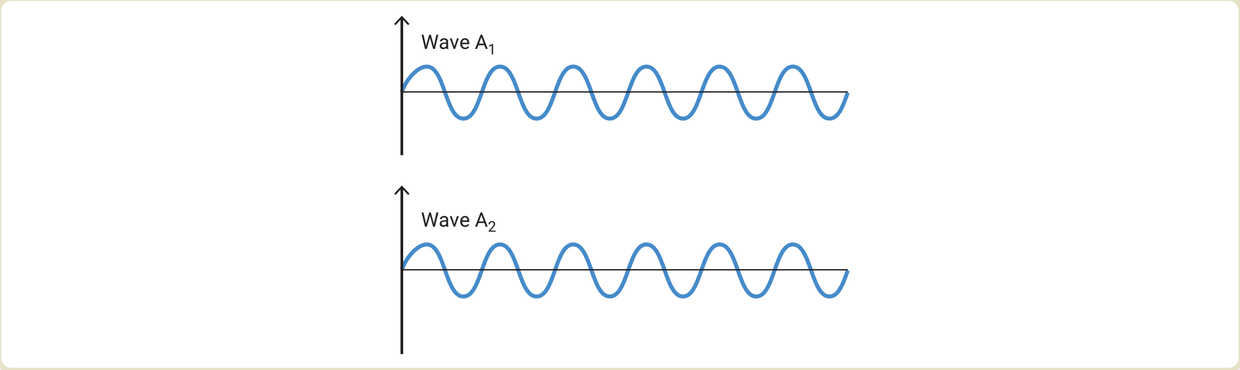
Complete cancellation occurs when the amplitudes of the interfering waves are equal, but they are out of phase by half a wavelength. This results in destructive interference, causing the waves to cancel each other out completely.

Partial cancellation occurs when the interfering waves have slightly different frequencies or are slightly out of phase. This results in reduced amplitude in the resultant wave, but not complete cancellation.

The superposition of waves leads to constructive or destructive interference, depending on the phase relationship between the waves. Constructive interference enhances the resultant wave's amplitude, whereas destructive interference can lead to partial or full cancellation of amplitude.

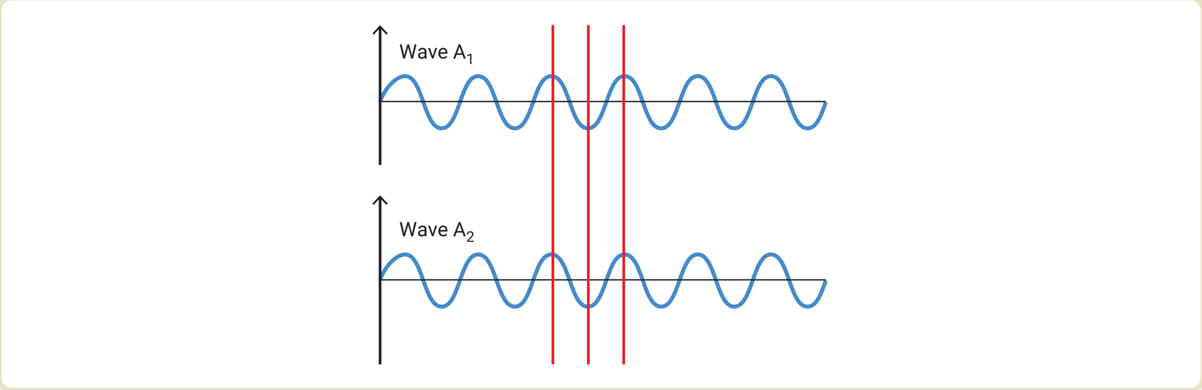
WORKED EXAMPLE 15.9.1

Two waves with equal amplitudes $A_1 = A_2$ and wavelengths $\lambda_1 = \lambda_2$ are superimposed. Determine the resultant wave form of the combined wave from this constructive interference.

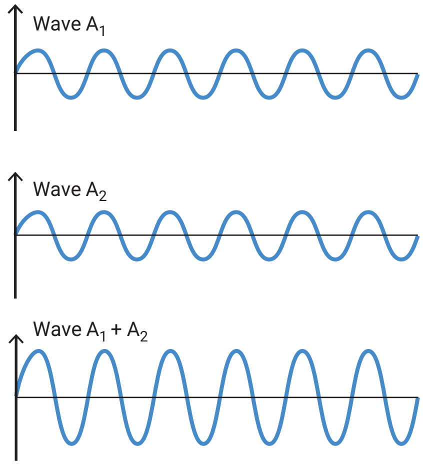


ANSWER

1 Select a range of key points to sum the amplitudes of A_1 and A_2.



2 Redraw the new combined wave form.

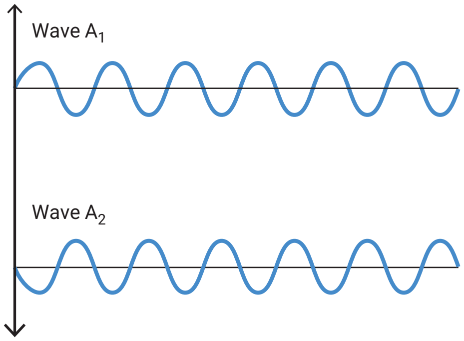


In this example, as $A_1 = A_2$, the total amplitude is twice the amplitude of each individual wave. Perfect constructive interference occurs when the crests of both waves coincide, resulting in maximum amplitude.

WORKED EXAMPLE 15.9.2

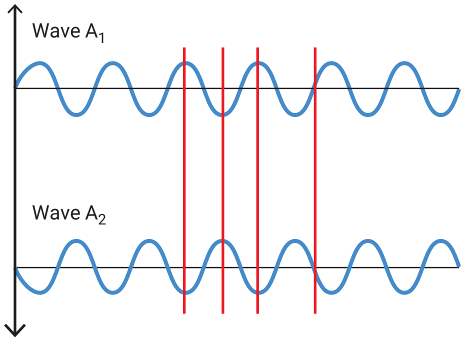
Destructive interference occurs when the crest of one wave coincides with the trough of another, resulting in cancellation. They may perfectly, or partially, cancel.

Two waves are precisely out of phase but with equal magnitude of amplitudes $A_1 = -A_2$ and the same wavelengths $\lambda_1 = \lambda_2$ are superimposed. Determine the resultant wave form of the combined wave from this destructive interference.

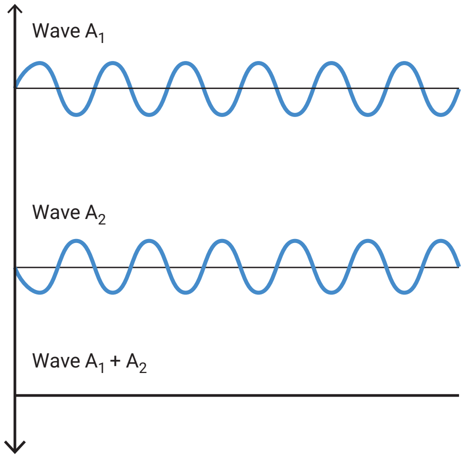


ANSWER

1 **Select a range of key points to sum the amplitudes of A_1 and $-A_2$. (Note how a positive amplitude may add to a negative amplitude, thereby cancelling.)**



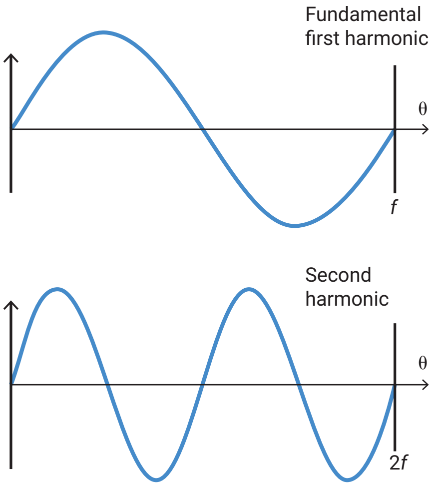
2 **Redraw the new combined wave form.**



In this example, as $A_1 = -A_2$, the total amplitude is zero. The amplitude of each individual wave cancels perfectly with the other. Perfect destructive interference occurs when the crest of one wave coincides with the trough of another wave, resulting in minimum amplitude.

WORKED EXAMPLE 15.9.3

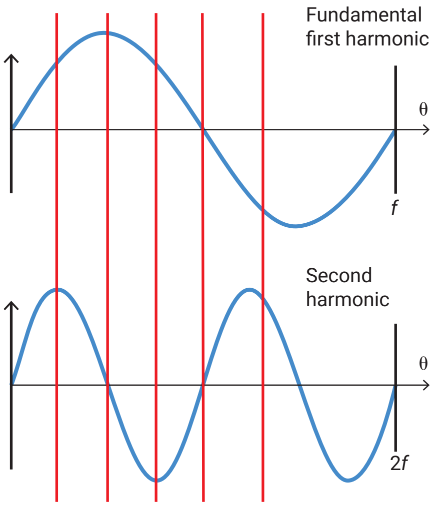
Two waves with different amplitudes and wavelengths are superimposed as shown. The waves represent the first and second harmonic of a sound wave. Determine the resultant wave form of the combined wave.



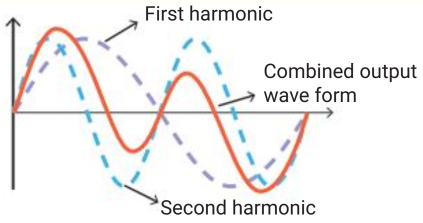
ANSWER

1 **Select a range of key points to sum the amplitudes of A_1 and A_2.**

For combined interference, calculate the resultant amplitude by adding the individual amplitudes where they constructively interfere and subtracting where they destructively interfere.



2 Redraw the new combined wave form.



Combining these two waves results in areas of constructive interference (both amplitudes are above the rest axis, or both below) and in areas of destructive interference (amplitudes are above and below the rest axis, leading to perfect or partial cancellation).

This example illustrates how the concepts of constructive and destructive interference in the superposition of waves combine to produce different outcomes based on their phase relationship.

The Doppler effect and the sonic boom

When a source of waves (e.g. a siren) is approaching a receiver, the pitch heard is greater than that emitted. This is because each wave is emitted a little closer to the observer than the previous wave. The reverse effect (i.e. a sound with lowered pitch) occurs when the source moves away from the receiver. This is known as the **Doppler effect** (Figure 15.9.4). It is the relative motion of source and receiver that changes the wavelength of the sound received relative to the sound emitted. The number of sound waves received per second, the frequency, depends on the relative speed of source and receiver.

Doppler effect the shift in the wavelength and frequency of waves that results from the relative motion of the source and the receiver

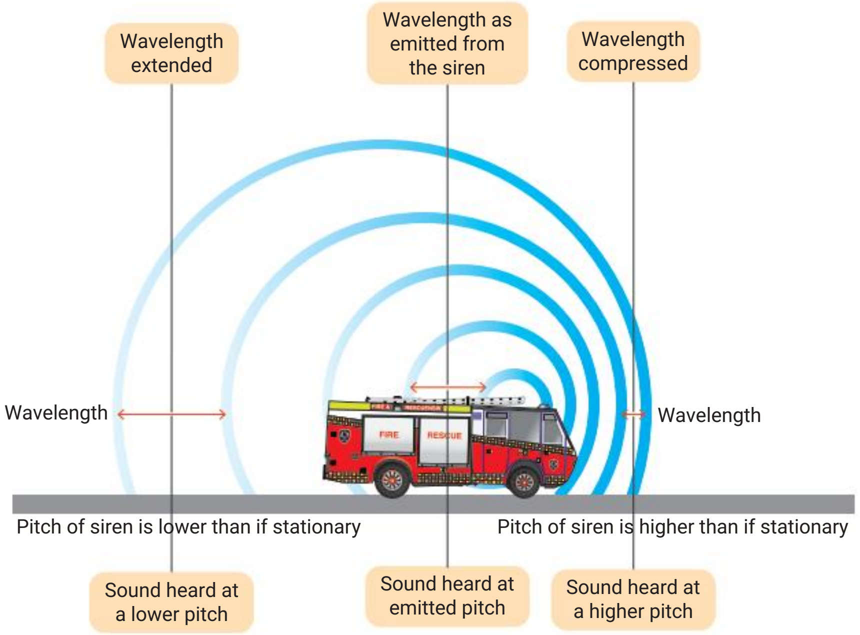


FIGURE 15.9.4 The Doppler effect for a fire engine siren. The wavelength of sound waves is compressed or extended because of the relative motion of the source and the receiver.

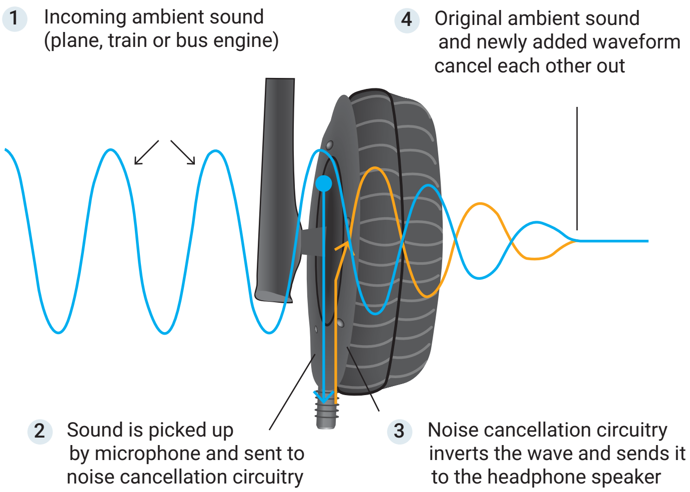
When a plane flies through the air, it creates a series of sound waves in front of it and behind it. The waves travel at the speed of sound. As the speed of the plane increases, the waves are forced closer together, and the principle of superposition applies. The sound waves merge into a single shockwave at the speed of sound. At 'supersonic' speeds, the plane begins pushing the air like a plough. This high-pressure shockwave sounds like a boom (hence, the name 'sonic boom'), and is continuous along what is called the boom carpet for the entire supersonic flight **(Figure 15.9.5)**. Low-pressure rarefactions cause rapid condensation, and hence clouds to form, around the plane.

US Navy Photo/Alamy Stock Photo

FIGURE 15.9.5 A jet fighter plane just breaking the sound barrier and forming a typical condensation cloud as the shockwave forms

Noise-cancelling earphones

A clever use of sound interference is to cancel noise. Headphones designed to cancel noise with destructive interference create a sound wave that is the exact opposite of the incoming sound. The headphones use a microphone to receive the sound waves and with real-time fast electronics produce a sound wave that is the exact reverse of the incoming signal. This new signal interferes with the original signal, as shown in **Figure 15.9.6**.



© BuzzyPedia.com

FIGURE 15.9.6 Noise-cancelling headphones work by creating a sound wave that is the exact opposite of the incoming sound.

LEARNING CHECK 15.9

DESCRIBING

1 **Describe:**
  - **a** interference
  - **b** constructive interference
  - **c** destructive interference.

2 **Recall** the conditions that are necessary for two wave pulses to be considered out of phase or in phase with each other.

3 **Explain** the principle of superposition.

4 **Explain** why the frequency of a fire engine siren increases when the fire engine begins moving towards you and decreases when it passes you.

APPLYING

5 Two wave pulses of equal frequency and wavelength are in phase as they travel towards each other on a rope.
Calculate the maximum amplitude of the wave that results when they meet. One wave has an amplitude of 6.0 cm and the other has an amplitude of 9.0 cm.

6 Two wave pulses of equal frequency and wavelength are out of phase as they travel towards each other on a rope.
Calculate the maximum amplitude of the wave that results when they meet. One wave has an amplitude of 6.0 cm and the other has an amplitude of 9.0 cm.

7 Using Figure 15.9.5 as a guide, illustrate the wavefronts for sound waves that are emanating from the front of a plane travelling at the speed of sound.

15.10 Standing waves

standing wave (stationary wave) a wave that oscillates in place, without transmitting energy along its extent; has stable points called nodes, where there is no oscillation

A **standing wave**, or **stationary wave**, is a wave that does not appear to be moving. If you shake waves onto a string that is fixed at the other end, the forward and reflected waves will interfere. Usually, the effect is messy. But if you get it just right, a fixed pattern of maximum and minimum displacement appears.

A standing wave (Figure 15.10.1) is created when two waves of the same frequency and amplitude but travelling in opposite directions exist in a medium.

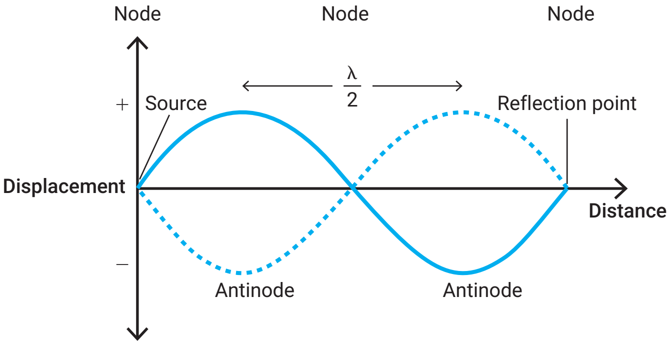


FIGURE 15.10.1 A standing wave in a stretched string fixed at both ends showing the nodes and antinodes. The solid line represents the string's displacement at an instant in time and the dotted line the string's displacement half a period $\left(\frac{T}{2}\right)$ later.

node a point along a standing wave at which the amplitude is zero; the result of a crest overlapping a trough

The **nodes** are points where destructive interference always occurs. At these points, at any moment in time, the amplitudes of the two waves are always the same magnitude but in opposite directions. Hence, when the crest of one wave passes through this point, a trough of the same size is also passing through. When the displacement due to one wave is half the amplitude, the displacement due to the other wave is also half the amplitude, but in the opposite direction, and so on. Whatever the displacement due to one wave, the displacement due to the other is the same size but the opposite direction. Superposition means that these two displacements add to give zero total displacement at any time at a node, hence a particle at a node does not move.

At the **antinodes**, the particles move up and down constantly and reach the maximum displacement possible. The maximum displacement occurs when two crests (or two troughs) meet at this point to give a displacement twice that of the amplitude of the individual waves. So, at an antinode the particles oscillate up and down between displacements of $^{-}2A$ and $2A$. The frequency with which they move up and down is the same as the wave frequency.

In between nodes and antinodes, the particles oscillate up and down with the same frequency, but with smaller amplitudes, to produce the pattern shown in Figure 15.10.1.

Standing wave patterns are always characterised by an alternating pattern of nodes and antinodes. The distance between nodes or between antinodes along the string or spring is half a wavelength, $\frac{\lambda}{2}$.

antinode a point along a standing wave at which the wave has maximum amplitude; the result of a crest overlapping a crest or a trough overlapping a trough

Musical instruments

Most acoustic instruments rely on the creation of standing waves to produce their unique tones. This may be vibrating strings, in the case of stringed instruments such as the guitar, harp or piano; moving air inside a column of air such as in a flute, saxophone or organ pipe; or a vibrating membrane or solid object as used in percussion instruments.

Each string on a harp **(Figure 15.10.2)** has a different wavelength and therefore frequency, and it is this fact that gives each string a different tone.

Joyfuldesigns/Dreamstime.com

FIGURE 15.10.2 Each string on a harp has a unique standing wave frequency and as such emits a unique tone.

LEARNING CHECK 15.10

DESCRIBING

1 **Describe** a standing wave.

2 **Contrast** a node and an antinode.

3 **Identify** the distance between a node and an antinode.

4 Match the terms in the first column of the table below with the conditions in the second column that describe what is causing them.

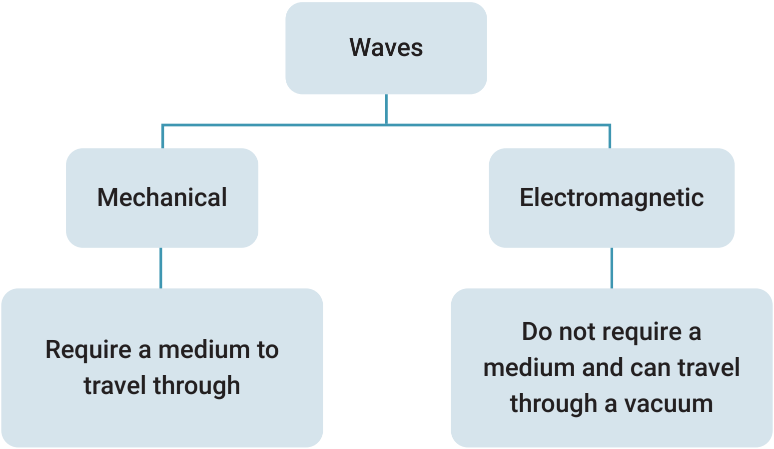
Node	Constructive interference
Antinode	Destructive interference

5 **Explain** why each string of a piano has a unique frequency.

CHAPTER SUMMARY

Waves

- Waves transfer energy.
- Examples of waves include mechanical and electromagnetic waves.



Types of waves

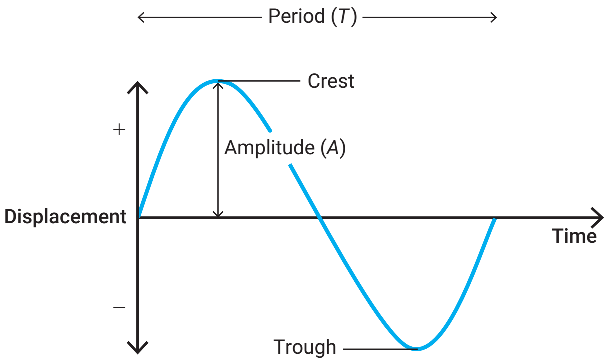
- Continuous waves move at constant speed in all directions.
- Transverse waves occur when particles move in a direction that is at right angle to the motion of the wave.
- Longitudinal waves occur when particles in the direction of the motion of the wave.

$$v = f\lambda$$

$$f = \frac{1}{T}$$

Waves and displacement–time graphs

- Displacement–time graphs scan be used to show the displacement of a particle from the mean.



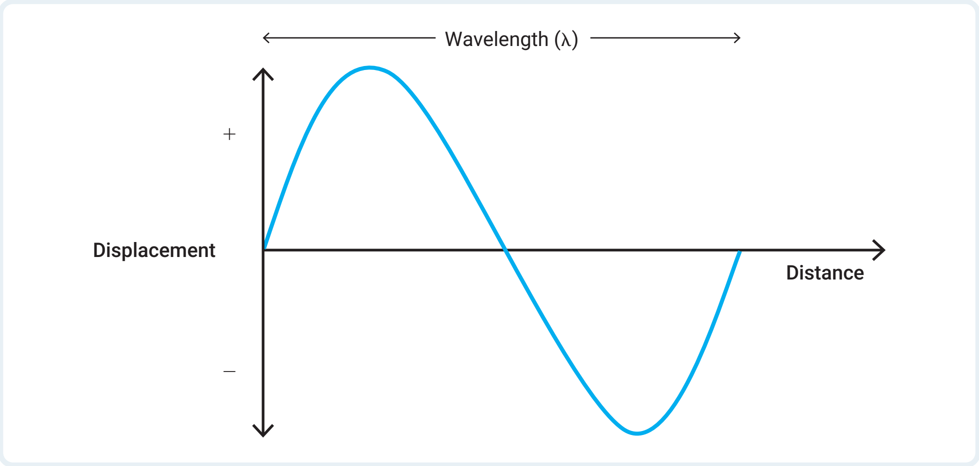
- The frequency of the wave can be calculated as:

$$f = \frac{1}{T}$$

where: f = frequency (Hz)
T = period (s)

Waves and displacement–distance graphs

- Displacement–distance graphs show the displacement of particles at different distances at a single moment in time.

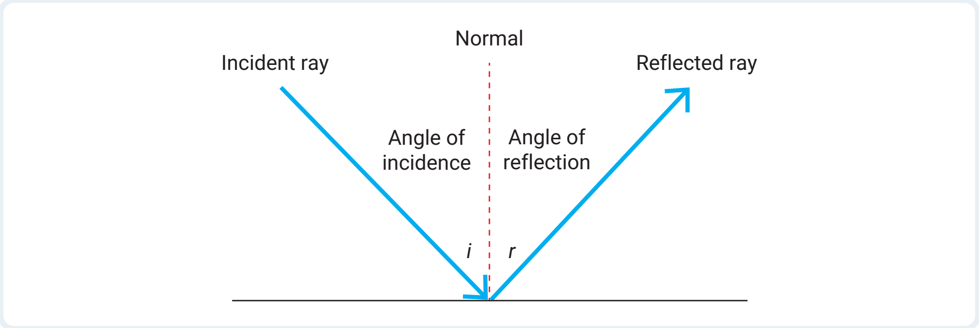


- This can be expressed as:

$$v = \frac{\lambda}{T} = f\lambda$$

where: v = wave velocity (m s^{-1})
λ = wavelength (m)
T = period (s)
f = frequency (Hz)

- When waves hit a surface or a boundary between two media, part of the wave will be reflected.
- When a 2D or 3D wave hits a surface at an angle, the wave is reflected at the same angle that it hits. This is the law of reflection.



Reflection

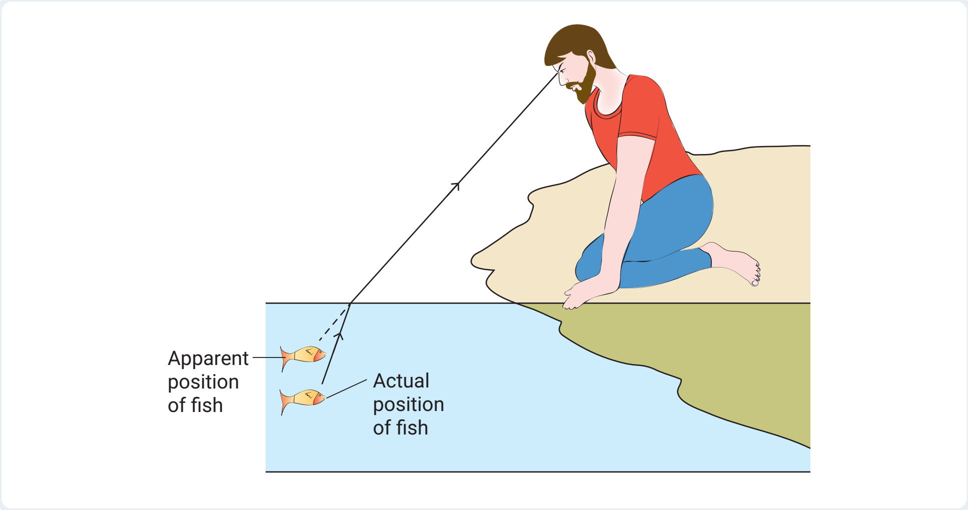
Law of reflection:

$$i = r$$

where: i = angle of incidence (degrees)
r = angle of reflection (degrees)

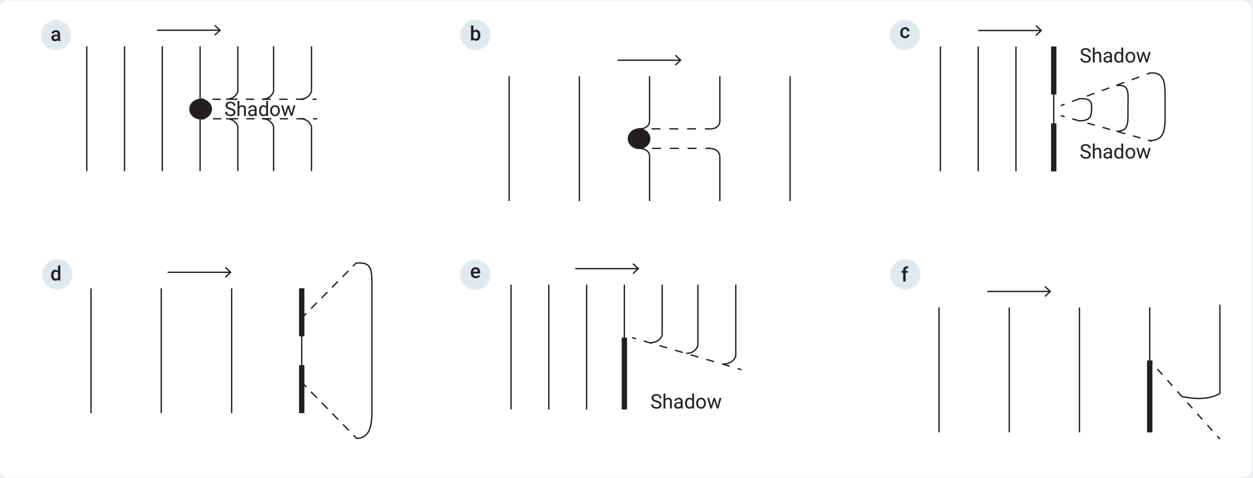
Refraction

- Refraction occurs when waves change direction when they pass from one medium to another. This is because of the differences in mass density of elastic property between the mediums.



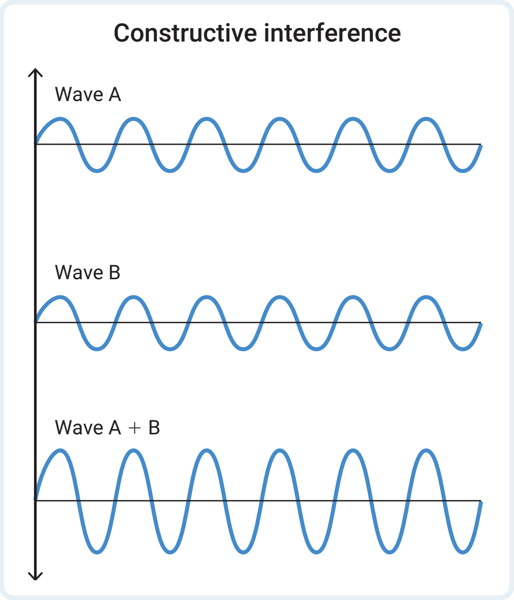
Diffraction

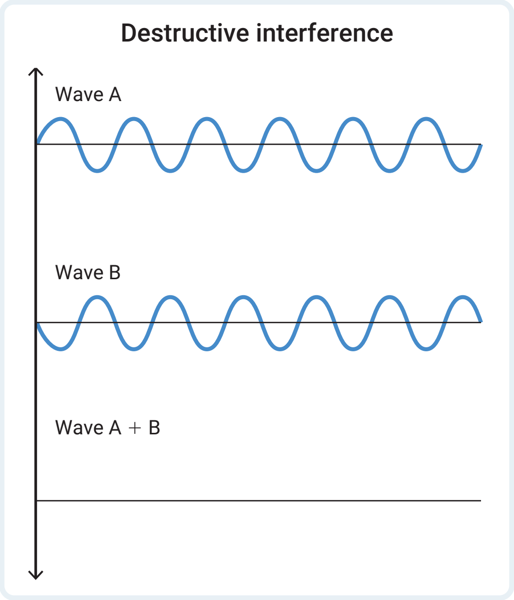
- When waves come across an obstacle or gap in a boundary, they bend around it.



Superposition

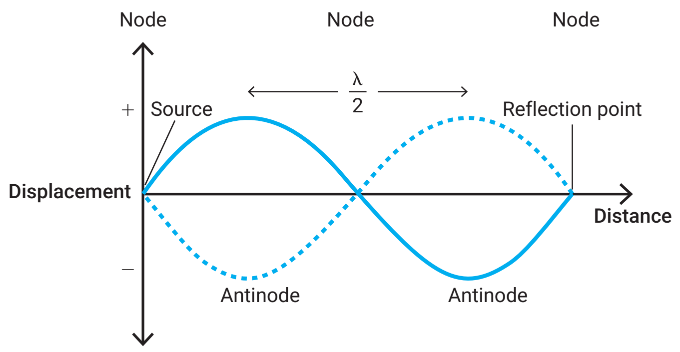
- When two waves of the same type travel through the same medium in the same place at the same time, they can overlap. This is called interference.
- Constructive interference happens when waves that meet result in a bigger wave with a higher amplitude to form.
- Destructive interference happens when the peak and trough of the waves line up oppositely, effectively cancelling each other out. A weaker wave is formed.





Standing waves

- Waves that don't appear to be moving are called standing or stationary waves.
- Standing waves are formed when two waves of the same frequency and amplitude are travelling in opposite directions in a medium.



CHAPTER EXAM

MULTIPLE CHOICE

1. The intensity of a wave is defined as a measure of the:

A power of a wave.
B energy of the wave.
C rate at which the power of a wave is travelling through a given area.
D rate at which the energy of a wave is travelling through a given area.

2. The direction of the particle motion in a medium containing a longitudinal wave is:

A parallel to the velocity of the wave.
B perpendicular to the velocity of the wave.
C at an acute angle to the velocity of the wave.
D at an obtuse angle to the velocity of the wave.

3. Which of the following wave features cannot be directly quantified from a displacement–time graph of a wave?

A Amplitude
B Frequency
C Period
D Wavelength

4. If a wave pulse travelling on a light string is incident upon the boundary with a heavy string, then the reflected wave pulse will be:

A inverted and amplified.
B upright and amplified.
C inverted and diminished.
D upright and diminished.

5. When two in-phase wave pulses meet at a point, their interaction results in:

A a standing wave.
B destructive interference.
C total internal reflection.
D constructive interference.

6. The lower the frequency of a wave, the:

A shorter its period.
B higher its velocity.
C smaller its amplitude.
D longer its wavelength.

7. A radio station broadcasts at a frequency of 660 kHz. Given that radio waves have a velocity of $3 \times 10^8\,\mathrm{m\,s^{-1}}$, what is the wavelength of these waves?

A 2.2 mm
B 455 m
C 4.55 km
D $1.98 \times 10^{14}\,\mathrm{m}$

8. Waves whose crests are 30 m apart reach an anchored boat once every 3.0 s. What is the wave velocity?

A $0.1\,\mathrm{m\,s^{-1}}$
B $5\,\mathrm{m\,s^{-1}}$
C $10\,\mathrm{m\,s^{-1}}$
D $900\,\mathrm{m\,s^{-1}}$

9. An example of a purely longitudinal wave is:

- **A** a water wave.
- **B** a sound wave.
- **C** an electromagnetic wave.
- **D** a wave in a stretched string that has been plucked.

10. Sound cannot travel though a

- **A** gas.
- **B** liquid.
- **C** solid.
- **D** vacuum.

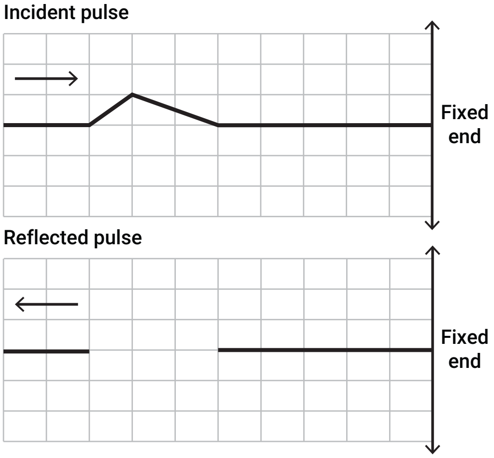
SHORT RESPONSE

11. A surfer notices that wave crests are passing underneath his board every 5.0 s. If he measures the distance between each wave to be 5.5 m, how fast are the waves travelling?

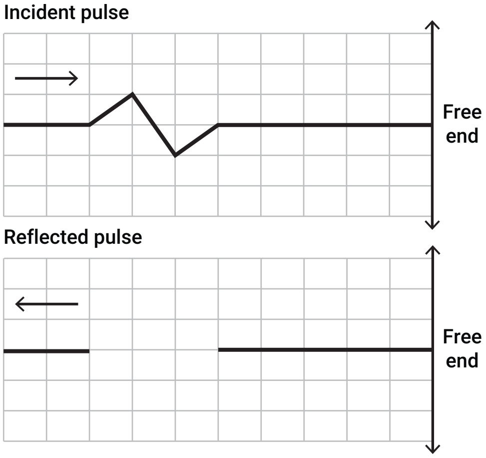
12. If a sound wave in air has a frequency of 215 Hz and is travelling with a speed of 343 m s^{-1}, how far apart are the compressions?

13. In the following cases. an incident pulse is travelling along a spring. It is approaching an end (either fixed or free). Copy the diagrams and **sketch** the shape of the reflected pulses.

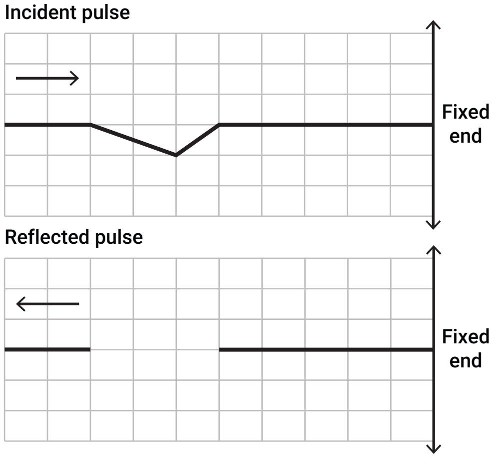
a



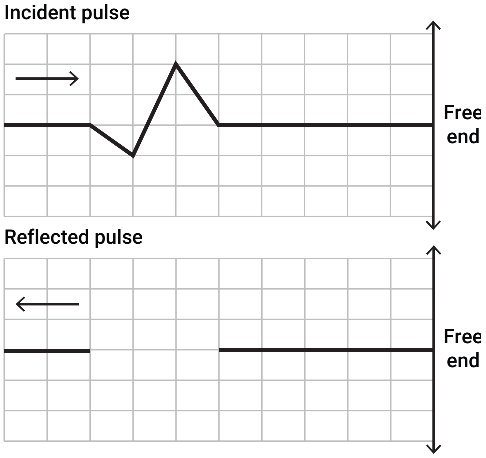
b



c



d

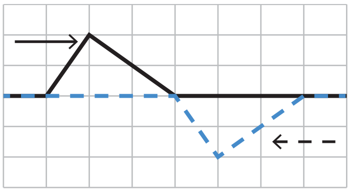


DATA ANALYSIS

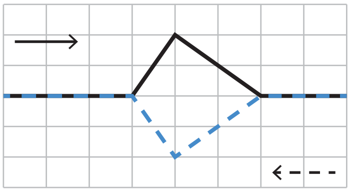
14. Analyse data

Copy each diagram and **sketch** the shape of the resultant wave form that is created by the two waves as they move through the region shown.

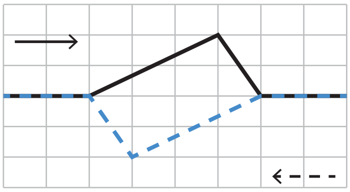
a



b



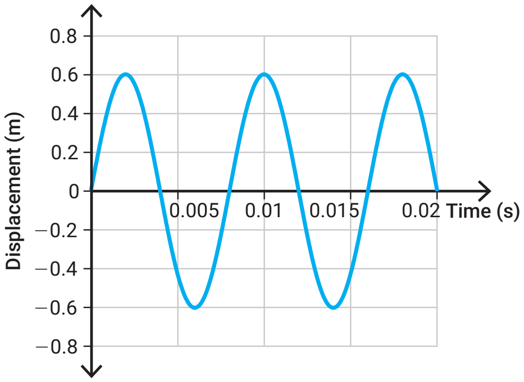
c

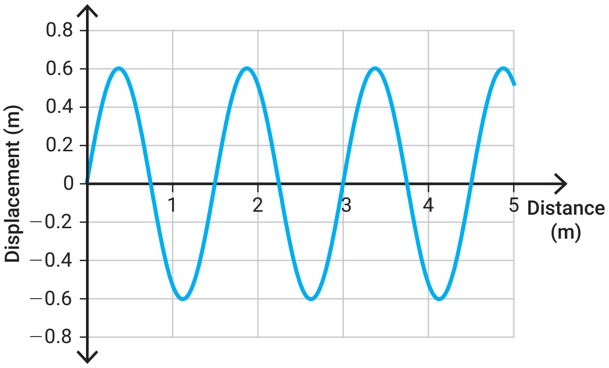


15. Analyse data

Analyse the following displacement–time graph and displacement–distance graph of the same wave to calculate the wave's:

- **a** amplitude
- **b** period
- **c** frequency
- **d** wavelength
- **e** velocity.





CHAPTER

16

Sound

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SYLLABUS DOT POINTS

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 INQUIRY

- Investigate fundamental and harmonic wavelengths in pipes.
- Investigate the speed of sound at a specific temperature.

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Introduction

We saw in the previous chapter that if the frequency of a repeated disturbance is just right, then a standing wave can be produced on a string. These standing waves are the source of the tones emitted by all stringed instruments. The fundamental concepts behind their formation can be extended to include vibrating air within a column or tube.

In this chapter, we will investigate the mechanics of standing wave production and examine the characteristic frequencies that result in a sound being produced by a string and in an air column.

Worksheets

- Predicting the fundamental frequency
- Resonance in bottles

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Standing waves consist of a node with zero displacement, and an antinode with maximum displacement.
- ✓ The wave equation is $v = f\lambda$.
- ✓ The unit for frequency is the hertz (Hz).

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ categorise vibrations as natural or forced
- ✓ describe and explain resonance
- ✓ describe and explain nodes, antinodes, fundamental frequency and harmonics on vibrating strings and pipes
- ✓ solve problems involving vibrating strings
- ✓ describe and explain the behaviour of sound waves in pipes
- ✓ solve problems involving sound waves in open and closed pipes
- ✓ conduct experiments investigating waves in pipes and strings.

16.1 Resonance

Natural vibrations

The **natural (or free) frequency** of an object is the frequency that the object vibrates at if it is displaced from its equilibrium position and left to vibrate by itself.

When a tuning fork is struck, the prongs vibrate about their mean position (**Figure 16.1.1**). Elastic restoring forces pull the prongs back towards their equilibrium position and momentum combines to drive the prongs back and forth. The tuning fork vibrates at its natural frequency.

natural (or free) frequency the vibration frequency that occurs when an object is displaced from its equilibrium position and then left to vibrate by itself

Weblink
What is sound?

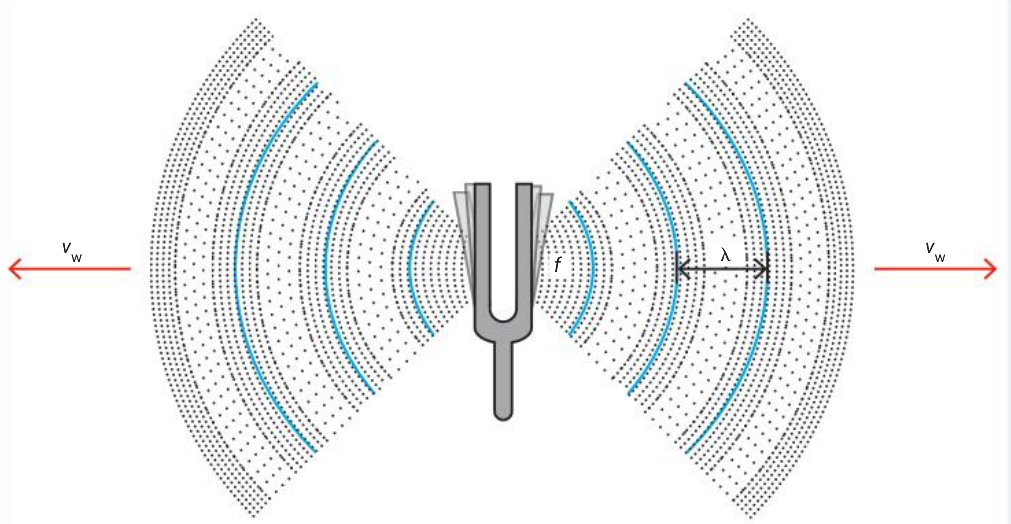


FIGURE 16.1.1 Sound waves produced from the freely vibrating tuning fork with a frequency f, speed v_w and wavelength λ

This phenomenon can be observed in guitar strings, organ pipes, wind instruments, drums, pendulums and masses hanging on the end of springs (think bungee jumping!) – all have natural frequencies.

The frequency (and period) of vibration is determined by the properties of the vibrating object. For example, a plucked guitar string vibrates at different natural frequencies depending on its length, mass per unit length and the tension in the string.

The only energy driving a free vibration is the initial energy; thus, in time these vibrations die away because of friction – energy transfers to the surroundings. For example, the tuning fork is repeatedly colliding with air molecules, leading to a momentum exchange. The tuning fork loses energy progressively while the kinetic energy of the air molecules that come into contact with the fork is increased, until eventually, the tuning fork comes to rest. Although the energy does eventually dissipate, the energy transfer in resonating systems is highly efficient.

Forced vibrations

A **forced vibration** occurs when one vibrating object makes another object vibrate. If a vibrating tuning fork is struck on a rubber stopper, it emits a low-intensity sound that can be heard only with difficulty. However, if the same vibrating tuning fork is held with its shaft on a wooden bench or tabletop, the sound is heard throughout a classroom.

forced vibration the vibration that occurs in an object when it is forced to vibrate by another vibrating object

The sound is louder when the fork is in contact with the bench because the fork causes the bench to vibrate with the same frequency. The benchtop has a larger vibrating area than the tuning fork. Consequently, these forced vibrations disturb a greater volume of air and produce a louder sound.

Resonance

If a person blows across the mouth of a bottle (Figure 16.1.2), the air in the bottle is made to vibrate and a note will be heard. The frequency of this note is determined by the dimensions of the bottle. The sound results from the free vibrations of the air in the bottle.

When a person purses their lips and blows through them, the sound of the rushing air can be heard. This sound is made up of waves of many different frequencies. This sort of sound is called 'white noise' in analogy to 'white light', which is composed of many frequencies of light.

When a person blows air across the top of a bottle, they are providing waves of many different frequencies to the air column inside the bottle. Most of these waves transfer energy very inefficiently to the air column. But waves of one particular frequency, the natural or **resonance** frequency, transfer energy very efficiently and set up a standing wave in the bottle. The frequency of this standing wave is the frequency of the note you hear. Resonance only occurs when the driving frequency matches the natural frequency and, as a result, the amplitude of vibration of the resonating object increases dramatically.

FIGURE 16.1.2 Blowing across an open bottle causes the air inside to vibrate and, in turn, a note to be emitted.

This is how woodwind instruments work; the musician makes a particular mouth shape, called the *embouchure*, and blows air through their lips over a reed. The reed vibrates with the many frequencies of the waves produced by the blowing. The wave of just the right frequency then creates a standing wave in the pipe of the instrument. In effect, the body of the instrument selects and amplifies one particular frequency from many. By covering different holes, the musician determines which frequency (which note) is selected. Brass instruments work in the same way, but the musician's vibrating lips do the job of the reed.

resonance when an object is made to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency

If a tuning fork is held over the mouth of the bottle and the frequency of the tuning fork (the **driving frequency**) differs from the natural frequency of the air column, only a weak

driving frequency the vibration of an object that causes a second object to undergo resonance sound is heard. The frequency of this weak sound is the same as the frequency of the fork and is due to the forced vibrations in the air column in the bottle.

When a tuning fork vibrating at the same natural frequency as the air column in the bottle is held over the mouth of the bottle, the sound intensity is increased considerably. The energy of the vibration across the top of the bottle is transferred very efficiently to the vibrating air column inside the bottle.

In these examples, a standing wave or resonance is produced when the frequency of the forced vibration coincides with the natural frequency of the system. Resonance can occur when the driving frequency coincides with any of the standing waves of the resonating object. The frequencies that are produced as a result are called **resonant frequencies**. When an object is resonating, energy is being transferred with maximum efficiency from the driving oscillator to the receiving oscillator.

Weblink
Resonance with sound waves

resonant frequencies the possible standing wave frequencies of an object

Figure 16.1.3 shows forced vibrations when two tuning forks are mounted on sounding boxes. The length of the sounding box should be one-quarter of the wavelength of the sound wave produced when the tuning fork vibrates.

Note the following points about resonance:

- Resonance will only occur when the driving frequency matches the natural frequency.
- The amplitude of the vibration of the resonating object will increase dramatically.
- When an object is resonating, energy is being transferred with maximum efficiency from the driving oscillator to the receiving oscillator.

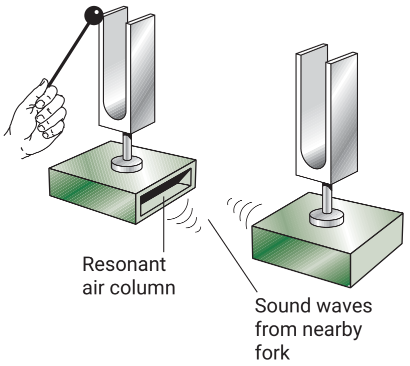


FIGURE 16.1.3 Energy supplied to one tuning fork forces the other to resonate.

LEARNING CHECK 16.1

DESCRIBING

1 **Describe:**
  - a natural frequency
  - b forced vibration
  - c resonance.

2 **Describe** the difference between a natural vibration and a forced vibration.

3 **Describe** the difference between the driving frequency and the resonant frequency of a resonating system.

4 **Explain** how blowing across the top of a bottle can produce a loud, clear note.

5 What conditions are required for resonance to occur?

6 **Explain** why the vibrating air in the bottle in Figure 16.1.2 is called a standing wave.

APPLYING

7 **Explain** how you could use a tuning fork to force another tuning fork to vibrate at its natural frequency.

8 Use the concept of resonance to **explain** how a glass can be shattered if the right frequency of sound is played loudly in its vicinity.

16.2 Vibrating strings

The formation of a standing wave in a fixed string is only one such possible pattern; every object has more than one possible standing wave pattern.

Figure 16.2.1 shows possible **vibration modes**, or **harmonics**, for stationary waves on a string or wire fixed at both ends. There is a node at each fixed end for all modes of vibrations.

vibration mode or harmonic standing wave pattern

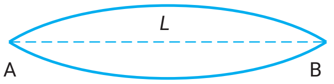
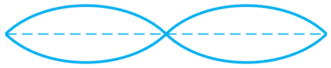
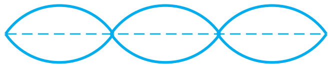
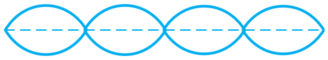
Vibration mode	Wave pattern	f and λ
Fundamental mode of vibration 1st harmonic		$\lambda_1 = 2L$ $f_1 = \frac{v}{2L}$
2nd harmonic		$\lambda_2 = L$ $f_2 = 2f_1$
3rd harmonic		$\lambda_3 = \frac{2}{3}L$ $f_3 = 3f_1$
4th harmonic		$\lambda_4 = \frac{1}{2}L$ $f_4 = 4f_1$
5th harmonic		$\lambda_5 = \frac{2}{5}L$ $f_5 = 5f_1$

FIGURE 16.2.1 The first five harmonics of a string fixed at both ends

The fundamental mode of vibration is also referred to as the **first harmonic**. Wires and strings of musical instruments can be made to vibrate at frequencies other than their fundamental frequency. These higher modes of vibration are notes or tones of higher frequency than the fundamental or natural frequency (and are of smaller amplitude). The second mode of vibration harmonic is the called the second harmonic; the third mode of vibration is called the third harmonic, and so on.

first harmonic the simplest mode of vibration that accounts for the fundamental tone

The frequency of each harmonic is its harmonic number multiplied by the fundamental frequency. If the fundamental frequency of a stretched string is 40 Hz, the fourth harmonic has a frequency of $4 \times 40 = 160$ Hz.

The fundamental mode of vibration (the first harmonic) is generated when the stretched string is plucked in the middle. If you look at the fundamental vibration mode in Figure 16.2.1, the pattern represents half a wave, so its wavelength, λ_1, is twice the length of the string: $L = \frac{\lambda_1}{2}$.

Weblink
Why does a violin sound different from a guitar?

The second harmonic is generated when the stretched string is plucked a quarter of the way along the string. The second harmonic mode in Figure 16.2.1 shows that the pattern represents a complete wave, so the wavelength of the second harmonic, λ_2, is equal to the length of the string: $L = \lambda_2$.

The third harmonic is generated when the stretched string is plucked a sixth of the way along the string. The pattern of the third vibrational mode in Figure 16.2.1 represents one and a half complete waves, so the wavelength of the third harmonic, λ_3, is equal to two-thirds the length of the string: $L = \frac{3\lambda_3}{2}$.

For strings attached at both ends to be resonating, the length of the string is related to the resonating wavelength by the relationship:

$$L = n\frac{\lambda_n}{2}$$

where: L = length of the string (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)

Putting this together with $v = f\lambda$, where v is the speed of the travelling wave in the string, the following relationships become apparent.

- The fundamental or first mode has frequency $f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$.
- The second harmonic has frequency $f_2 = \frac{v}{\lambda_2} = \frac{v}{L} = 2f_1$.
- In general, the nth harmonic has frequency $f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$.

KEY FORMULA

Relationship between the length of a string and its resonant frequencies

$$L = n\frac{\lambda_n}{2}$$

where:
L = length of the string (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)

KEY FORMULA

Frequency of resonant frequencies on a string

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

where:
f_n = frequency of the nth mode or harmonic (Hz)
L = length of the string (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)
f_1 = fundamental frequency (Hz)
v = wave velocity (m s^{-1})

WORKED EXAMPLE 16.2.1

The fundamental frequency of a string 2.4 m long and fixed at both ends is 22 Hz.

a What are the frequencies of the next three harmonics?

b Is it possible to produce stationary waves of frequency 50 Hz in this string?

c What is the speed of the waves in the string?

d What is the wavelength of the first harmonic?

ANSWERS

a **The frequency of each harmonic is its harmonic number multiplied by the fundamental frequency.**

- **i** $2 \times 22\ \text{Hz} = 44\ \text{Hz}$
- **ii** $3 \times 22\ \text{Hz} = 66\ \text{Hz}$
- **iii** $4 \times 22\ \text{Hz} = 88\ \text{Hz}$

b **As 50 Hz is not the frequency of one of the harmonics of this string (a whole number multiple of the fundamental frequency), it is not possible to produce stationary waves of this frequency with the string under the same tension.**

c **1** **State the equation.**

$$f_n = n\frac{v}{2L}$$

2 **Rearrange to find the unknown.**

$$v = f_n n2L$$

3 **Substitute known values.**

$$v = 22\ \text{Hz} \times 1 \times 2 \times 2.4\ \text{m}$$

4 **Calculate the answer.**

$$v = 105.6\ \text{m s}^{-1}$$

5 **Give the answer to the correct number of significant figures.**

$$v = 110\ \text{m s}^{-1}$$

d **1** **Apply the equation.**

$$L = n\frac{\lambda_n}{2}$$

2 **Rearrange to find the unknown.**

$$\lambda_n = \frac{2L}{n}$$

3 **Substitute known values.**

$$\lambda_1 = \frac{2 \times 2.4\ \text{m}}{1}$$

4 **Calculate the answer with the correct number of significant figures.**

$$\lambda_1 = 4.8\ \text{m}$$

LEARNING CHECK 16.2

DESCRIBING

1 What is the difference between the fundamental mode and the second mode of vibration in a string?

2 A standing wave in a spring results from the interference between an incident wave and its reflection. The two waves cancel at the nodes.

Does this mean that energy is destroyed? **Explain** your answer.

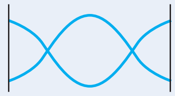
3 Two component waves producing a standing wave pattern each have a wavelength of L. **Identify** the distance between:

- **a** adjacent nodes
- **b** adjacent antinodes
- **c** a node and the closest antinode.

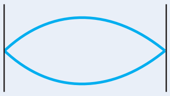
APPLYING

4 Which of the following pattern(s) could represent a standing wave pattern on a string of length L fixed at both ends?

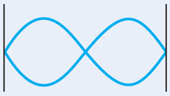
A



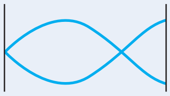
B



C



D



5 The apparatus used to investigate the vibrations of a stretched string or vibrating wire is called a sonometer or monochord (Figure 16.2.2).

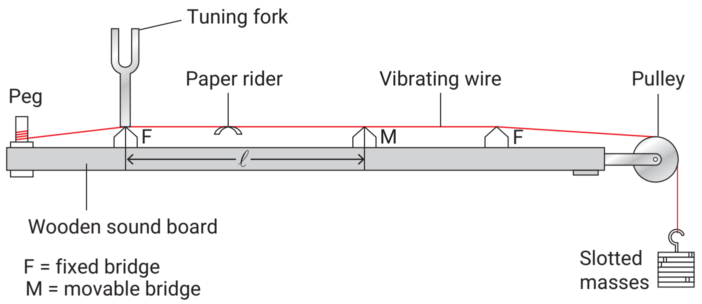


FIGURE 16.2.2 A sonometer

The stretched wire on a monochord is 0.80 m long.

- **a** What is the wavelength of the fundamental mode of vibration?
- **b** If the speed of the wave travelling in the wire is 200 m s^{-1}, what is the fundamental frequency?
- **c** If the vibrating length of the wire is shortened, does the fundamental frequency increase or decrease? Give a reason for your answer.
- **d** If you added more slotted masses to the sonometer, the frequency of the note it produces will increase. **Explain** why.

6 What is the longest wavelength of a standing wave that can be created on a string stretched between fixed supports 12 cm apart?

7 Two successive harmonics of a vibrating string are 300 Hz and 360 Hz. What is the fundamental frequency of the string?

16.3 Air columns

Longitudinal stationary sound waves can be created in both open and closed pipes, such as is the case in woodwind, pipe organ and brass instruments (Figure 16.3.1).

Resonance occurs when sound waves match one of the harmonic wavelengths of the pipe. **Open pipes** are open at both ends and **closed pipes** are open at only one end. Resonance in air columns is related to the length of the pipe and the speed of sound in air, which is temperature dependent.

open pipe a pipe that is open at both ends

closed pipe a pipe that is open at one end and closed at the other end

Reflection of sound waves in pipes

Waves confined in pipes travel as plane waves, not spherical waves as they do in the open air. As a compression travels along the pipe, it continually reflects off the walls of the pipe. This maintains the compression. When the compression reaches the end of an open pipe, it is no longer confined and rapidly expands into the air, leaving behind a rarefaction that travels back down the pipe. The compression has been reflected as a rarefaction. This is similar to a fixed-end reflection in strings and springs.

When a rarefaction travels along the pipe, it continually reflects off the walls of the pipe. This maintains the rarefaction. When the rarefaction reaches the end of an open pipe, the higher-pressure air outside the pipe rapidly expands into the rarefaction, creating a compression that travels back down the pipe. The rarefaction has been reflected as a compression.

When a compression strikes the closed end of a pipe (the non-yielding part of a pipe), it is reflected as a compression. This is similar to a free-end reflection in strings and springs.

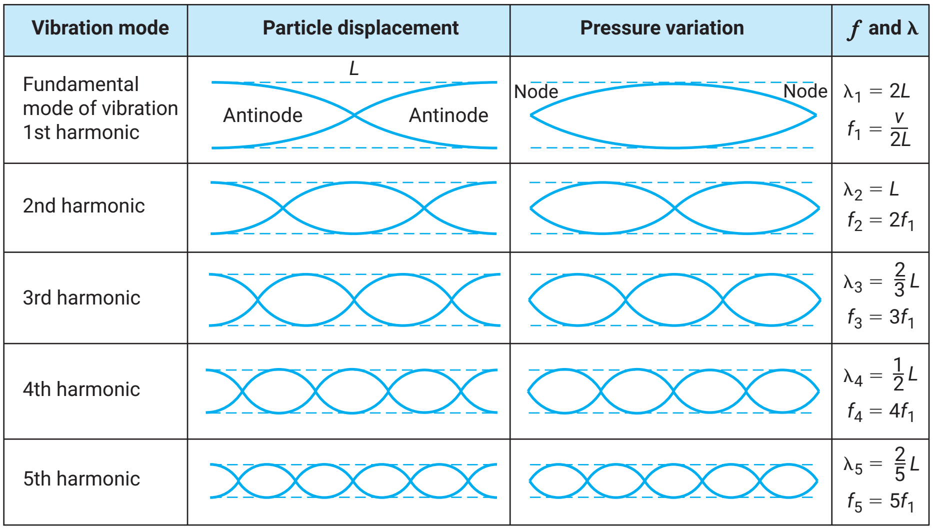
Rarefactions are also reflected as rarefactions from the closed end of the pipe. The standing wave formed in the tube has its maximum air displacement (an antinode) at the open end. This means there will be a pressure node at the open end of the pipe and a pressure antinode at the closed end.

FIGURE 16.3.1 In trombones, the length of the resonator can be changed by sliding one tube through another.

iStock.com/DaveLongMedia

Stationary waves in open pipes

To indicate the stationary wave pattern in an air column, you can use either the pressure variation or the particle displacement. **Figure 16.3.2** represents the particle displacement and pressure variations in an open pipe. In all open pipes, the maximum air displacements (displacement antinode or a pressure node) occur at both ends of the pipe, so that its natural frequencies are different from those of a pipe closed at one end.



Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic	L Antinode Antinode	Node Node	$\lambda_1 = 2L$ $f_1 = \frac{v}{2L}$
2nd harmonic			$\lambda_2 = L$ $f_2 = 2f_1$
3rd harmonic			$\lambda_3 = \frac{2}{3}L$ $f_3 = 3f_1$
4th harmonic			$\lambda_4 = \frac{1}{2}L$ $f_4 = 4f_1$
5th harmonic			$\lambda_5 = \frac{2}{5}L$ $f_5 = 5f_1$

FIGURE 16.3.2 The particle displacement and pressure variations of the resonant frequencies of a pipe open at both ends

Weblink
How do we tune a pan flute?

For pipes open at both ends to resonate, the length of the pipe must be related to the resonating wavelength by the relationship:

$$L = n\frac{\lambda_n}{2}$$

where: L = length of the pipe (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)

KEY FORMULA

Relationship between the length of an open pipe and the wavelength of its resonant frequencies

$$L = n\frac{\lambda_n}{2}$$

where:

L = length of the pipe (m)

n = mode or harmonic number (n = 1, 2, 3 . . .)

λ_n = wavelength of the nth mode or harmonic (m)

In open pipes, all harmonics are possible and, as such, the frequency of the resonating tone can be found as:

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

where: f_n = frequency of the nth mode or harmonic (Hz)

L = length of the pipe (m)

n = mode or harmonic number (n = 1, 2, 3 . . .)

λ_n = wavelength of the nth mode or harmonic (m)

f_1 = fundamental frequency (Hz)

KEY FORMULA

Frequency of resonant tones of an open pipe

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

where:

f_n = frequency of the nth mode or harmonic (Hz)

L = length of the pipe (m)

n = mode or harmonic number (n = 1, 2, 3 . . .)

λ_n = wavelength of the nth mode or harmonic (m)

f_1 = fundamental frequency (Hz)

WORKED EXAMPLE 16.3.1

Calculate the wavelength of the fundamental frequency resonating in a flute of length 62 cm, which can be modelled as an open pipe.

ANSWER

1 State the equation.

$$L = n\frac{\lambda_n}{2}$$

2 Rearrange to find the unknown.

$$\lambda_n = \frac{2L}{n}$$

3 Substitute known values.

$$\lambda_1 = \frac{2 \times 0.62\ \text{m}}{1}$$

4 Calculate the answer.

$\lambda_1 = 1.24\ \text{m}$

5 Give the answer to the correct number of significant figures.

$\lambda_1 = 1.2\ \text{m}$

WORKED EXAMPLE 16.3.2

Calculate the length of a pipe open at both ends whose fundamental frequency is 320 Hz, when the temperature is such that the speed of sound in the air is 340 m s^{-1}.

ANSWER

1 State the equation.

$$f_n = n\frac{v}{2L}$$

2 Rearrange to find the unknown value.

$$L = \frac{nv}{2f_n}$$

3 Substitute known values.

$$L = \frac{1 \times 340\ \text{m s}^{-1}}{2 \times 320\ \text{Hz}}$$

4 Calculate the answer.

$L = 0.531\ 25$

5 Give the answer to the correct number of significant figures.

$L = 0.53\ \text{m}$

Stationary waves in closed pipes

Consider an air column that is in a pipe closed at one end. When it is resonating, a pressure antinode (displacement node) occurs at the closed end. Figure 16.3.3 represents the particle displacement and pressure variations in a pipe closed at one end.

For a closed pipe to resonate, the length of the pipe must be related to the resonance wavelength by the relationship:

$$L = (2n - 1)\frac{\lambda_n}{4}$$

where: L = length of the pipe (m)
n = mode number (n = 1, 2, 3 . . .)
λ_n = wavelength of the nth mode (m)

Worksheet
Resonance in bottles

The fundamental resonance mode when $n = 1$ (1st harmonic):

$$L = \frac{\lambda}{4}$$

The resonance mode when $n = 2$ (3rd harmonic):

$$L = \frac{3\lambda}{4}$$

Worksheet
Predicting the fundamental frequency

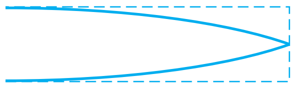
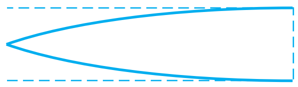
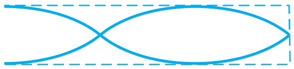
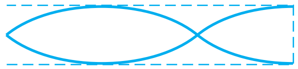
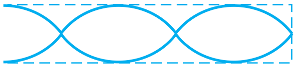
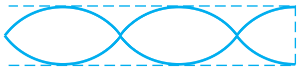
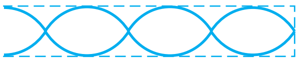
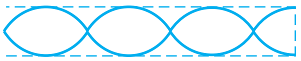
Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic			$\lambda_1 = 4L$ $f_1 = \frac{v}{4L}$
3rd harmonic			$\lambda_2 = \frac{4L}{3}$ $f_2 = 3f_1$
5th harmonic			$\lambda_3 = \frac{4L}{5}$ $f_3 = 5f_1$
7th harmonic			$\lambda_4 = \frac{4L}{7}$ $f_4 = 7f_1$
9th harmonic			$\lambda_5 = \frac{4L}{9}$ $f_5 = 9f_1$

FIGURE 16.3.3 The particle displacement and a pressure variation representation of the resonant frequencies of a pipe closed at one end. All harmonics have maximum particle displacement at the open end and none at the closed end.

The resonance mode when $n = 3$ (5th harmonic):

$$L = \frac{5\lambda}{4}$$

Note that only the odd harmonics are present in a closed pipe. This means that musical instruments with one closed end can only produce half the notes that can be produced by instruments containing open ends. Therefore, the frequencies of the harmonic modes can be calculated as:

$$f_n = \frac{v}{\lambda_n} = (2n - 1)\frac{v}{4L} = (2n - 1)f_1$$

where: f_n = frequency of the nth mode (Hz)
v = speed of sound in air (m s^{-1})
L = length of the pipe (m)
n = mode number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode (m)
f_1 = fundamental frequency (Hz)

KEY FORMULA

Relationship between the length of a closed pipe and the wavelength of its resonating frequencies

$$L = (2n - 1)\frac{\lambda_n}{4}$$

where:
L = length of the pipe (m)
n = mode number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode (m)

KEY FORMULA

Frequency of resonant tones of a closed pipe

$$f_n = \frac{v}{\lambda_n} = (2n - 1)\frac{v}{4L} = (2n - 1)f_1$$

where:
f_n = frequency of the nth mode (Hz)
v = speed of sound in air (m s^{-1})
L = length of the pipe (m)
n = mode number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode (m)
f_1 = fundamental frequency (Hz)

WORKED EXAMPLE 16.3.3

Calculate the wavelength of the second mode of a bamboo pipe closed at one end, if the pipe is 32 cm long.

ANSWER

1 **State the equation.**

$$L = (2n - 1)\frac{\lambda_n}{4}$$

2 **Rearrange to find the unknown.**

$$\lambda_n = \frac{4L}{2n - 1}$$

3 **Substitute the known values.**

$$\lambda_n = \frac{4 \times 0.32\text{ m}}{2 \times 2 - 1}$$

4 **Calculate the answer.**

$\lambda_n = 0.426\,67\text{ m}$

5 **Give the answer to the correct number of significant figures.**

$\lambda_n = 0.43\text{ m}$

WORKED EXAMPLE 16.3.4

If the speed of sound in a closed organ pipe is 334 m s^{-1}, calculate the length of a pipe that resonates with a fundamental frequency of 57 Hz.

ANSWER

1 **State the equation.**

$$f_n = (2n - 1)\frac{v}{4L}$$

2 **Rearrange to find the unknown.**

$$L = (2n - 1)\frac{v}{4f_n}$$

3 **Substitute the known values.**

$$L = (2 \times 1 - 1)\frac{334\text{ m s}^{-1}}{4 \times 57\text{ Hz}}$$

4 **Calculate the answer.**

$L = 1.4649\text{ m}$

5 **Give the answer to the correct number of significant figures.**

$L = 1.5\text{ m}$

LEARNING CHECK 16.3

DESCRIBING

1 Outline the differences between a closed and open pipe in terms of:

  a their physical structure

  b the wavelengths of their resonant frequencies.

APPLYING

2 A tube of length L is open at both ends. A stationary wave is set up in the tube. Only waves with certain frequencies will cause resonance within the tube. Which of the following gives the set of wavelengths that can exist in a tube open at both ends ($n = 1, 2, 3, \ldots$)?

  A n

  B $\frac{L}{n}$

  C $\frac{4L}{2n-1}$

  D $\frac{2L}{n}$

3 A tube of length L is closed at one end. A stationary wave is set up in the tube. Only waves with certain frequencies will cause resonance within the tube. Which of the following gives the set of wavelengths that can exist in a tube open at both ends ($n = 1, 2, 3, \ldots$)?

  A n

  B $\frac{L}{n}$

  C $\frac{4L}{2n-1}$

  D $\frac{2L}{n}$

4 Water is poured into a long metal tube closed at one end until the shortest resonant length is found for a tuning fork of frequency 256 Hz. If the length of the air column in the tube is 31.0 cm, what is the velocity of sound in the air?

5 The average human ear is most sensitive to sounds of a frequency of about 5000 Hz. The outer ear canal can be modelled as a tube closed at one end **(Figure 16.3.4)**. Assuming that this frequency corresponds to the fundamental frequency, what is the length of the outer ear canal of a human?

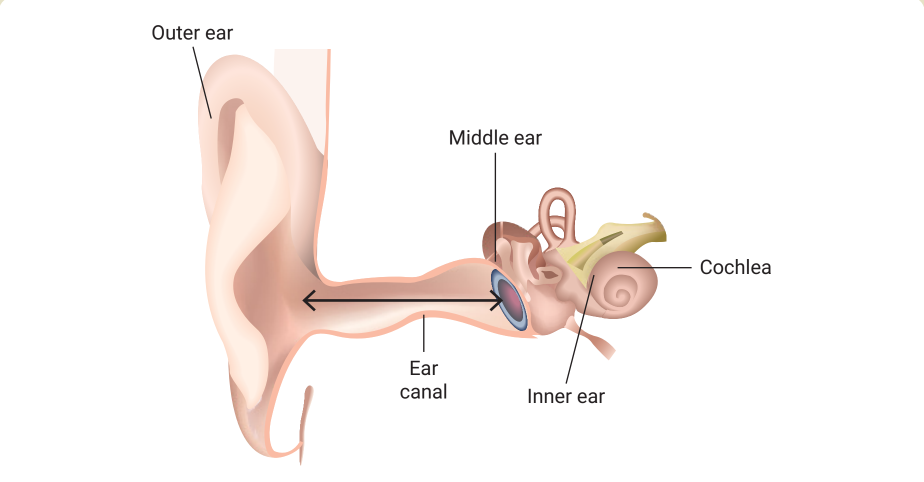


FIGURE 16.3.4 The outer ear canal can be modelled as a tube closed at one end.

CHAPTER SUMMARY

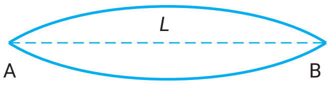
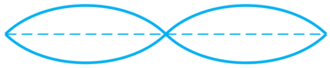
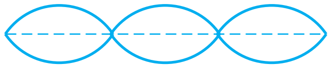
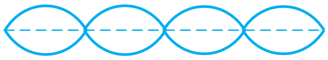
Vibrations

- Natural vibration of a wave is the frequency that the object vibrates at when it's displaced from its equilibrium position.
- Forced vibrations occur when one vibrating object makes another vibrate.

Waves and strings fixed at both ends

- Harmonics or vibration modes are standing wave patterns.
- Wires and strings can be made to vibrate at frequencies other than their fundamental frequency. For strings with fixed ends:

Vibration modes and wave patterns for standing waves

Vibration mode	Wave pattern	f and λ
Fundamental mode of vibration 1st harmonic		$\lambda_1 = 2L$ $f_1 = \frac{v}{2L}$
2nd harmonic		$\lambda_2 = L$ $f_2 = 2f_1$
3rd harmonic		$\lambda_3 = \frac{2}{3}L$ $f_3 = 3f_1$
4th harmonic		$\lambda_4 = \frac{1}{2}L$ $f_4 = 4f_1$
5th harmonic		$\lambda_5 = \frac{2}{5}L$ $f_5 = 5f_1$

- The relationship between the length of a string and its resonant frequencies:

$$L = n\frac{\lambda_n}{2}$$

where: L = length of the string (m)
n = mode or harmonic number (n = 1, 2, 3 . . .)
λ_n = wavelength of the nth mode or harmonic (m)

- The frequency of resonant frequencies on a string:

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

where: f_n = frequency of the nth mode or harmonic (Hz)
L = length of the string (m)
n = mode or harmonic number (n = 1, 2, 3 . . .)
λ_n = wavelength of the nth mode or harmonic (m)
f_1 = fundamental frequency (Hz)
v = wave velocity (m s^{-1})

Waves and open pipes

- The relationship between the length of an open pipe and the wavelength of its resonant frequencies:

$$L = n\frac{\lambda_n}{2}$$

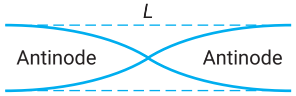
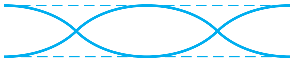
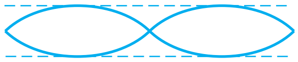
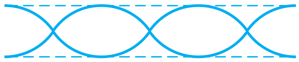
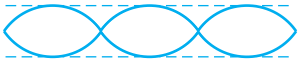
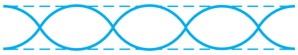
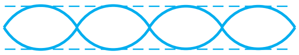
where: L = length of the pipe (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)

- The frequency of resonant tones of an open pipe:

$$f_n = \frac{v}{\lambda_n} = n\frac{v}{2L} = nf_1$$

where: f_n = frequency of the nth mode or harmonic (Hz)
L = length of the pipe (m)
n = mode or harmonic number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode or harmonic (m)
f_1 = fundamental frequency (Hz)

Particle displacement and pressure variation for open pipes

Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic			$\lambda_1 = 2L$ $f_1 = \frac{v}{2L}$
2nd harmonic			$\lambda_2 = L$ $f_2 = 2f_1$
3rd harmonic			$\lambda_3 = \frac{2}{3}L$ $f_3 = 3f_1$
4th harmonic			$\lambda_4 = \frac{1}{2}L$ $f_4 = 4f_1$
5th harmonic			$\lambda_5 = \frac{2}{5}L$ $f_5 = 5f_1$

Waves and closed pipes

- The relationship between the length of a closed pipe and the wavelength of its resonating frequencies:

$$L = (2n - 1)\frac{\lambda_n}{4}$$

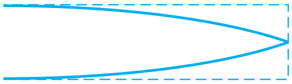
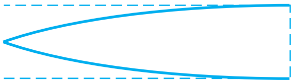
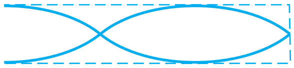
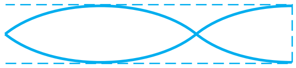
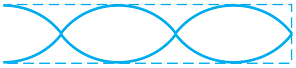
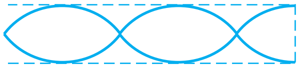
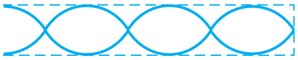
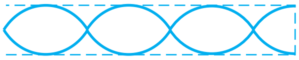
where: L = length of the pipe (m)
n = mode number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode (m)

- The frequency of resonant tones of a closed pipe:

$$f_n = \frac{v}{\lambda_n} = (2n-1)\frac{v}{4L} = (2n-1)f_1$$

where: f_n = frequency of the nth mode (Hz)
v = speed of sound in air (m s^{-1})
L = length of the pipe (m)
n = mode number ($n = 1, 2, 3 \ldots$)
λ_n = wavelength of the nth mode (m)
f_1 = fundamental frequency (Hz)

Particle displacement and pressure variations for closed pipes

Vibration mode	Particle displacement	Pressure variation	f and λ
Fundamental mode of vibration 1st harmonic	 	 	$\lambda_1 = 4L$ $f_1 = \frac{v}{4L}$
3rd harmonic			$\lambda_2 = \frac{4L}{3}$ $f_2 = 3f_1$
5th harmonic			$\lambda_3 = \frac{4L}{5}$ $f_3 = 5f_1$
7th harmonic			$\lambda_4 = \frac{4L}{7}$ $f_4 = 7f_1$
9th harmonic			$\lambda_5 = \frac{4L}{9}$ $f_5 = 9f_1$

MULTIPLE CHOICE

1. The natural frequency of an object is the frequency with which it will vibrate if:

A it is placed in the vicinity of another object.
B its elastic properties are altered while vibrating.
C it is displaced from its equilibrium position repeatedly.
D it is displaced from its equilibrium position and left to vibrate.

2. Which of the following instruments is an example of a closed pipe?

A A clarinet
B A flute
C An organ
D A guitar

3. Which of the following wavelengths corresponds to the second harmonic of a stringed instrument?

A $\lambda = 2L$
B $\lambda = L$
C $\lambda = \frac{2L}{3}$
D $\lambda = \frac{L}{2}$

4. Which of the following frequencies corresponds to the fundamental frequency of a closed pipe?

A $f = \frac{v}{4L}$
B $f = \frac{3v}{4L}$
C $f = \frac{v}{2L}$
D $f = \frac{v}{L}$

5. In a standing wave pattern on a stretched string, what is the significance of nodes?

A Maximum displacement
B Minimum displacement
C Points of destructive interference
D Points of constructive interference

6. What happens to the wavelength of a standing wave in a pipe closed at one end compared to in a pipe open at both ends?

A It doubles.
B It is halved.
C It quadruples.
D It remains the same.

7. How does the length of a pipe open at both ends affect the wavelength of the standing wave?

A No change to the wavelength
B Longer pipe, longer wavelength
C Longer pipe, shorter wavelength
D It depends on the material of the pipe.

8. In a pipe closed at one end, the standing wave pattern of the fundamental frequency is characterised by how many antinodes?
   - **A** 0
   - **B** 1
   - **C** 2
   - **D** 3

9. In a resonating system, what is the relationship between the driving frequency and the natural frequency for maximum energy transfer?
   - **A** They must be equal.
   - **B** They are unrelated.
   - **C** Natural frequency is twice the driving frequency.
   - **D** Driving frequency is twice the natural frequency.

10. On a stretched string, what type of wave is responsible for standing wave formation?
   - **A** Longitudinal wave
   - **B** Transverse wave
   - **C** Sine wave
   - **D** Surface wave

SHORT RESPONSE

11. The fundamental frequency of a 3.0 m long string fixed at both ends is 15 Hz.
   - **a** What are the frequencies of the next three harmonics?
   - **b** What is the speed of the waves in the string?
   - **c** What is the wavelength of the first harmonic?

12. **Calculate** the length of a pipe that is open at both ends if its fundamental frequency is 280 Hz when the speed of sound is 343 m s^{-1}.

13. Draw a diagram of a didgeridoo resonating at its second vibrational mode. On the diagram, show the:
   - **a** pressure variation
   - **b** displacement variation.

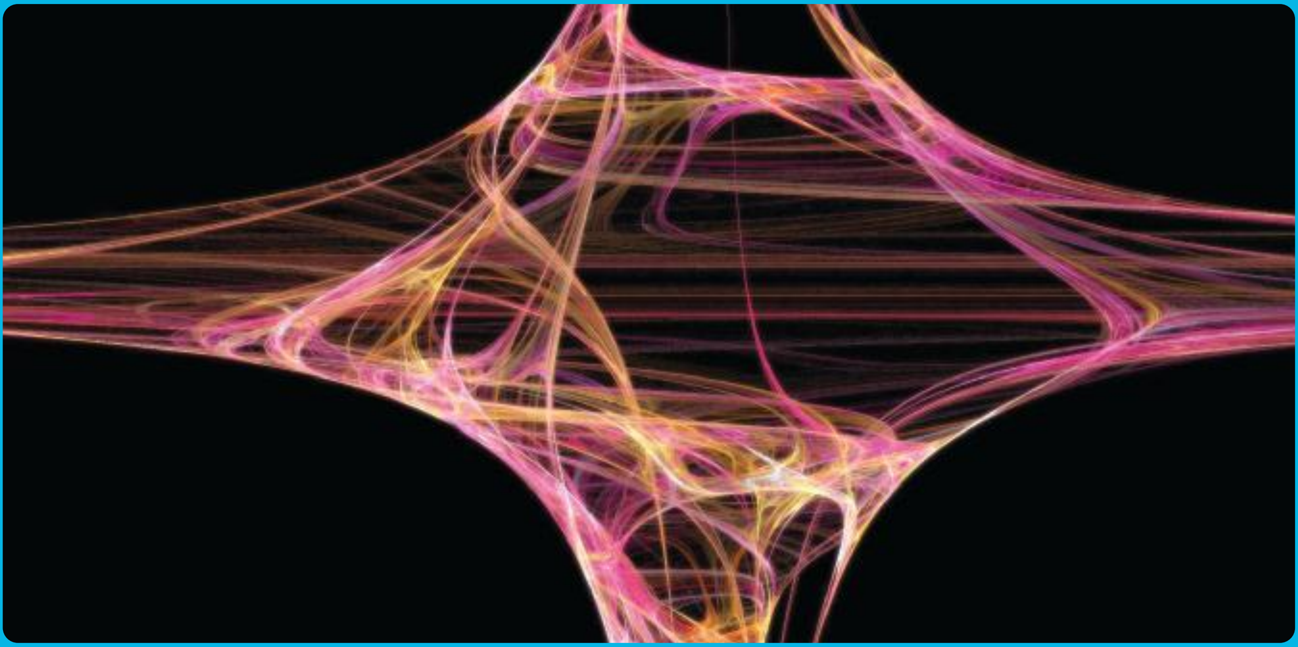
14. If the average frequency range of human hearing is 20–20 000 Hz, how many of the vibrational modes of a 2.2 m open-ended pipe can be heard if the speed of sound is 340 m s^{-1}?

CROSS-CHAPTER QUESTION

15. The speed of sound in a 2.0 m closed pipe is 340 m s^{-1}.
   - **a** **Calculate** the wavelength of the first three vibrational modes of the pipe.
   - **b** **Calculate** the frequency of the first three vibrational modes of the pipe.

CHAPTER 17

Light



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SYLLABUS DOT POINTS

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 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 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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Introduction

'What is light?' This question is somewhat difficult to answer. Light reflects from surfaces, goes through transparent materials and produces electricity in solar cells. If we illuminate a green surface with orange light, it appears black. It is the interaction between light and matter that must be explained. Therefore, the better question is: 'What does light act like when it interacts with matter?'

In this chapter, we will investigate different models of light and use the wave and ray models to describe the phenomena of light intensity, polarisation, reflection, diffraction and refraction.

Practical

- Snell's law

Worksheets

- Single-slit experiment
- Interference and light

Nelson MindTap

To access resources above, visit **cengage.com.au/nelsonmindtap**

ASSUMED KNOWLEDGE

- ✓ Waves can interact with interfaces in many ways, including reflection, refraction and diffraction.
- ✓ The power of a light source can be calculated as the energy per unit time $\left(P = \frac{E}{t}\right)$.
- ✓ Light is an electromagnetic wave and does not need to travel through a medium.

LEARNING OUTCOMES

By the end of this chapter, you should be able to:

- ✓ describe and explain the electromagnetic wave model, ray model and photon (particle) model of light
- ✓ use the models of light to explain the behaviour of light
- ✓ describe how the luminiferous aether theory was discounted by the Michelson–Morley experiment
- ✓ contrast the speed of light with the velocities of mechanical waves
- ✓ calculate light intensity and link it to the inverse-square propagation of light from a source
- ✓ describe and explain the polarisation of light
- ✓ identify the principal axis, principal foci, focal length and lens axis on ray diagrams
- ✓ solve problems involving lenses and mirrors using ray diagrams
- ✓ describe image types using lens diagrams
- ✓ describe and explain Snell's law of refraction
- ✓ solve problems using Snell's law of refraction and refractive indices
- ✓ calculate absolute and relative refractive index
- ✓ determine refractive indices experimentally
- ✓ determine the refractive index of a material by graphical analysis
- ✓ solve problems involving critical angle
- ✓ describe applications of total internal reflection in information and communications technology
- ✓ describe and explain chromatic dispersion
- ✓ categorise lenses as converging or diverging according to how they refract light
- ✓ categorise lenses as concave or convex according to their shape
- ✓ describe and explain diffraction
- ✓ describe and explain Young's double-slit experiment in terms of diffraction and interference
- ✓ describe how the results of Young's double-slit experiment and the Michelson–Morley experiment have contributed to humanity's understanding of light.

17.1 Models of light

In some experiments, light seems to travel as a wave but interact with matter as a particle. These experiments cannot be explained without the use of both the wave and particle models together. Scientists call this need for these two apparently quite different models the **wave–particle duality**. In fact, there are three current models used to explain the propagation of light and the interactions between light and matter.

wave–particle duality
the need to model light as both a wave and a particle

Ray model

In the **ray model**, light is described as travelling in straight lines (rays) from any source. The rays can change direction whenever light interacts with a material. The ray model is useful for analysing the interaction of light with large objects or surfaces such as lenses and mirrors. We can model reflection and refraction using the ray model.

ray model a model that describes light as travelling in rays that can change direction during interactions with matter

Wave model

In the **wave model**, light is treated as a wave that propagates through a vacuum or a medium at a speed that depends on the electric and magnetic properties of the medium. The wave model is useful for analysing the interaction of light with objects that are similar in size to the wavelength of the light, such as small apertures and obstacles, and the edges of objects. We can model interference and diffraction using the wave model.

wave model a model that describes light as travelling as waves

Syllabus link
The photon model and wave–particle duality will be investigated further in Units 3 & 4.

Photon (particle) model

Some interactions of light with matter cannot be explained by treating light solely as a wave. To understand these interactions, we model light as consisting of particles called **photons**, each with a characteristic energy. When light interacts with matter, an entire photon, but not part of a photon, may be absorbed (or emitted). This is the quantum particle model of light, as the photons are discrete quanta of light energy.

In this chapter, we shall be using the ray and wave models.

photon a particle of light

LEARNING CHECK 17.1

DESCRIBING

1 Name the three models of light.
2 What is a photon?
3 **Compare** the key features of the three models of light.

APPLYING

4 Why is the question ‘What is light?’ misleading? How should the question be restated? **Explain** your answer.

Weblink
Is light a particle or a wave?

17.2 The wave model of light

Modelling light as a wave is very effective in describing many observed phenomena. However, there is one major difficulty with this model that took many years to resolve: all mechanical waves need some medium to transfer energy, so what exactly do light waves travel through?

The modern understanding of the expanses of space is that it consists of an effective vacuum and, as such, light from objects such as the Sun does not travel through a medium and therefore cannot be considered as mechanical waves.

Electromagnetic waves

In the second half of the 19th century, James Clark Maxwell used the new discovery of a relationship between electricity and magnetism to construct a mathematical model that

electromagnetic radiation energy that travels as waves and moves at the speed of light

Syllabus link
Electromagnetic waves are discussed in greater detail in Units 3 & 4.

electromagnetic wave model a model that states that light acts like a transverse wave that has electric and magnetic components

luminiferous aether a non-existent substance that was proposed to exist in early wave models of light as the medium through which light could travel

Syllabus link
Einstein's theory of relativity and its strange predictions is investigated in Units 3 & 4.

predicted the existence of **electromagnetic radiation** that travelled as waves. His theories suggested that an oscillating electric charge in one direction (*E* in **Figure 17.2.1**) causes a magnetic effect at right angles (*B* in Figure 17.2.1), which would result in an electromagnetic wave travelling off at right angles to both.

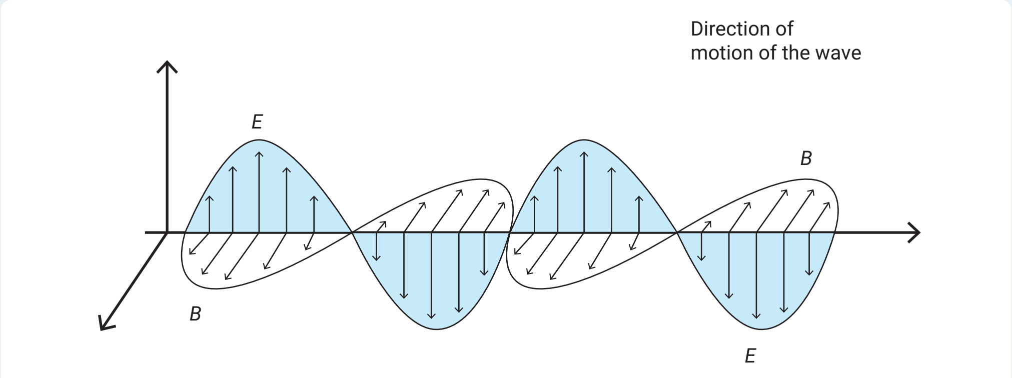


FIGURE 17.2.1 In an electromagnetic wave, the electric (*E*) and magnetic (*B*) effects oscillate at right angles to each other, while the wave travels in the third dimension at right angles to both effects.

Maxwell's model explained all the light phenomena that had been observed up until that time and, importantly, explained that these waves could propagate through empty space.

The **electromagnetic wave model** of light states that, in its interactions with matter, light acts like a three-dimensional transverse wave.

Luminiferous aether

Considering the success of the mechanical wave theory, it was natural for physicists to assume that if light was a wave, it must also travel through a medium. They postulated the existence of a transparent substance that permeated all of space, which they called the **luminiferous aether**.

In this theory, the aether was stationary while Earth travelled through it and therefore light had to travel at different speeds in different directions. Scientists designed many experiments to observe this prediction. The most famous was the Michelson–Morley experiment (**Figure 17.2.2**).

Michelson and Morley's experiment sought to detect Earth's motion through the luminiferous aether, a hypothetical medium thought to fill space and carry light waves. However, their meticulous measurements of the speed of light in different directions yielded unexpected results: there was no discernible difference in the speed of light, regardless of Earth's motion (Figure 17.2.2). This experimental outcome challenged the notion of the luminiferous aether and provided compelling evidence against its existence. It supported the wave theory of light, which posits that light propagates through a vacuum as a wave, independent of any medium. The significance of wave properties in this experiment underscores the power of empirical evidence in shaping scientific understanding. By embracing experimentation and challenging established beliefs, scientists like Michelson and Morley paved the way for transformative advancements in physics and reshaped our perception of the universe.

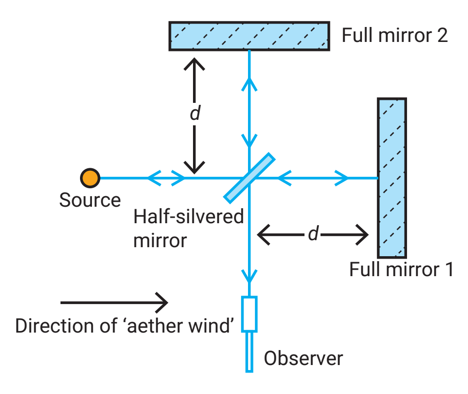


FIGURE 17.2.2 The Michelson–Morley experiment showed that the time taken for light to travel in different directions through the hypothetical luminiferous aether was the same.

Ray model of light waves

In the ray model of light, light waves are modelled as travelling in straight lines from their source (Figure 17.2.3). This can be shown for the waves emanating from a light globe.

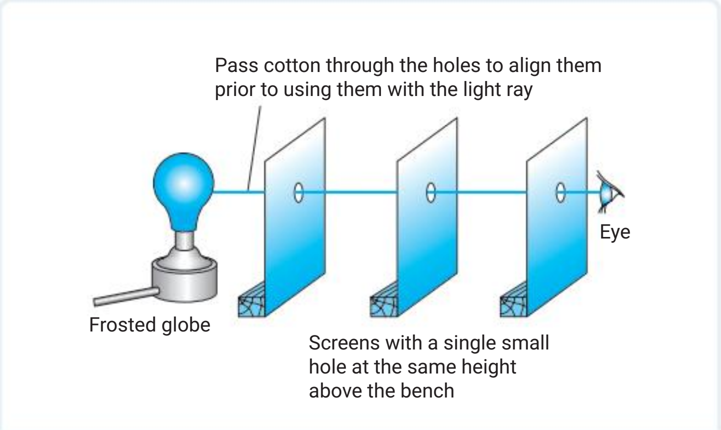
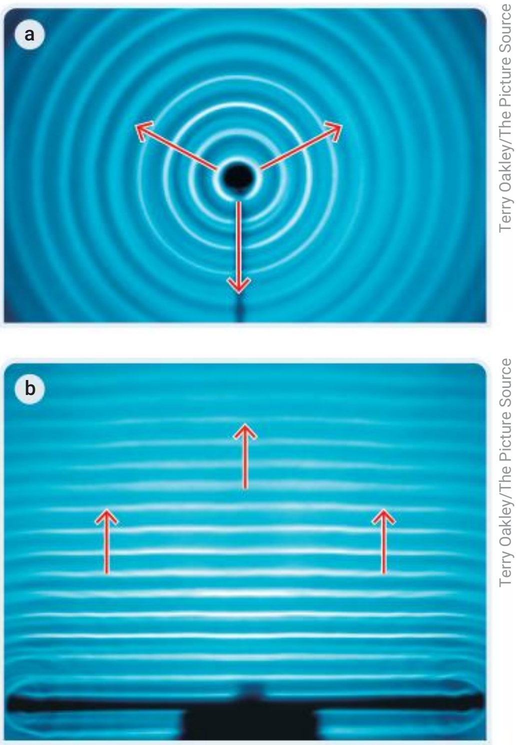


FIGURE 17.2.3 Light travels along a straight line from its source.

These rays represent the direction travelled by the light waves. The waves emanating from a light source can be considered to act like the water waves produced when a stone is dropped into a pond. Each direction is represented by a straight-line ray emanating from the source and acting at right angles to the wavefronts, as in Figure 17.2.4.

If the source of light is being observed from far away, the wavefronts will appear similar to plane waves and the rays will become more parallel. In fact, if the source of light is infinitely far away (and the Sun and stars can be considered as approaching this) these rays would become precisely parallel (Figure 17.2.5).



Terry Oakley/The Picture Source

Terry Oakley/The Picture Source

FIGURE 17.2.4 Light rays used in the ray model are always drawn at right angles to the wavefront. (**a**) Circular waves from a point source showing radial rays at right angles to the wavefront; (**b**) straight waves showing rays at right angles to the wavefront.

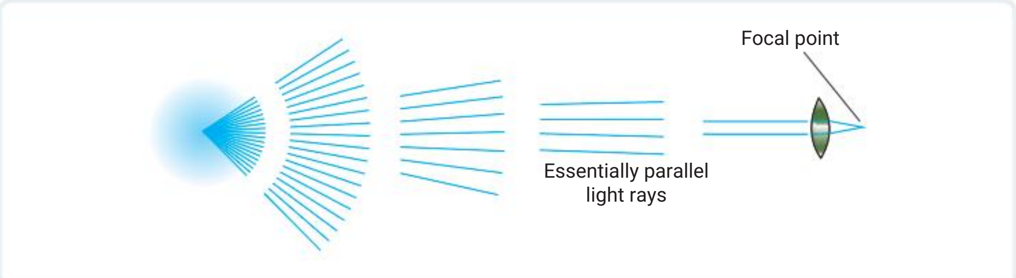


FIGURE 17.2.5 Light rays emanating from a distant source become effectively parallel when viewed from a distance.

Sources of light

Luminous light sources (light bulbs, the Sun, lasers) produce light directly by internal processes. **Non-luminous** sources (the Moon, a photographer's silver umbrella) reflect light.

luminous a source that produces light

non-luminous a source that reflects light

Contrasting the speed of light and the speed of mechanical waves

Between 1848 and 1862, Hippolyte Fizeau (1819–96) and Léon Foucault (1819–68) used precision clocks and clockwork motors to make the first terrestrial measurements of the speed of light in air and water. They showed that light travels more slowly in water than in air **(Figure 17.2.6)**.

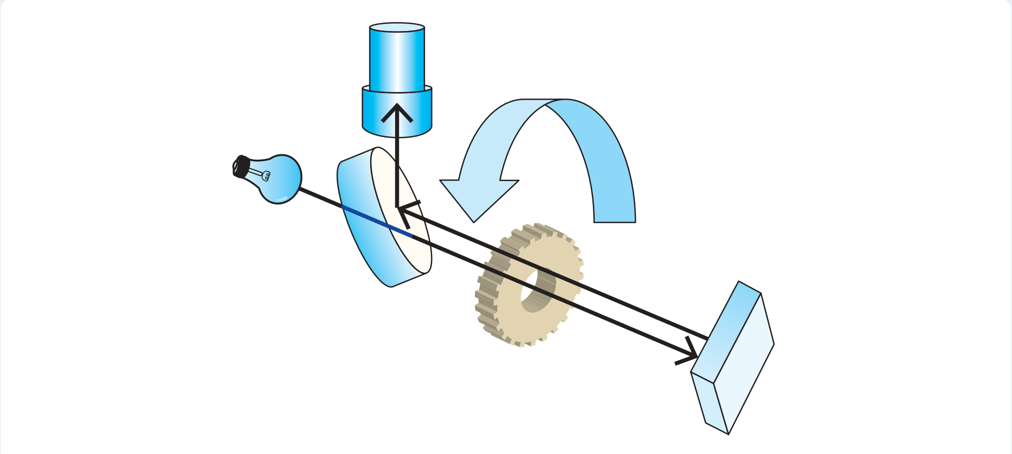


FIGURE 17.2.6 Fizeau's method for measuring the speed of light. A ray of light passes between adjacent teeth of a toothed wheel and is reflected. When the wheel is turned fast enough, the reflected light is blocked by the next tooth.

The medium affects the speed of light. Foucault's best result for the speed of light, found in 1862, was $2.998 \times 10^8\,\mathrm{m\,s^{-1}}$.

The current accepted value for the speed of light in a vacuum and air is $2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ ($3.0 \times 10^8\,\mathrm{m\,s^{-1}}$). This is an important constant that is often used, so it is given a unique symbol, *c*. Compare this velocity to that of sound, which travels at about $346\,\mathrm{m\,s^{-1}}$ in air. Light is almost 875 000 times faster than sound!

WORKED EXAMPLE 17.2.1

A race official will traditionally fire a starter's pistol to signal the beginning of a 100 m sprint. Calculate the delay that a spectator standing at the finish line will observe between seeing the flash of smoke from the pistol to hearing its sound.

ANSWER

1 State the equation.

$$t = \frac{s}{v}$$

2 Substitute known values for light.

$$t = \frac{s}{v}$$

$$= \frac{100\,\mathrm{m}}{3.0 \times 10^8\,\mathrm{m\,s^{-1}}} = 3.33 \times 10^{-7}\,\mathrm{s}$$

3 Substitute known values for sound.

$$t = \frac{s}{v}$$

$$= \frac{100\,\text{m}}{346\,\text{m s}^{-1}} = 0.289\,\text{s}$$

4 Calculate the difference.

$\Delta t = t_{\text{sound}} - t_{\text{light}}$

$= 0.289\,\text{s} - 3.33 \times 10^{-7}\,\text{s} = 0.289\,\text{s}$

The spectator will hear the pistol fire 0.289 s after she sees the smoke of the pistol.

As with all waves, the velocity of light can be calculated from the frequency and wavelength with the formula $v = f\lambda$. But since the speed of light is constant in a given medium, the velocity (v) in this equation can be replaced with a constant (c) representing the speed of light in that medium ($c_{\text{air}} = 3.0 \times 10^8\,\text{m s}^{-1}$). Because the wavelengths of visible light are so small, they are often expressed in nanometres (nm), where 1 nm = 1×10^{-9} m. If wavelength is provided in these units, they must be converted to metres when using the wave equation.

$$c = f\lambda$$

where:

c = the speed of light = $3.0 \times 10^8\,\text{m s}^{-1}$

f = the frequency of the light wave (Hz)

λ = the wavelength of light (m)

KEY FORMULA

The speed of light

$c = f\lambda$

where:

c = the speed of light = $3.0 \times 10^8\,\text{m s}^{-1}$

f = the frequency of the light wave (Hz)

λ = the wavelength of light (m)

WORKED EXAMPLE 17.2.2

If a light wave has a wavelength of 450 nm in air, calculate its frequency.

ANSWER

1 State the equation.

$c = f\lambda$

2 Rearrange to find the unknown.

$$f = \frac{c}{\lambda}$$

3 Substitute known values.

$$f = \frac{3 \times 10^8\,\text{m s}^{-1}}{450 \times 10^{-9}\,\text{m}}$$

4 Calculate the answer.

$f = 6.6667 \times 10^{14}\,\text{Hz}$

5 Give the answer to the correct number of significant figures.

$f = 6.7 \times 10^{14}\,\text{Hz}$

Light intensity

KEY FORMULA

Intensity of a wave

$$I = \frac{\frac{E}{t}}{A} = \frac{P}{A}$$

where:
I = intensity (W m^{-2})
E = energy (J)
t = time (s)
A = area (m^2)
P = power (W)

Light from a point source spreads uniformly into the surrounding space in much the same way as the energy of mechanical waves. The light intensity is calculated as the energy per unit time (power) that is transported through an area perpendicular to the direction of travel and has the unit of watts per square metre (W m^{-2}).

$$I = \frac{\frac{E}{t}}{A} = \frac{P}{A}$$

where:
I = intensity (W m^{-2})
E = energy (J)
t = time (s)
A = area (m^2)
P = power (W)

A light wave travels out in all directions from its source in a three-dimensional sphere. As the wave moves outwards, the energy that was emitted from the source becomes spread over a larger spherical surface **(Figure 17.2.7)**. As a result, the intensity of the wave decreases the further the wave gets from the source.

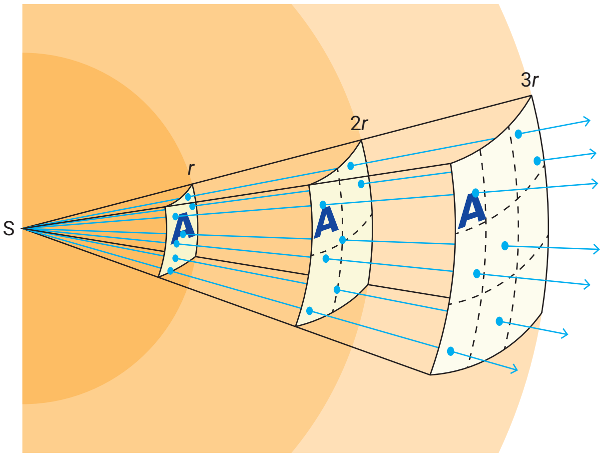


FIGURE 17.2.7 Light from a point source spreads uniformly into the surrounding space.

KEY FORMULA

Light wave intensity

$$I \propto \frac{1}{r^2}$$

where:
I = intensity (W m^{-2})
r = distance from the source (m)

The intensity at any point can be calculated as the power over the area ($4\pi r^2$):

$$I = \frac{P}{4\pi r^2}$$

If we assume the power at the source is constant, then we can see that the intensity is inversely proportional to the square of the distance from the source:

$$I \propto \frac{1}{r^2}$$

In Figure 17.2.7, if the source (S) emits a wave of power P, then at a distance r from the source, the wave has an intensity I_1 of:

$$I = \frac{P}{r^2}$$

which can be rearranged:

$$P = I_1 r^2$$

Similarly, at a distance 2*r* from the source:

$$I_2 = \frac{P}{(2r)^2} = \frac{P}{4r^2}$$

or:

$$P = 4I_2r^2$$

Since the power of the source, *P*, is constant:

$$4I_2r^2 = I_1r^2$$

or:

$$I_2 = \frac{1}{4}I_1$$

This shows that if the distance doubles ($2r/r = 2$), then the intensity is reduced to a quarter.

WORKED EXAMPLE 17.2.3

If the wave in Figure 17.2.7 has an intensity of 900 W m^{-2} at a distance *r* from the source, calculate its intensity at a distance 3*r* from the source.

ANSWER

1 State the equation.

$$I_1 = \frac{P}{r^2}$$

2 Rearrange to find the unknown.

$$P = I_1r^2 \qquad (1)$$

3 Substitute known values.

$$I_3 = \frac{P}{(3r)^2}$$

4 Expand the bracket and rearrange.

$$I_3 = \frac{P}{9r^2}$$

$$I_3 = \frac{1}{9} \times \frac{P}{r^2} \qquad (2)$$

5 Substitute equation (1) into equation (2).

$$I_3 = \frac{1}{9}I_1$$

6 Substitute known values.

$$I_3 = \frac{1}{9} \times 900\ \text{W m}^{-2}$$

7 Calculate the answer.

$$I_3 = 100\ \text{W m}^{-2}$$

Use of the wave model of light to describe phenomena

The wave model of light, coupled with the ray model, is very effective at describing many common observations. This chapter will use these models to investigate polarisation, reflection, total internal reflection, refraction, dispersion, diffraction and interference.

LEARNING CHECK 17.2

DESCRIBING

1 **Describe** the key features of an electromagnetic wave.
2 What is the difference between luminous and non-luminous sources of light?
3 **Explain** the great benefit of the electromagnetic theory of light.
4 **Explain** why light rays emanating from distant objects can be considered parallel.
5 **Explain** how the wave model of light can explain the intensity law for point sources of light.

APPLYING

6 If the frequency of a light wave is 5.0×10^{14} Hz, **calculate** its wavelength.
7 If the intensity of light from a constant power light source is 200 W m^{-1} at a distance of 1.5 m from the source, **calculate** the intensity of light 3.0 m further out.
8 **Discuss** how you could use Fizeau's experiment to measure the distance to objects.

17.3 Polarisation and the transverse wave model

polarisation orientation in one direction of the electrical part of electromagnetic waves

polariser material that selects the direction of polarisation

analyser material that allows or stops polarised electromagnetic radiation

Polaroid material is made from many small, naturally polarising and transparent crystals on a polyvinyl plastic base. When two sheets are arranged so that their polarising planes are parallel, light is transmitted. However, when one sheet is rotated through 90°, no light is transmitted.

Polarisation can be observed in natural and human-constructed environments. It shows that electromagnetic waves are transverse waves. A mechanical analogy or model can be used to explain polarisation. In **Figure 17.3.1a**, both slits 1 and 2 are arranged vertically. If slit 2 is placed horizontally, the vertically polarised waves from slit 1 (**polariser**) cannot pass through slit 2 (**analyser**), as seen in **Figure 17.3.1b**.

Longitudinal waves cannot be polarised. They travel in the same plane, so the oscillations can always go through both slits 1 and 2.

LEARNING CHECK 17.3

DESCRIBING

1 **Describe** and **explain** 'polarisation'.
2 **Describe** why longitudinal waves cannot be polarised.
3 Explain the use of the polariser and the analyser in the mechanical model of polarisation.

APPLYING

4 **Explain** how sunglasses use polarised lenses to reduce the intensity of light from the Sun.

5 Light from an electric globe passes through a polariser. An analyser is placed over the polariser, making the globe look dark. With every quarter turn, the transmitted light goes from a dark minimum to a bright maximum. Use the electromagnetic wave model of light to **explain** this phenomenon.

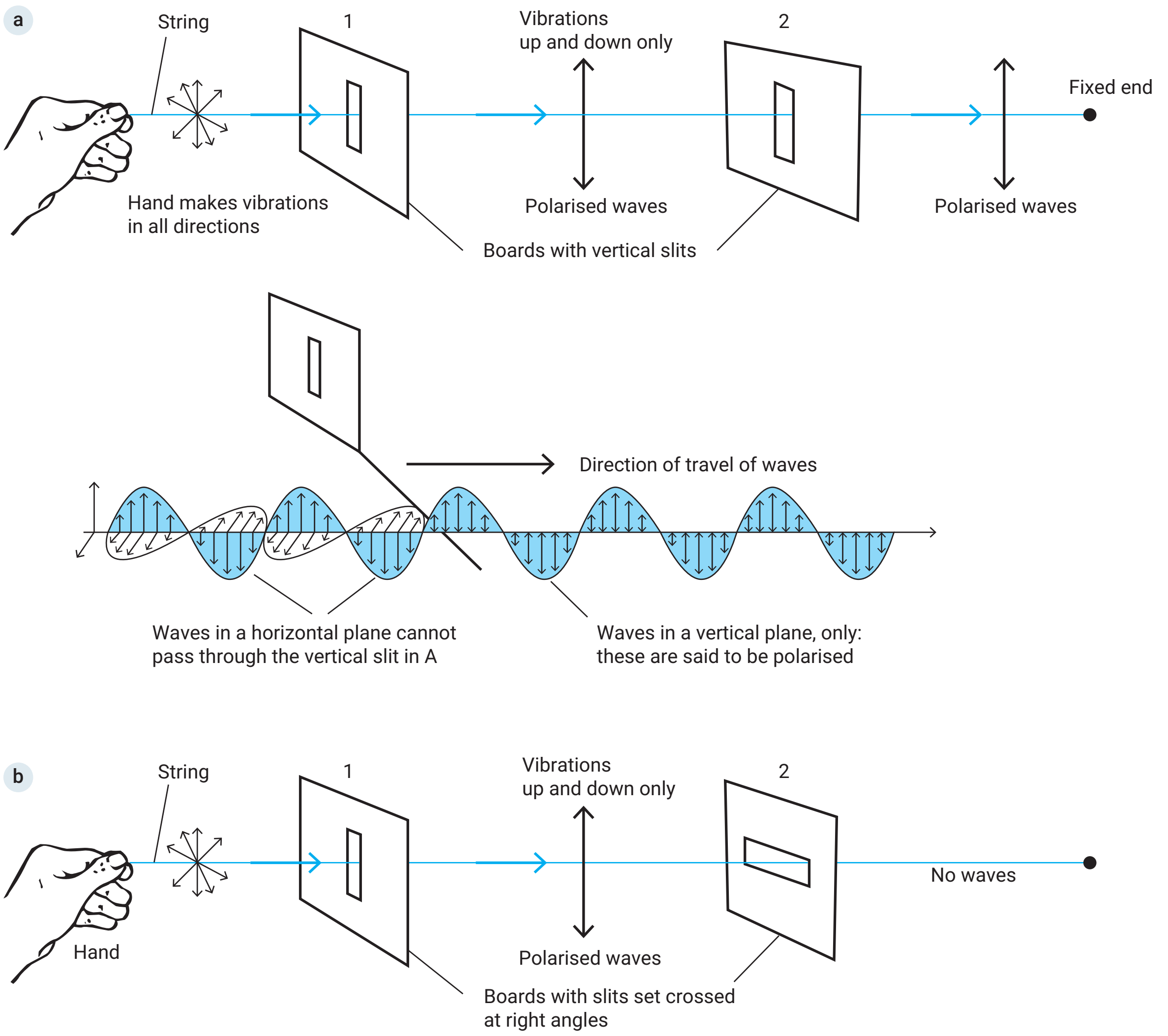


FIGURE 17.3.1 A mechanical model for explaining polarisation. (a) Vertically oriented transverse waves pass through slits 1 and 2. (b) Vertically polarised waves pass through slit 1 but cannot pass through slit 2, which is perpendicular to 1.

17.4 Reflection of light

When a beam of light is incident on a smooth, polished surface such as a **plane mirror** or a very still water surface, the rays of light forming the beam are reflected in a predictable way. This is **regular** or **specular reflection** (Figure 17.4.1).

plane mirror a mirror with a plane (flat) reflecting surface

regular (or specular) reflection predictable reflection from a very smooth surface; rays in a beam all reflect in the same direction

diffuse reflection (scattering) reflection from a rough surface; rays in a beam reflect in different directions

opaque not transparent; not able to be seen through

normal a line drawn perpendicular to a surface

coplanar in the same plane

angle of incidence the angle made between an incident wave and a normal drawn to the surface at the point of incidence

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

puttsk/Shutterstock.com

FIGURE 17.4.1 An almost perfect reflection in a still pool of water is an example of specular reflection.

Most surfaces reflect incident light in all directions. This is known as **diffuse reflection** (or **scattering**). For example, a sheet of paper or a painted wall appears smooth, but a microscopic examination of the surface shows it to be rough (Figure 17.4.2). Parallel rays incident on a rough surface are scattered in all directions. This is a particularly important property – **opaque** objects are visible from many different angles.

Terry Oakley/The Picture Source

FIGURE 17.4.2 Diffuse and regular reflection from a mirror in front of a white piece of paper. The mirror is mainly dark because light is not reflected to the camera, while the paper reflects light in all directions, including towards the camera. The candle and its image are recorded by diffuse reflection to the camera.

Law of reflection

Reflection from surfaces always follows the law of reflection. This is true for specular and diffuse reflection; however, it is easier to observe specular reflection. The law of reflection has two parts:

1. The incident ray, the **normal** perpendicular to the surface, and the reflected ray all lie in the same flat surface (they are **coplanar**).
2. The angle between the incident ray and the normal (the **angle of incidence**) is equal to the angle between the normal and the reflected ray (the **angle of reflection**): $\angle i = \angle r$.

This applies at any point on a surface (Figure 17.4.3). Figure 17.4.3a shows the simple case of a flat surface, and hence

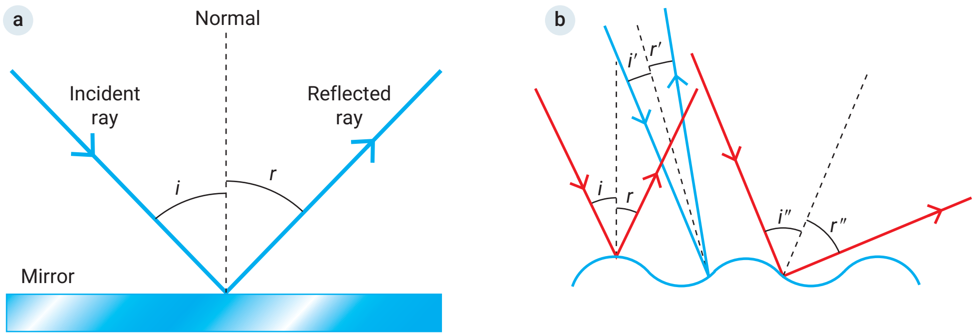


FIGURE 17.4.3 (a) Specular reflection; (b) diffuse reflection

Weblink
Reflection of light

is specular reflection. Figure 17.4.3b shows the case of a rough surface, and hence shows diffuse reflection.

Solving problems: reflection of light using ray diagrams

Problems involving the reflection and refraction of light waves off mirrors and through lenses can often be diagrammatically solved with the use of the **ray diagram** convention.

In this convention, light rays are drawn both for the incident and for the reflected and refracted rays.

The angles of the rays are measured from the normal to the surface rather than the surface itself. The normal is drawn perpendicular to the surface, and in the plane of the two rays.

ray diagram a diagram that traces the path taken by light

Reflection using the ray model

When a person stands in front of a plane mirror, they see a reflection of themselves. This reflection appears to be in front of them, beyond the mirror, but it isn't; it is an **image** of the person.

Light radiates from a **point source** in all directions. When the rays strike a plane mirror, they reflect ($\angle i = \angle r$). They appear to come from an image point, a **virtual image**, behind the mirror. The rays that enter our eyes must affect our retinas. Reflected rays form a **real image** in our eyes. Psychologically, we perceive a virtual image of the object to be where it is not physically present.

Figure 17.4.4 shows how the image is formed and seen by an observer. Rays of light from the object, O, travel to the mirror and reflect such that the angle of incidence is equal to the angle of reflection. Two rays are shown, which reflect at points A and B. When we look towards points A and B on the mirror, it appears that light is coming from these points. If we extend the rays behind the mirror, they intersect at point I behind the mirror. Point I is the position of the image.

image a picture of an object

point source a single located source from light transmits equally in all directions

virtual image an image of an object where the rays do not pass through the image; the image cannot be projected onto a screen

real image an image of an object where the rays of the image do not pass through the image itself; the image can be projected onto a screen

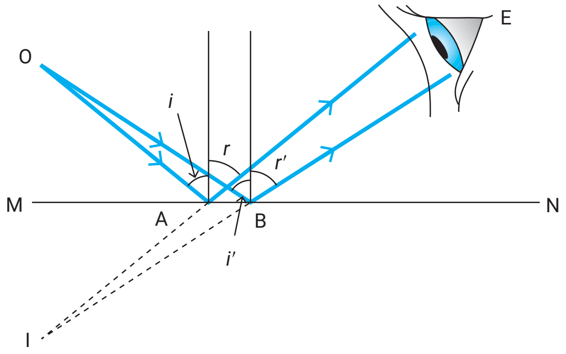


FIGURE 17.4.4 Reflected rays are perceived to be coming from behind the mirror. The image is virtual because the rays do not pass through the image. A real image is formed on the retina of the eye.

Figure 17.4.5 shows a ray diagram that allows us to find the magnification and position of the image. We draw our object as having some actual size, such as the arrow in Figure 17.4.5. We draw rays coming from the top of the object and reflecting from the mirror. The rays must obey the law of reflection as shown. We again extend the reflected rays behind the mirror to the point at which they intersect. This point corresponds to the top of the image, the arrowhead. Our object has a height equal to the distance between the mirror, M, and point O; the image has a height equal to the distance between the mirror, M, and point I. The ratio of these distances is the **magnification**. For a plane mirror:

$$M = \frac{h_i}{h_o} = 1$$

magnification (*M*) the ratio of image height to object height

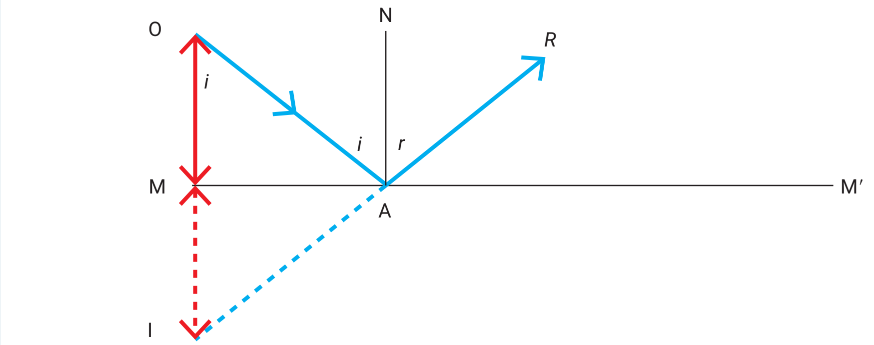


FIGURE 17.4.5 A geometric construction to show the law of reflection

LEARNING CHECK 17.4

DESCRIBING

1 Write down both statements for the law of reflection. Draw a diagram to show this law.

2 Use the ray model to illustrate diffuse reflection.

APPLYING

3 A ray from a point object strikes a plane mirror at an angle of incidence of 30°. Use a carefully measured diagram to show that the object and the image are equidistant on opposite sides of the mirror.

4 How do we see a virtual image in a plane mirror? Use a ray diagram to assist in your explanation.

ANALYSING

5 The eyes of a 170 cm tall woman are 160 cm above the ground. She stands 0.60 m in front of a plane mirror that is mounted vertically and sees her entire image. What is the shortest mirror that can be used for such a purpose? Illustrate your answer with a diagram.

6 Prove that the image is exactly the same distance behind the mirror as the object is in front of the mirror. (MO = MI in Figure 17.4.5).

17.5 Snell’s law and the refraction of light

Terry Oakley/The Picture Source

FIGURE 17.5.1 A straight stick apparently bends or breaks at the interface between air and water.

When a ray of light travels from one transparent medium into another at an angle other than 90° to the boundary, it changes direction. This phenomenon is called refraction. The amount of refraction is mainly related to differences in the electrical properties of each medium. The electromagnetic wave changes speed depending on how well the electromagnetic wave is permitted to move through the medium.

Refraction is responsible for many strange optical effects, such as the apparent bending of a straight stick that is partly in water and partly in air **(Figure 17.5.1)**.

Refractive index

Refraction can occur whenever light passes from one medium into another. We can characterise any medium by its refrangibility. **Refrangibility** is a measure of how much refraction occurs when light moves into a particular material from a vacuum.

The number used to compare refrangibilities is called the **refractive index**. The value of the refractive index of a vacuum is defined as the value 1.00. Other values express the ratio of the refrangibility of a medium to that of a vacuum. Relative to a vacuum, all other values are greater than 1.00 for visible light.

When light moves from one material to a second material with a similar refractive index, there is very little refraction. This is the case when light moves from a vacuum to air, which has a refractive index close to 1.00. When light moves from one medium to a second medium with a very different refractive index, there is strong refraction. For example, diamond has a refractive index of 2.42 for visible light. Hence, light entering a diamond from air is slowed down a lot and bends significantly.

refrangibility a measure of how much refraction occurs when light moves into a particular material from a vacuum

refractive index a measure of refrangibility; a measure of the relative change of direction of waves or light rays when travelling from one medium to another

angle of refraction (*r*) the angle that a refracted ray makes with the normal

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Refraction and Snell's law

Snell's law of refraction

When a light ray refracts at a boundary between two different transparent media, it makes an angle of incidence (*i*) with the normal to the boundary in the first medium. The refracted ray makes an **angle of refraction (*r*)** with the normal in the second medium.

All experiments conducted for refraction at a boundary demonstrate the two laws of refraction.

1. The incident ray, the normal and the refracted ray are coplanar.
2. Snell's law is the quantitative expression of the relationship between the incident and refracted rays:

$$\frac{\sin i}{\sin r} = \text{constant}$$

where:
i = the angle of incidence (degrees)
r = the angle of refraction (degrees)
constant = a constant number (dependent upon the refractive indices of the two media)

KEY FORMULA

Snell's law of refraction

$$\frac{\sin i}{\sin r} = \text{constant}$$

where:
i = the angle of incidence (degrees)
r = the angle of refraction (degrees)
constant = a constant number (dependent upon the refractive indices of the two media)

WORKED EXAMPLE 17.5.1

If a wavelength of light is incident at 15° upon a substance, it is observed it has an angle of refraction of 25°. Calculate the angle of refraction that would result if the angle of incidence was increased to 21°.

ANSWER

1 **State the equation.**

$$\frac{\sin i}{\sin r} = \text{constant}$$

2 **Determine the relationship between the two scenarios.**

$$\frac{\sin i_1}{\sin r_1} = \frac{\sin i_2}{\sin r_2}$$

3 Rearrange to find the unknown.

$$\sin r_2 = \sin i_2 \frac{\sin r_1}{\sin i_1}$$

4 Substitute known values.

$$\sin r_2 = \sin(21°)\frac{\sin(25°)}{\sin(15°)}$$

5 Calculate the answer.

$\sin r_2 = 0.5852$

6 Rearrange to find the unknown.

$r_2 = \sin^{-1}(0.5852)$

7 Calculate the answer.

$r_2 = 35.815°$

8 Give the answer with the correct number of significant figures.

$r_2 = 36°$

Snell's law for waves

Figure 17.5.2 shows the wavefronts of waves moving from deep water into shallow water. The waves are bending towards the normal, from which it can be deduced that they are slowing down. The wavelength is also changing when this happens – it is becoming shorter. **Figure 17.5.3** is a schematic diagram showing the wavefronts and interface in Figure 17.5.2.

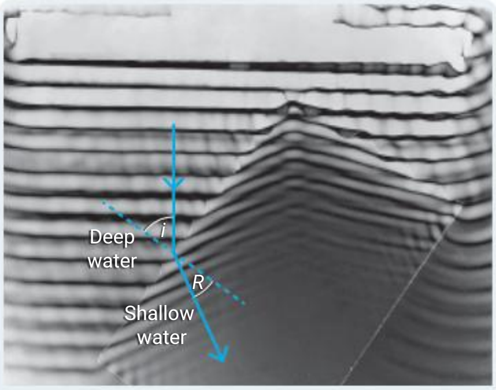


FIGURE 17.5.2 Water waves in deeper water refract towards the normal when they pass into shallower water. Their speed in the shallower water is less than in the deeper water.

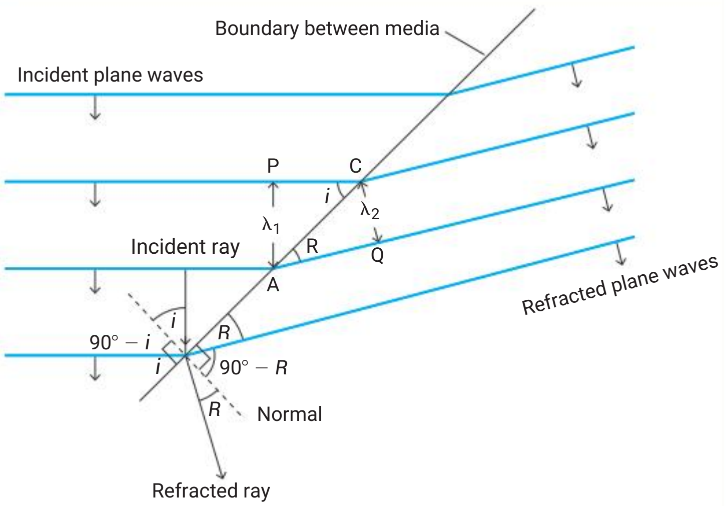


FIGURE 17.5.3 Schematic of refraction of waves. Incident rays in medium 1 and refracted rays in medium 2 are drawn at right angles to the wavefronts. Wavelengths λ_1 and λ_2 relate to medium 1 and 2 respectively.

When light crosses the interface between two media, it may slow down or speed up depending on the difference in the optical properties of the media. This difference is encapsulated in the relative difference between the refractive indices. If the light slows down, then the ray that describes its direction of travel bends towards the normal to the interface. If the light speeds up, then it bends away from the normal. Hence, in Figure 17.5.3 in which light is shown bending towards the normal when it moves from medium 1 into medium 2, the light must be slowing down as it crosses the interface.

The geometry of Figure 17.5.3 can be used to show two useful results:

$$\frac{\sin i}{\sin r}=\frac{\lambda_1}{\lambda_2} \quad \text{and} \quad \frac{\sin i}{\sin r}=\frac{v_1}{v_2}$$

In ΔACP:

$$\sin i=\frac{\lambda_1}{\text{AC}}$$

and in ΔACQ:

$$\sin r=\frac{\lambda_2}{\text{AC}}$$

Thus:

$$\frac{\sin i}{\sin r}=\frac{\lambda_1/\text{AC}}{\lambda_2/\text{AC}}$$

Finally:

$$\frac{\sin i}{\sin r}=\frac{\lambda_1}{\lambda_2}$$

This result enables us to show the ratio of speeds. The waves enter and leave the boundary at the same rate because the frequency of the waves does not change. From the equation $v=f\lambda$, we can easily show that:

$$\frac{f\lambda_1}{f\lambda_2}=\frac{v_1}{v_2}$$

or:

$$\frac{\lambda_1}{\lambda_2}=\frac{v_1}{v_2}$$

So:

$$\frac{\sin i}{\sin r}=\frac{v_1}{v_2}$$

This expression shows that waves slow down in a medium in which the wavelength decreases and the refraction is towards the normal. The decrease in speed is not a cause of the refraction. Neither is the decrease in wavelength a cause of the speed change. The speed decreases because of the interaction of the waves with the medium. For electromagnetic radiation, this means that the different materials have different electrical and magnetic properties. It is the interaction of light with these properties of the materials that causes the change of speed.

absolute refractive index a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light

relative refractive index the comparative difference in refrangibility between two media with different absolute refractive indices

Absolute refractive index

The **absolute refractive index** is a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light. Each absolute refractive index is experimentally determined. Refractive index is one of the ways by which materials can be identified. Notice that we often shorten ‘absolute refractive index’ to ‘refractive index’, when it is clear what we mean **(Table 17.5.1)**.

TABLE 17.5.1 Refractive indices of some common materials

Material	Refractive index
Vacuum	1.0000
Air	1.0003
Water	1.33
Crown glass	1.52
Flint glass	1.65
Diamond	2.42

Air has almost the same refractive qualities as a vacuum. In fact, the two media do not differ until the fourth decimal place. Rounded to two decimal places, the two media are effectively the same, which is why air is usually used as a good approximation to a vacuum in cases where very high levels of accuracy are not required.

Relative refractive index

The **relative refractive index** is the comparative difference in refrangibility between two media with different absolute refractive indices. From Table 17.5.1, we see that water is 1.33 times, and diamond is 2.42 times, more refractive than air. If a diamond is placed in water, its refrangibility is reduced – it is only $\frac{2.42}{1.33} = 1.82$ times as refractive as it is in air: ($n_{\text{diamond rel water}} = 1.82$). This is still highly refractive compared with various types of glass.

If a piece of sand, $n_{\text{sand}} = 1.46$, is placed in oleic acid of a similar colour, $n_{\text{oleic acid}} = 1.46$, it cannot be distinguished optically from the oleic acid because their refractive indices are the same:

$$n_{\text{sand rel oleic acid}} = \frac{1.46}{1.46} = 1.00$$

The relative difference in refractive index between two media does not have to be very much for the effect to be noticed. Hot air has a slightly lower refractive index than cold air, of the order of 0.1%, yet this difference is why we can see a shimmering heat haze above a fire or near the road surface on a hot day. We shall see that quite small differences in the refractive indices of different types of glass enables light to travel very efficiently down optical fibres.

Refraction towards and away from the normal

Relative refractive indices can be greater than or less than 1.00. If the relative refractive index is greater than 1.00, then the refracted ray deviates from the straight-through ray towards the normal. **Figure 17.5.4a** shows a ray refracting towards the normal as it travels from air to glass. The relative refractive index is:

$$n_{\text{glass rel air}} = \frac{1.33}{1.00} = 1.33$$

If the relative refractive index is greater than 1.00, then the refracted ray deviates towards the normal **(Figure 17.5.4a)**.

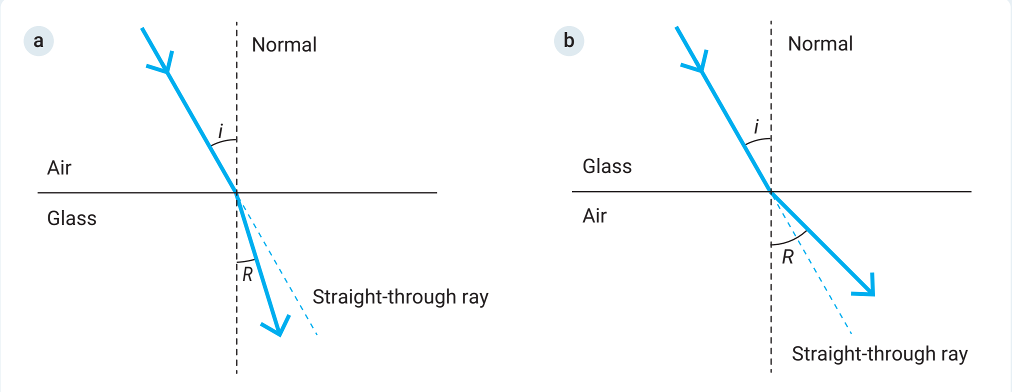


FIGURE 17.5.4 (a) Refraction at the air–glass boundary is towards the normal. (b) but away from the normal when the rays are reversed (glass–air).

If the rays are reversed and travel from glass to air (**Figure 17.5.4b**), the relative refractive index becomes less than 1.00, and refraction away from the normal occurs:

$$n_{\text{air rel glass}} = \frac{1.00}{1.33} = 0.75$$

Snell's law for waves

In defining refrangibility in terms of relative refractive indices, we have used the general form of Snell's law:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

Combining this with the expression of Snell's law for waves, we can summarise Snell's law as follows:

$$\frac{\sin i}{\sin r} = \frac{\lambda_i}{\lambda_R} = \frac{v_i}{v_R} = \frac{n_2}{n_1} = \text{constant}$$

where:

i = angle of incidence (degrees)
r = angle of refraction (degrees)
λ_i = wavelength of the incident wave (m)
λ_R = wavelength of the refracted wave (m)
v_i = velocity of the incident wave (m s^{-1})
v_R = velocity of the refracted wave (m s^{-1})
n_1 = refractive index of the medium in which the incident wave is travelling
n_2 = refractive index of the medium in which the refracted wave is travelling
constant = relative refractive index of the two media

KEY FORMULA

Snell's law for waves

$$\frac{\sin i}{\sin r} = \frac{\lambda_i}{\lambda_R} = \frac{v_i}{v_R} = \frac{n_2}{n_1} = \text{constant}$$

where:

i = angle of incidence (degrees)
r = angle of refraction (degrees)
λ_i = wavelength of the incident wave (m)
λ_R = wavelength of the refracted wave (m)
v_i = velocity of the incident wave (m s^{-1})
v_R = velocity of the refracted wave (m s^{-1})
n_1 = refractive index of the medium in which the incident wave is travelling
n_2 = refractive index of the medium in which the refracted wave is travelling
constant = relative refractive index of the two media

WORKED EXAMPLE 17.5.2

Light of wavelength 550 nm travels in water ($n_w = 1.33$) before it strikes the interface with flint glass ($n_g = 1.65$) at an angle of 36° to the normal.

a What is the wavelength of the light in flint glass? Give your answer in nm.

b What is the angle of refraction in the glass?

c Draw a diagram of the scenario.

d If the light has a velocity of 1.81×10^8 m s^{-1} when it is in the flint glass, with what velocity must it have been travelling in water?

ANSWERS

a **1** **State the equation.**

$$\frac{\lambda_i}{\lambda_R} = \frac{n_2}{n_1}$$

2 **Rearrange to find the unknown.**

$$\lambda_R = \frac{\lambda_i \times n_1}{n_2}$$

3 **Substitute the known values.**

$$\lambda_R = \frac{550 \times 10^{-9}\ \text{m} \times 1.33}{1.65}$$

4 **Calculate the answer.**

$$\lambda_R = 4.433 \times 10^{-7}\ \text{m}$$

5 **Give the answer in the correct format and with the correct number of significant figures.**

$$\lambda_R = 440\ \text{nm}$$

b **1** **State the equation.**

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

2 **Rearrange to find the unknown.**

$$\sin r = \frac{n_1 \times \sin i}{n_2}$$

3 **Substitute known values.**

$$\sin r = \frac{1.33 \times \sin 36°}{1.65}$$

4 **Calculate.**

$$\sin r = 0.477$$

5 **Rearrange to find the unknown.**

$$r = \sin^{-1}(0.477)$$

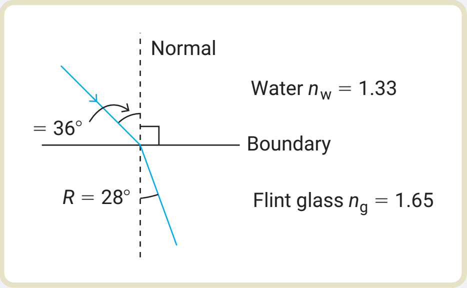
6 **Calculate the answer.**

$$r = 28.28°$$

7 **Give the answer with the correct number of significant figures.**

$$r = 28°$$

c



d 1 State the equation.

$$\frac{v_i}{v_R} = \frac{n_2}{n_1}$$

2 Rearrange to find the unknown.

$$v_i = \frac{n_2 \times v_R}{n_1}$$

3 Substitute the known values.

$$v_i = \frac{1.65 \times 1.81 \times 10^8\ \text{m s}^{-1}}{1.33}$$

4 Calculate the answer.

$v_i = 2.245\,488\,72 \times 10^8\ \text{m s}^{-1}$

5 Give the answer in the correct format and with the correct number of significant figures.

$v_i = 2.25 \times 10^8\ \text{m s}^{-1}$

WORKED EXAMPLE 17.5.3

The refractive index for materials may be determined by using Snell's law and measurements of angles of incidence and of refraction. Snell's law states:

$$\frac{\sin i}{\sin r} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

where: n_1 and n_2 are the refractive indices of the two media
i is the angle of incidence (the angle between the incident ray and the normal)
r is the angle of refraction (the angle between the refracted ray and the normal)

Determine the refractive index of Perspex in air algebraically, using the experimental data collected below.

Angle of incidence (*i*) (degrees)	Angle of refraction (*r*) (degrees)
10	7
20	14
30	21
40	28
50	34

ANSWER

1 **Using Snell's law, we can calculate the refractive index of Perspex for each pair of angles:**

$$n_{\text{Perspex}} = \frac{n_{\text{air}} \times \sin i}{\sin r}$$

The refractive index of air (n_{air}) is approximately 1.00.

2 **Calculate the refractive index of Perspex for each pair of angles.**

For the first pair:

$$\begin{aligned} n_{\text{Perspex}} &= \frac{n_{\text{air}} \times \sin i}{\sin r} \\ &= \frac{1.00 \times \sin 10}{\sin 7} \\ &= 1.42 \end{aligned}$$

For the second pair:

$$\begin{aligned} n_{\text{Perspex}} &= \frac{n_{\text{air}} \times \sin i}{\sin r} \\ &= \frac{1.00 \times \sin 20}{\sin 14} \\ &= 1.41 \end{aligned}$$

We repeat this calculation for each pair of angles, 1–5.

3 **After obtaining the refractive indices for each pair of angles, we can take the average to find the theoretical refractive index of Perspex in air:**

$$\begin{aligned} \text{Average refractive index} &= \frac{1.42+1.41+1.40+1.37+1.47}{5} \\ &= 1.39 \end{aligned}$$

The refractive indices for all angles calculated and averaged is found to be approximately $n_{\text{Perspex}} = 1.50$.

4 **Find the theoretical refractive index of Perspex in air in the scientific literature or through manufacturer specifications.**

The refractive index of Perspex (acrylic) is approximately 1.49.

5 **Compare the experimental and the theoretical values.**

After comparing the experimental result ($n_{\text{Perspex}} = 1.39$) with the theoretical value ($n_{\text{Perspex}} = 1.49$), we see that they are in close agreement, validating the experimental procedure.

WORKED EXAMPLE 17.5.4

Determine the refractive index of a liquid in air graphically, using the experimental data collected below.

Angle of incidence (*i*) (degrees)	Angle of refraction (*r*) (degrees)
10	6
20	12
30	17
40	23
50	28

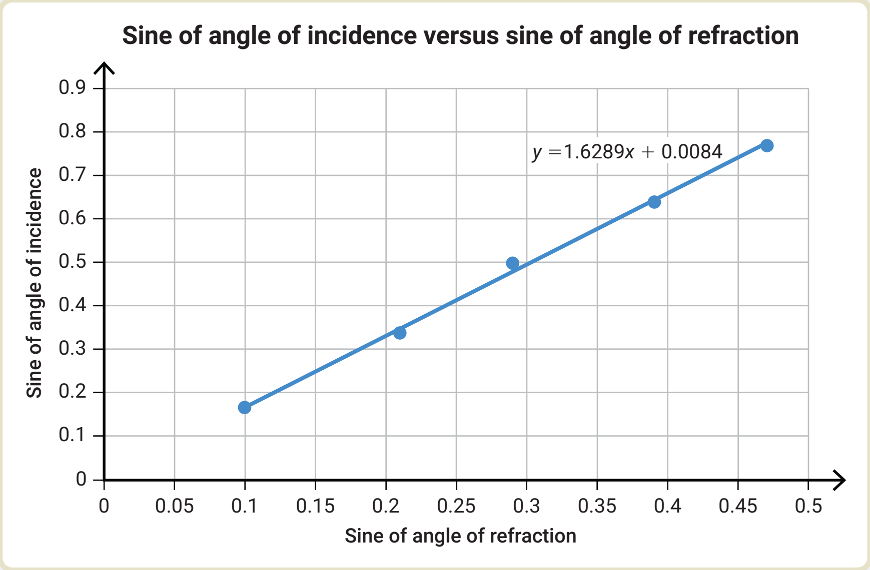
ANSWER

Using Snell's law, we can calculate the refractive index of a liquid by graphing the sine of the angle of incidence and the sine of the angle of refraction, based on the measurements of each pair of angles.

1 **Add the table of data with both sets of values for the sine of the angle.**

Angle of incidence (*i*) (degrees)	Sine of angle of incidence	Angle of refraction (*r*) (degrees)	Sine of angle of refraction
10	0.17	6	0.10
20	0.34	12	0.21
30	0.50	17	0.29
40	0.64	23	0.39
50	0.77	28	0.47

2 **Graph the sine of the angle of incidence and the sine of the angle of refraction.**



3 **After plotting a graph of sin *r* versus sin *i* for each pair of angles, we can measure the gradient to find the experimental refractive index of the liquid.**

In this case, the experimental value for $n_{\text{liquid}} = 1.63$.

PRACTICAL ACTIVITY 17.5.1

SNELL'S LAW

Introduction

Refraction can occur when a light ray travels from one medium into another. The effect depends on the angle of incidence and the relative difference in the optical properties of the media.

Research question

Does the experimental value for the refractive index of a particular material remain constant if the angle of incidence is altered?

Aim

To determine the refractive indices of different materials

Materials

- semicircular glass block
- semicircular plastic or glass dish
- ruler
- protractor
- pencil
- black, fine point marker
- graph paper

Procedure

1 Draw a line to divide the graph paper.

2 On the semicircular glass block, draw a vertical line at the centre of the curved edge. (This is your object.)

3 Place the straight edge of the semicircular glass block along the line on the graph paper.

4 Trace the outline of the block.

5 Mark the point where the vertical black line meets the graph paper.

6 Look towards the straight edge and observe the position of the black line.

7 Use the ruler to draw the sight line towards the object.

8 Repeat this for five different viewing angles.

9 Remove the glass block.

10 For each observation:

   a draw lines from the object position to the point where the sight line touches the block

   b construct the normal at the glass block.

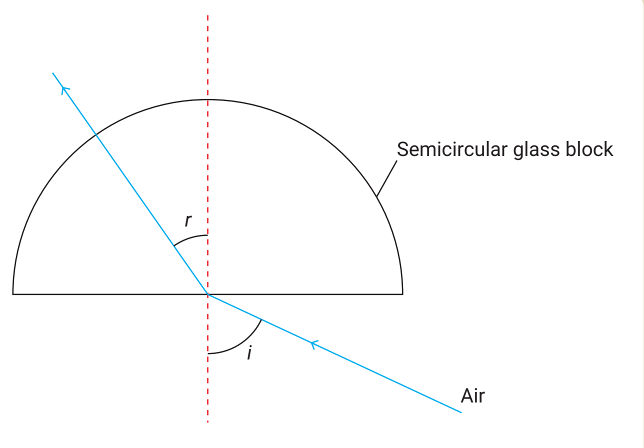


FIGURE 17.5.5 The arrangement for finding the refractive index of different materials

Results

1 Record the following data in a properly constructed data table.

   a Raw data:

      i angle of incidence, i

      ii angle of refraction, r

   b Derived data:

      i $\frac{i}{r}$

      ii $\sin i$

      iii $\sin r$

Analysis of results

1 Plot the following graphs:

   a $\frac{i}{r}$ versus i

   b $\sin r$ versus $\sin i$

Interpretation

2 Provide a justified answer to the research question.

3 Explain how you can derive the refractive index of glass from the graph of $\sin r$ versus $\sin i$.

Evaluation

4 How was the reversibility of light used in this experiment to find the refractive index of glass?

5 Provide an estimate of the uncertainty in the value of the refractive index.

6 Outline how this experiment could be extended to further investigate the refractive indices of liquids.

Total internal reflection

At every boundary between media, reflection always occurs. Mostly, so does refraction. However, for refraction away from the normal, there is an angle of incidence for which no refraction occurs. At angles of incidence greater than this **critical angle** (i_c), the ray is totally reflected back into the medium in which it was travelling when it reached the boundary. At the critical angle of incidence, the refracted angle is 90°.

critical angle the angle of incidence for which the angle of refraction is 90° (total internal reflection occurs); beyond the critical angle, reflection but not refraction occurs

Thus:

$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$$

but, at the critical angle, $i = i_c$ and $r = 90°$.

So:

$$\frac{\sin i_c}{\sin 90°} = \frac{n_2}{n_1}$$

or:

$$\frac{\sin i_c}{1} = \frac{n_2}{n_1}$$

where:

i_c = critical angle (degrees)

n_2 = refractive index of the second medium

n_1 = refractive index of the first medium

The critical angle can be calculated for any two substances as long as their relative refractive index is also less than one (i.e. $n_2 < n_1$). If the angle of incidence exceeds this critical angle, total internal reflection will occur and no light will be refracted.

KEY FORMULA

Critical angle

$$i_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

where:

i_c = critical angle (degrees)

n_2 = refractive index of the second medium

n_1 = refractive index of the first medium

WORKED EXAMPLE 17.5.5

Calculate the critical angle for light that is travelling in flint glass if the light is incident on a boundary with crown glass.

ANSWER

1 State the equation.

$$i_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

2 Substitute known values.

$$i_c = \sin^{-1}\left(\frac{1.33}{1.65}\right)$$

3 Calculate the answer.

$i_c = 53.713°$

4 Give the answer to the correct number of significant figures.

$i_c = 53.7°$

Fibre optic cables

optical fibre a transparent light guide making use of total internal reflection at a boundary between materials of similar refractive index

core the inner glass of optical fibre

cladding the outer glass of optical fibre

An **optical fibre** is made of a glass **core** that has a refractive index slightly higher than that of the surrounding glass **cladding** (Figure 17.5.6).

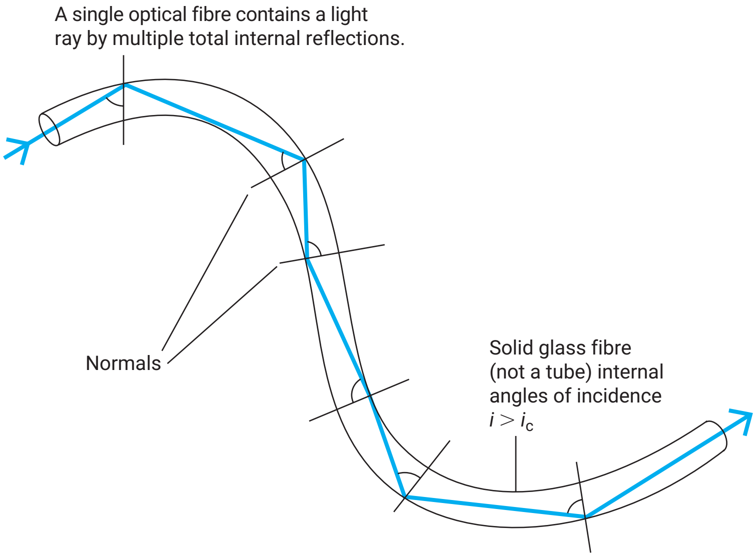


FIGURE 17.5.6 An optical fibre is made from core and cladding glass, and carries light around corners by total internal reflection.

In this way, light that spreads to the boundary is mostly constrained to travel down the core by total internal reflection. The energy loss per reflection is about 500 times less than for a highly polished mirror surface. Optical fibres are highly flexible so that the light can be readily carried around corners. Every bend causes an increase in energy loss, but this is still much better than for ordinary mirror surfaces.

Dispersion

chromatic dispersion the effect of different colours refracting by different amounts in the same medium; colours spreading

Different colours of light refract by different amounts as shown in Table 17.5.2. This effect is called **chromatic dispersion**. Red light refracts least, blue light refracts most: $n_{\text{red}} < n_{\text{blue}}$. Rainbows are a result of colour dispersion. Colours disperse in every drop and the raindrops produce different colours at slightly different angles (Figure 17.5.7).

TABLE 17.5.2 Refractive indices for different-coloured light in two types of glass

Colour	Crown glass	Flint glass
Red	1.514	1.638
Yellow	1.520	1.650
Blue	1.527	1.664
Violet	1.533	1.675

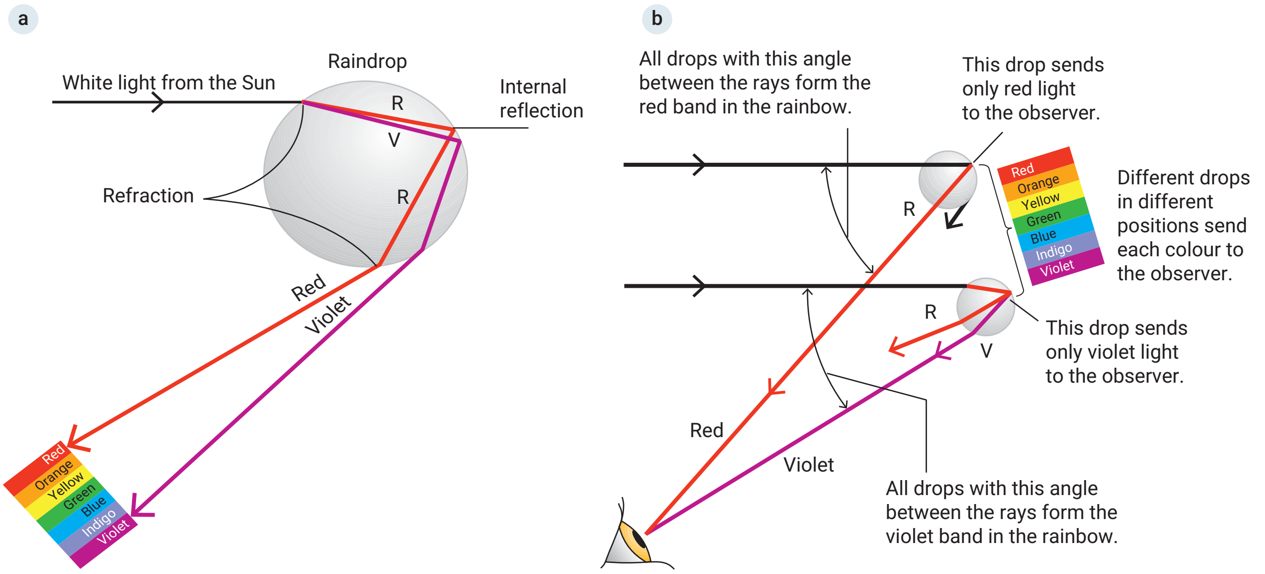


FIGURE 17.5.7 A rainbow is formed by the addition of the dispersed light coming from all the raindrops.

Solving problems: ray diagrams and refraction through lenses

Ray diagrams can be useful when solving problems involving the refraction of light through a lens. These problems can involve magnification, position, orientation and the nature of the formed image. This is an important skill to many scientists whose experiments rely on the precise manipulation and focusing of light. It is equally important to opticians who use it to restore clear vision to many.

Lenses

Lenses are shaped, transparent objects that have varying cross-sectional thickness. They may be convex, like the lens in the eye, or concave (Figure 17.5.8). A **converging (convex) lens** is thicker at the centre than at the edges. **Diverging (concave) lenses** are thicker at the edges than at the centre. Lenses can produce real or virtual images by refraction.

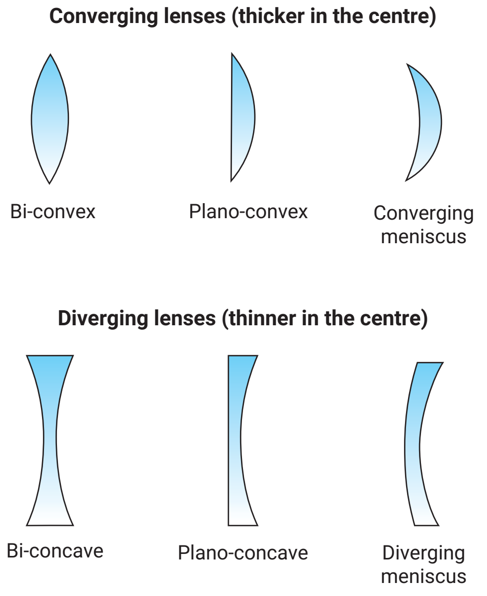


FIGURE 17.5.8 Types of converging and diverging lenses

Key optical features of lenses

Figure 17.5.9 shows how rays of light are refracted in converging (convex) and diverging (concave) lenses.

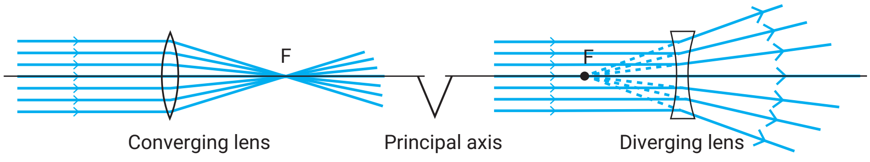


FIGURE 17.5.9 Rays that are parallel to the principal axis refract to a real focus (F) in a converging lens, and in line with a virtual focus in a diverging lens.

converging (convex) lens
a lens that is thicker in the middle than at the ends

diverging (concave) lens
a lens that is thicker at the edges than in the middle

principal axis the line through both the focus and the centre and perpendicular to the axis of a curved lens

optical centre the centre of curvature of a lens

focal point the point to which light is parallel to the axis of a lens is focused

focal length the distance from lens to focal point

Figure 17.5.10 shows the geometry of a convex lens system. The **principal axis**, or axis, is a line that passes through the centre of the lens at right angles to the plane in which the lens stands (the lens axis). The **optical centre** is the point at which these two axes cross. The **focal point**, or focus nearest the object is at the **focal length**, *f*. There is also another focal point at a symmetrical point on the opposite side of the lens. The focal point is so named because it is the point to which light that is parallel to the axis of a lens is focused.

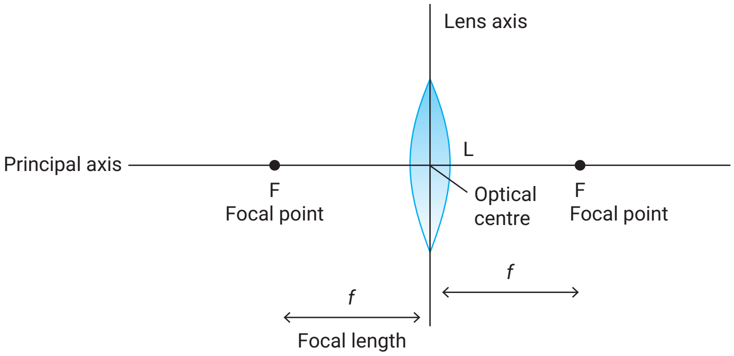


FIGURE 17.5.10 The geometry of the convex lens image-forming system showing lens axis, principal axis, optical centre and two foci

Paraxial assumptions

To use ray diagrams to solve problems involving refraction and image formation in lenses, it is necessary to make the following paraxial assumptions.

1. The rays striking the lens are not too far away from the principal axis.
2. The lens is small and thin so that it can be replaced in the diagram with a straight line. (However, we always draw a small lens around the centre to remind us of what we are doing.)
3. When a ray strikes the straight line that represents a lens, it refracts as though the line were the lens or curved mirror.

Convex lens refraction

The convex (converging) lens refracts parallel incoming rays towards the principal axis. The rays converge and cross at the focal point on the opposite side of the lens to the source of the light. The converging lens forms a real image on the opposite side of the lens to the object. A real image is one for which the light is *actually* coming from the point it appears to be coming from. A screen placed at this point will have an image on it, and a photodetector placed at this point will detect light.

Of the millions of rays striking a lens, three are useful to help trace the rays to the image in a convex lens:

- A ray parallel to the axis refracts through the lens and passes through the principal focus on the other side (R_1 in **Figure 17.5.11**).
- A ray through the focus nearer the object refracts at the lens and travels parallel to the axis (R_2 in Figure 17.5.11).
- A ray directed through the centre of the lens travels to the image unrefracted (R_3 in Figure 17.5.11).

If drawn correctly, these rays intersect on the opposite side of the lens. This is where the image is formed. If the initial object's height and distance from the lens is drawn to scale, the height of the image and its distance from the lens can then be calculated by using the same scale.

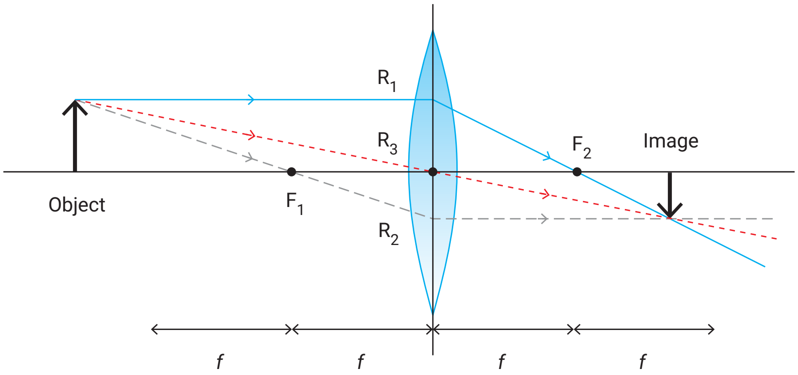


FIGURE 17.5.11 The ray diagram for a converging (convex) lens showing the three useful rays for finding the image

The image can then be described in terms of its:

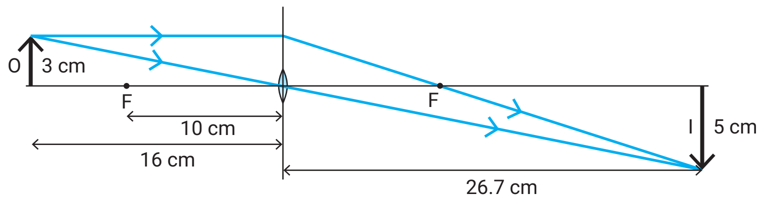
- size
- distance from the lens
- magnification (using the formula) $M = \dfrac{\text{height of image}}{\text{height of object}} = \dfrac{h_i}{h_o}$
- nature (virtual or real)
- orientation (upright or inverted).

WORKED EXAMPLE 17.5.6

An object 3.0 cm high is placed 16.0 cm in front of a converging lens of focal length 10.0 cm. Use an accurately drawn ray-tracing diagram to find the:

a position of the image
b nature of the image
c size of the image
d magnification of the image.

ANSWER



a **1** **Construct an axes with the appropriate labels.**
Draw the axes correctly, label the foci and mark in the object correctly.
Use a consistent scale.

2 **Include the image in the diagram.**
Draw two useful rays to and from the mirror.
Locate the image correctly. It must be located correctly, both horizontally and vertically.

3 **Identify the position of the image.**
From the accurately drawn ray diagram, the image is 26.7 cm from the lens on the opposite side from the object.

b Use the image to describe the nature of the image.

From the accurately drawn ray diagram, the image is real but inverted.

c Use the diagram to determine the size.

From the accurately drawn diagram, the size is 5 cm.

d 1 Apply the equation.

$$M = \frac{h_i}{h_o}$$

2 Substitute values taken from the accurately drawn diagram.

$$M = \frac{-5\text{ cm}}{3\text{ cm}}$$

3 Calculate the answer with the correct number of significant digits.

$M = 1.7$

Concave lens refraction

The concave (diverging) lens refracts light so that the parallel rays diverge, and do not cross each other on the far side of the lens from the source. However, if we trace the rays backwards from the right-hand side of the lens, we see that they appear to originate from the focal point on the same side of the lens as the object. A diverging lens forms a virtual image, which is an image formed at a position where the light rays do not actually converge. A photodetector placed at this point will not detect light, nor will a screen show an image here. This is similar to the way a plane mirror forms a virtual image. The image still exists and can be seen and photographed. It is just not due to light coming from the image position; rather the light making the image is being collected by the lens to form a real image in the camera.

Three rays are useful in a concave lens ray diagram:

- A ray parallel to the axis refracts through the lens and diverges at an angle that looks as if it comes from the principal focus on the same side as the object (R_1 in **Figure 17.5.13**).
- A ray that is directed towards the focus on the other side of the lens passes through and continues parallel to the axis once it reaches the lens (R_2 in Figure 17.5.13).
- A ray directed through the centre of the lens (R_3 in Figure 17.5.13) passes through unaffected.

If drawn correctly, these rays will look as though they originate from a point on the same side of the lens as the object and will once again give an indication of the size, distance from the lens, magnification, nature and orientation of the image formed.

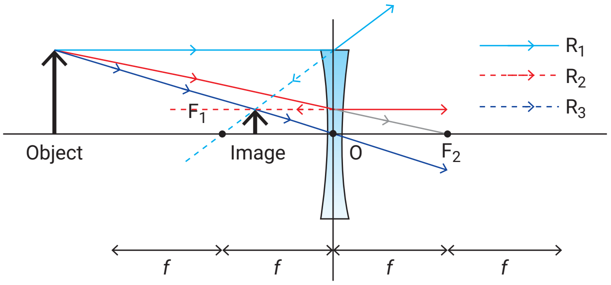


FIGURE 17.5.13 Ray diagram for a diverging (concave) lens showing the three useful rays for finding the image

LEARNING CHECK 17.5

DESCRIBING

1 Draw a diagram of light refraction to illustrate the:
  a angle of incidence
  b angle of refraction
  c normal.

2 State Snell's law.

3 a **Describe** and **explain** the term 'absolute refractive index'.
  b Why is it necessary to use a specific wavelength of light in the definition?

4 An absolute refractive index is really an example of a relative refractive index. **Explain**.

5 Draw and label an optical fibre to show the core, cladding and total internal reflection at the core–cladding boundary.

6 **Explain** the key differences between convex and concave lenses.

APPLYING

7 A ray of light of wavelength 981 nm travels in air at a speed of 3.00×10^8 m s^{-1}. It meets a transparent medium of refractive index 1.39 at an angle of 25°.
  a **Calculate** the frequency of the light in:
    i air
    ii the transparent medium.
  b **Calculate** the speed of the light in the transparent medium.
  c What is the angle of refraction as the light passes into the transparent medium?

8 An object 5.0 cm tall is placed 20 cm in front of a convex lens of focal length 10 cm. Use an accurate drawing to **determine** the distance of the image from the mirror.

ANALYSING

9 Red laser light is incident at the core from air and travels in an optical fibre.
  a What is the critical angle at the core–cladding boundary?
  b What is the maximum angle of refraction at the air–core boundary to ensure all the red light is transmitted down the fibre?

  For red light: $n_{\text{core}} = 1.495$, $n_{\text{cladding}} = 1.480$

10 An object is placed 20.0 cm in front of a converging lens, and an inverted image three times the size of the object is obtained.

  Show this situation with a geometric scale drawing and **determine** the focal distance.

17.6 Diffraction

Diffraction occurs when a narrow beam of light passes through a narrow gap, and spreads out into the space beyond. Diffraction is regarded as a wave effect; thus light diffraction through a single gap is explained by analogy with wave phenomena – the wave model – with which we are familiar.

When light is incident on a narrow gap, it forms a distinctive diffraction pattern (Figure 17.6.1) that shows 'structure'. It has a large central bright spot, and less intense bright patches on each side. Between the bright patches are dark patches.

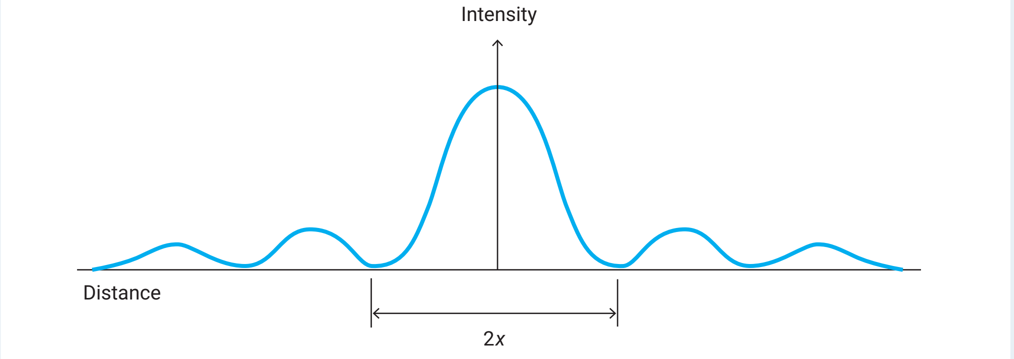


FIGURE 17.6.1 A plot of intensity versus distance from the centre for a single-slit diffraction pattern

In the wave model, the angular spread of the bright central patch, θ, is explained in terms of the wavelength of the light, λ, and the slit width (w):

$$\theta \propto \frac{\lambda}{w}$$

Diffraction effects become noticeable when wavelength and slit width are comparable. This means that when $\frac{\lambda}{w} > 1 \Rightarrow \lambda > w$, the light simply spreads into most of the area, and the central maximum is quite wide (large θ).

Diffraction effects are more pronounced when the ratio is large:

$$\frac{\lambda}{w} \gg 1$$

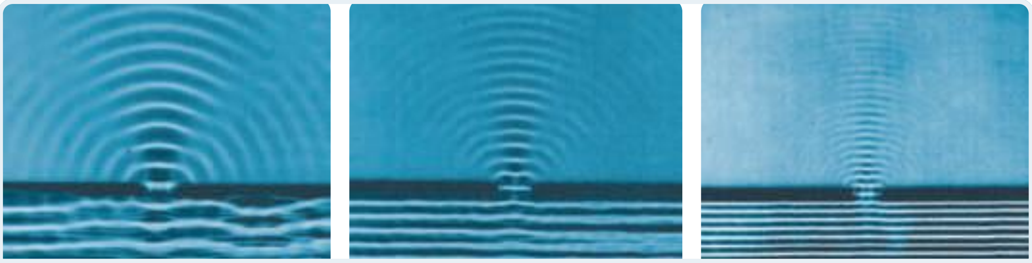


FIGURE 17.6.2 Diffraction of water waves – a model for light diffraction. Waves spread into the region beyond the gap. The spread of the central maximum decreases as the wavelength becomes similar to, or smaller than, the gap width.

Young's double-slit experiment

When a narrow beam of light strikes two slits, the slits produce diffraction patterns, which then overlap. A pattern of bright and dark patches is noticeable on a screen some distance away. Unlike a single slit, the central maximum, while still the brightest, is less wide **(Figure 17.6.3)**.

The double-slit phenomenon can be explained as a wave interference effect (Figure 17.6.3). The light from the original source spreads out as waves into the region behind the slits. Each wavefront that strikes the double slit is sampled by the slits. The slits act effectively as new sources of circular waves. A plane wave crest becomes a circular crest at each slit. A plane wave trough becomes a circular trough at each slit. Because the waves from these new sources come from the same original wavefront, they overlap. Waves that are in phase have peaks and troughs occurring at the same time. Hence, a peak is incident on, and leaves from, each slit simultaneously. The troughs coming behind these peaks do the same, and so on. This happens

Worksheet
Single-slit experiment

Weblink
Young's double-slit experiment

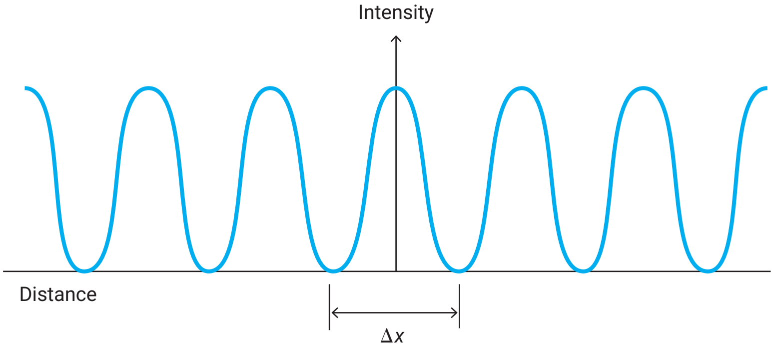


FIGURE 17.6.3 Intensity vs distance from centre for a double-slit interference pattern. Δx is the distance between dark bands.

for all wavefronts, even if they were emitted from the original source in a random way **(Figure 17.6.4)**. This leads to the formation of an interference pattern on a screen that does not change with time **(Figure 17.6.5)**.

A wave train may be considered as a series of positive crests and negative troughs. If two crests or two troughs overlap, they increase the amplitude. This is called constructive interference. Destructive interference occurs when a crest and a trough overlap.

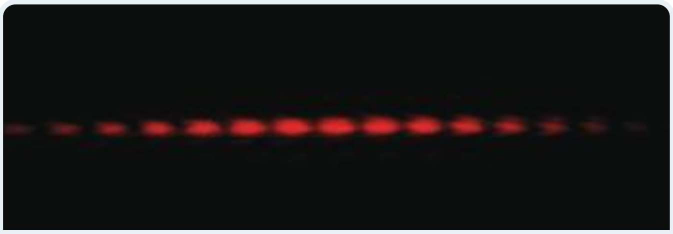


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FIGURE 17.6.4 A laser beam produces an interference pattern when passed through a double-slit arrangement.

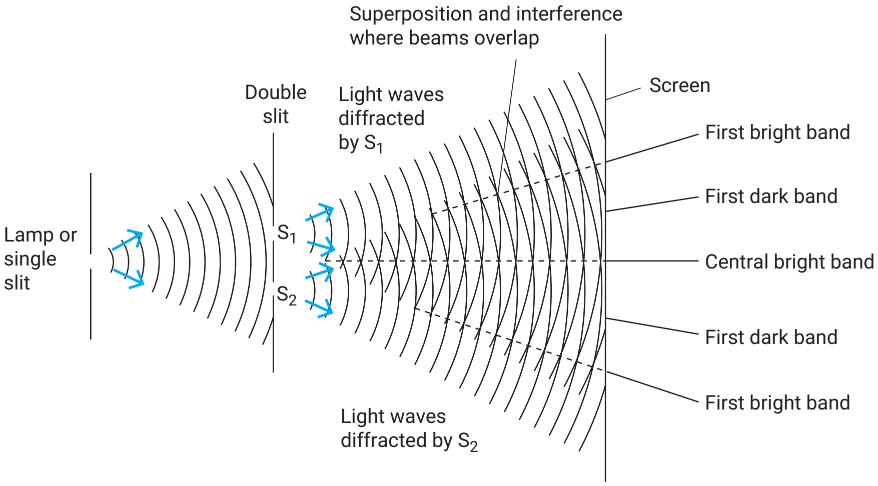


FIGURE 17.6.5 Waves from a source producing waves randomly are incident on a double-slit arrangement. Each wavefront is sampled simultaneously at both slits, leading to the formation of a consistent pattern of maxima and minima.

Constructive interference

Everywhere along the perpendicular line between the slits, crests and troughs that have been produced from the same wavefront will overlap. This gives rise to the central maximum. Other maxima occur as a result of constructive overlap between crests and troughs that have been emitted earlier at one slit relative to the other slit. When the path difference between these waves is a whole number of wavelengths, there will be constructive interference.

Syllabus link
The double-slit experiment is considered to be the defining evidence of something having wave-like properties. We will revisit the experiment when we discuss matter waves in Units 3 & 4.

For constructive interference, path difference = $n\lambda$, where $n = 1, 2, 3, \ldots$

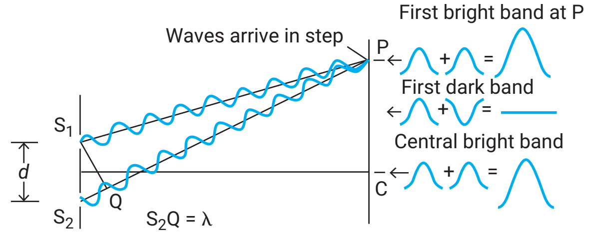


FIGURE 17.6.6 Path differences lead to maxima and minima. The formation of the first bright band is shown.

Destructive interference

In between these maxima there are minima, also called nodes or nodal points, where crests produced earlier at one slit overlap with troughs produced later. In these cases, the path difference is an odd number of half wavelengths.

For destructive interference, path difference = $(2n-1)\dfrac{\lambda}{2}$, where $n = 1, 2, 3, \ldots$

Historically, experiments such as those conducted by Thomas Young with his double-slit experiment and Augustin-Jean Fresnel's investigations into interference and diffraction provided compelling evidence for the wave nature of light. These experiments demonstrated phenomena such as interference patterns and wavefront propagation, which were consistent with wave theory. Furthermore, modern experiments utilising advanced techniques such as laser interferometry and diffraction gratings continue to confirm and refine our understanding of light's wave-like behaviour. These experiments allow scientists to explore intricate phenomena like coherence, polarisation, and the wave–particle duality of light. By appreciating the role of experiments in furthering our understanding of light, physics students gain insight into the iterative nature of scientific inquiry and the importance of empirical evidence in validating theoretical concepts.

Worksheet
Interference and light

LEARNING CHECK 17.6

DESCRIBING

1 Draw a diagram to show the intensity of light on a screen when light:
  - **a** diffracts through a single slit
  - **b** interferes after travelling through a double-slit arrangement.

2 Write down the path difference relationship and the sequence of values for *n* for:
  - **a** constructive interference
  - **b** destructive interference.

3 **Explain** what happens to the diffraction effect when the width of the obstruction becomes greater.

APPLYING

4 If the path difference to the second dark band away from the central maximum of a Young's double-slit experiment is 750 nm, what is the wavelength associated with the source of light used?

CHAPTER SUMMARY

Models of light

- The current models of light are the ray model, the wave model and the photon (particle) model.

Speed of light

- The medium affects the speed of light.
- The speed of light can be determined using:

$$c = f\lambda$$

where: c = the speed of light = $3.0 \times 10^8\,\text{m s}^{-1}$
f = the frequency of the light wave (Hz)
λ = the wavelength of light (m)

Intensity of a wave

- Light from a point source spreads uniformly into the surrounding space.
- Intensity of a wave can be determined using:

$$I = \frac{\frac{E}{t}}{A} = \frac{P}{A}$$

where: I = intensity (W m^{-2})
E = energy (J)
t = time (s)
A = area (m^2)
P = power (W)

- The intensity of a wave decreases as it moves away from the source.
- The light wave intensity at a point can be determined by:

$$I \propto \frac{1}{r^2}$$

where: I = intensity (W m^{-2})
r = distance from the source (m)

Snell's laws

- We can calculate how much refraction occurs when light moves through a medium.
- Snell's law of refraction:

$$\frac{\sin i}{\sin r} = \text{constant}$$

where: i = the angle of incidence (degrees)
r = the angle of refraction (degrees)
constant = a constant number (dependent upon the refractive indices of the two media)

- Snell's law for waves helps us to understand how waves undergo refraction when travelling through different media.

$$\frac{\sin i}{\sin r} = \frac{\lambda_i}{\lambda_R} = \frac{v_i}{v_R} = \frac{n_2}{n_1} = \text{constant}$$

where: i = angle of incidence (degrees)
r = angle of refraction (degrees)
λ_i = wavelength of the incident wave (m)
λ_R = wavelength of the refracted wave (m)
v_i = velocity of the incident wave (m s^{-1})
v_R = velocity of the refracted wave (m s^{-1})
n_1 = refractive index of the medium in which the incident wave is travelling
n_2 = refractive index of the medium in which the refracted wave is travelling
constant = relative refractive index of the two media

Critical angle

- When the angle of incidence is greater than the critical angle, the ray is reflected back into the medium in which it was travelling when it arrived at the boundary.
- The critical angle can be found using:

$$i_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

where: i_c = critical angle (degrees)
n_2 = refractive index of the second medium
n_1 = refractive index of the first medium

Diffraction

- Diffraction occurs when a narrow beam of light moves through a narrow gap and spreads into the space beyond.

CHAPTER EXAM

MULTIPLE CHOICE

1. The absorption and emission of photons of light is a feature of the:

A ray model of light.
B wave model of light.
C particle model of light.
D corpuscular model of light.

2. In the electromagnetic wave model, light is modelled as a:

A two-dimensional transverse wave.
B two-dimensional longitudinal wave.
C three-dimensional transverse wave.
D three-dimensional longitudinal wave.

3. Which of the following options would not affect the intensity of a light wave measured at a distance *r* from a point source of light?

A The power of the source
B The wavelength of light emitted from the source
C The distance of the measuring point from the source
D The size of the area in which the intensity is measured

4. A spacecraft is approaching Earth. Relative to the radio signals it sends out, the signals received on Earth have:

A a higher velocity.
B a lower frequency.
C a shorter wavelength.
D all of the above.

5. A virtual image is one that:

A is computer-generated.
B the light rays pass through the image.
C the light rays are projected onto a screen.
D the light rays do not pass through the image.

6. When a light ray passes from a medium of lower optical density such as air to one of high optical density such as glass the:

A angle of refraction is towards the normal.
B angle of reflection is towards the normal.
C angle of refraction is away from the normal.
D angle of reflection is away from the normal.

7. A biconcave lens has:

A diverging rays with a real image.
B converging rays with a real image.
C diverging rays with a virtual image.
D converging rays with a virtual image.

8. Diffraction occurs when a narrow beam of light:

A encounters a convex mirror and the rays diverge.
B encounters an object that is very much larger than its wavelength.
C passes through a narrow gap and spreads out into the space beyond.
D passes through a dense optical medium with sides that are not parallel and spreads out into the space beyond.

9. In the electromagnetic wave model of light, the:

A electric field oscillates in the same direction as the wave propagates.
B magnetic field oscillates in the same direction as the wave propagates.
C electric field, magnetic field and direction of propagation are all at right angles to each other.
D electric and magnetic fields are parallel to each other and at right angles to the direction of propagation.

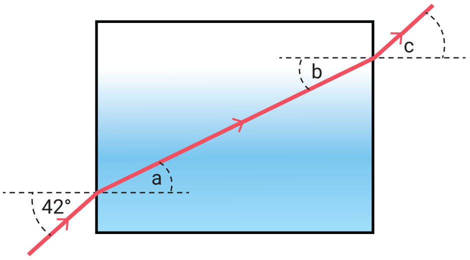
10. Polarised electromagnetic waves:

A are not transverse.
B are two-dimensional.
C have their magnetic fields aligned with their electric fields.
D have all their electric fields oriented in the same direction.

SHORT RESPONSE

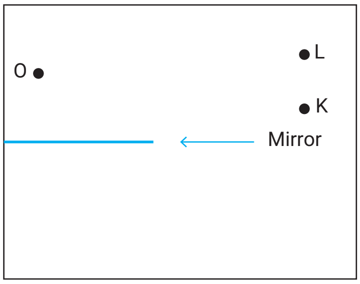
11. If the intensity of light is 400 W m^{-2} at a certain distance from a point source of light, **calculate** its intensity at a distance that is three times further from the source.

12. The diagram shows a laser beam shining through a glass rectangular prism. Using Snell's law, determine angles a, b and c given that $n_{\text{glass}} = 1.52$ and $n_{\text{air}} = 1.00$.



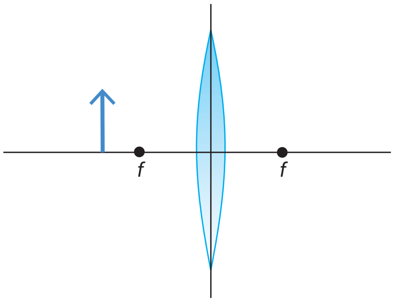
13. Object O is placed in front of a plane mirror as shown.

a Construct a ray model diagram to locate the positions of the images of O as observed at L and K.
b From the point of view of an observer moving from L to K, how does the image of O move?



14. The diagram below shows an object placed in front of a biconvex lens.

a Determine the image formed.



b **Describe** the characteristics of the image.

CROSS-CHAPTER QUESTION

15. **Calculate** the amount of time it would take a sound wave travelling at 343 m s^{-1} to cover the distance travelled by light in 0.01 s.

SCIENCE AS A HUMAN ENDEAVOUR

Syllabus dot point

- Appreciate the significant contributions of scientists such as Laura Bassi, Willebrord Snellius, Albert A. Michelson and Edward W. Morley.

Physics 2025 v1.1 General Senior Syllabus © QCAA 2024

Illuminating insights: from pioneers to modern communications

Several remarkable scientific contributions have been made to our understanding of light and its applications and particularly that of total internal reflection in the context of fibre optics and global communications.

Laura Maria Catarina Bassi made significant strides in the field of optics. Her work extended beyond total internal reflection and her influence on the scientific community was profound: Bassi became the first woman to hold a physics professorship at a European university and several of Bassi's theses demonstrated the influence of Isaac Newton's works on optics and light. She championed Newtonian physics and incorporated it into her teaching.

Willebrord Snell was a Dutch astronomer and mathematician. Renowned for Snell's law (the law of refraction). he laid the foundation for modern geometrical optics. Snell derived a mathematically equivalent form of the law, which relates the degree of light bending to the properties of the refractive material. It states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for a given pair of media. This very law paved the way for modern fibre optic cables.

Albert A. Michelson made groundbreaking contributions to optics and the measurement of the speed of light. His collaboration with Edward W. Morley led to the famous Michelson–Morley experiment. In 1887, Michelson and Morley aimed to detect Earth's motion through the hypothetical luminiferous aether. Their experiment, based on total internal reflection principles, sought to measure the speed of light in different directions. The null result of the experiment challenged the prevailing aether theory and paved the way for Einstein's theory of special relativity.

Total internal reflection in communications

Fibre optics is one of the most significant applications of total internal reflection in modern communications. Fibre optics employs the transmission of light down thin strands of glass or plastic fibres. When light encounters the boundary between the core and cladding of the fibre, it undergoes total internal reflection **(Figure 1)**, allowing it to travel long distances with minimal loss or distortion, and at speeds approaching the speed of light.

Fibre optics has enabled reliable and high-speed data, telephone and internet communication and transmission.

The contributions of these scientists, combined with the application of total internal reflection in fibre optics have revolutionised global communications.

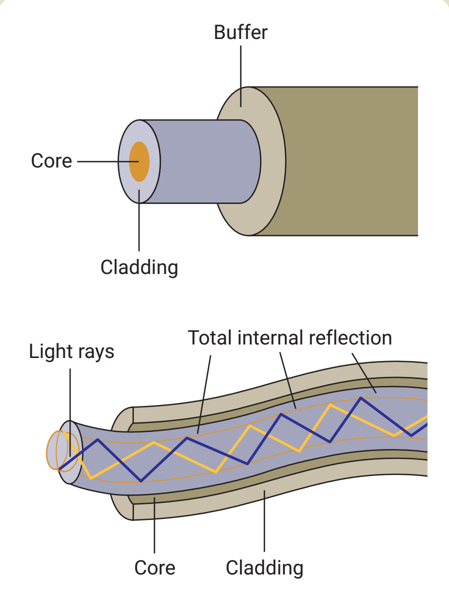


FIGURE 1 An optical fibre with total internal reflection

ANSWERS

CHAPTER 1 KINETIC PARTICLE MODEL AND HEAT TRANSFER

LEARNING CHECK 1.1

DESCRIBING

1 Solid: fixed shape, fixed volume

Liquid: no fixed shape, fixed volume

Gas: no fixed shape, no fixed volume

2 The pollen particles were moving randomly even though the water was motionless. This was due to the water particles constantly moving and bumping into the pollen, causing the motion.

3 Kinetic energy and potential energy

4 A displacement of the particles from their mean position as determined by their intermolecular forces

5 Since temperature is directly proportional to the average kinetic energy of the particles in a substance, an increase in the temperature of a substance is accompanied by an increase in the average kinetic energy of the particles in that substance.

6 Solid: The particles oscillate around a mean position, but the kinetic energy of the particles is insufficient to overcome the bonding caused by the intermolecular forces.

Liquid: The kinetic energy of the particles is sufficient to allow them to move significantly away from their mean position and ultimately slide past one another.

Gas: The kinetic energy of the particles is sufficient to allow them to break entirely free from their intermolecular bonds.

LEARNING CHECK 1.2

DESCRIBING

1 Kinetic energy is found in the motion of the particles. Potential energy is found in the intermolecular forces found in the bonds between particles.

2 The internal energy of a substance will also increase if the average kinetic energy increases.

3 The internal energy of a substance decreases if the amount of potential energy stored in its intermolecular bonds decreases.

4 Chemical energy stored in the coal is transferred to heat energy during combustion; this is then transformed to kinetic and potential energy in the water as it turns to steam. The kinetic energy in the steam is transferred to kinetic energy in the rotating turbines.

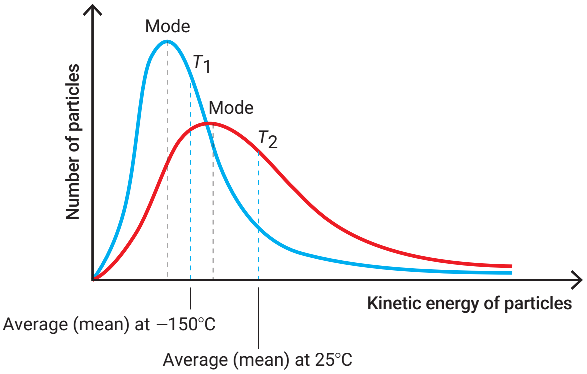
5 The potential energy in a bond is at a minimum when its particles are at their mean separation, so an increase or a decrease in this length results in an increase of the potential energy stored.

6 Heat is a transfer of energy between objects, whereas temperature is a measure of the average kinetic energy of the particles in an object.

7 An increase in the internal energy of an object can be due to an increase in the kinetic energy of its particles, an increase in the potential energy stored in its bonds, or both. Since temperature is a measure of the average kinetic energy of the particles of an object, it will not increase if the increase in internal energy is due to an increase in an object's potential energy.

APPLYING

8



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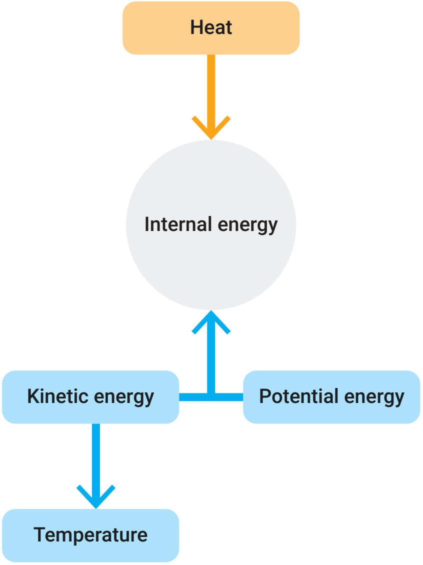


LEARNING CHECK 1.3

DESCRIBING

1 Situations will vary. Some suggested situations are:

a Conduction: Heating a metal spoon in hot water, holding an ice cube and your hand getting cold, walking on a hot surface in bare feet

b Convection: Heating water in a pot on a stove, the formation of the sea breeze during the day, warming a room with a heater

c Radiation: Heat from the Sun or a heater

2 Infrared, visible, X-ray

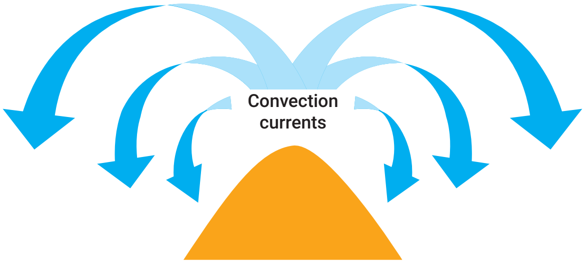
APPLYING

3 Copper, as with most metals, has many free electrons which can move around the sample unhindered and quickly transport kinetic energy through the sample. Wood has tightly bound electrons that are fixed in place. The transfer of kinetic energy is dependent upon the movement of particles.

4 The water at the top of a body of water is exposed to radiation from the Sun and to conduction with the warmer air, whereas water further down is completely dependent upon the conduction of heat from the upper sections.

5 Heat is transferred from the Sun in the form of radiation until it comes in contact with particles in the atmosphere. Heat from these particles is transferred by either conduction or convection to other particles in the atmosphere until eventually heat is transferred from these particles to the surface of Earth by conduction.

6



CHAPTER EXAM

MULTIPLE CHOICE

1	A	**2**	A	**3**	D	**4**	D	**5**	C
6	C	**7**	C	**8**	A	**9**	D	**10**	B

SHORT RESPONSE

11 When heat is added to a substance, the energy can be transformed into either an increased velocity of the particles or to a change in the distance between particles. An increase in the velocity of the particles means an increase in the amount of kinetic energy of the particles, while a change in the distance between the particles means an increase in the amount of potential energy stored in the intermolecular bonds.

12 The total internal energy of a system can be calculated using the formula:

Internal energy = kinetic energy + potential energy

$U = E_k + E_p$

Rearrange to solve for E_k:

$$\begin{aligned} E_k &= U - E_p \\ &= 10000 - 6000 \\ &= 4000\,\text{J} \end{aligned}$$

13 At 70°C, the individual kinetic energy per particle is higher than that of individual particles at 60°C. However, the larger volume of water in the bathtub would mean that the total internal energy is greater in the bathtub.

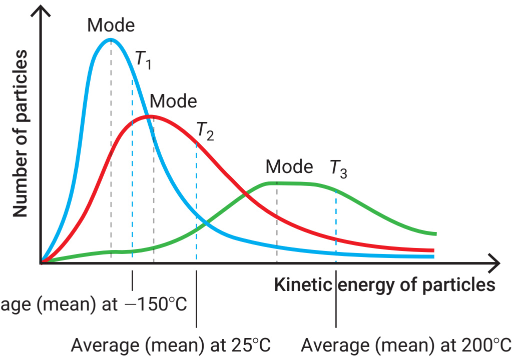
DATA ANALYSIS

14 As the wavelength decreases, the frequency increases and the energy of the wave increases.

The wavelength is inversely proportional to frequency and energy.

Frequency and energy are proportional to each other.

15



CHAPTER 2 TEMPERATURE AND SPECIFIC HEAT CAPACITY

LEARNING CHECK 2.1

DESCRIBING

1 0 K is the coldest of all temperatures, where the motion of particles ceases. Also, since temperature is proportional to kinetic energy, it is where the temperature is zero.

2 It is important to have a universal temperature scale so that findings, calculations and observations can be clearly communicated.

3 There are no negative values, which means that it is convenient for measuring very low temperatures and it is simpler to compare different temperatures.

4 **a** Qualitative **b** Quantitative
c Quantitative **d** Qualitative
e Quantitative

APPLYING

5 Use the temperature conversion formula:

$T_K = T_C + 273$

Substitute known values:

$T_K = 54 + 273$

Calculate answer:

$T_K = 327$

Give answer to correct number of significant digits and with correct unit.

$T_K = 300$ K

6 Use the temperature conversion formula:

$T_K = T_C + 273$

Subtract 273 from both sides:

$T_K - 273 = T_C$

Make T_C the subject of the formula:

$T_C = T_K - 273$

7
- Most people are not familiar with the kelvin scale.
- Common everyday temperatures are relatively high.

LEARNING CHECK 2.2

DESCRIBING

1 A device that measures temperature or a temperature gradient

2 They both use the variation in resistivity of a material with temperature.

3 Reacts to a temperature change in a predictable and measurable way

APPLYING

4 Railway lines have expansion joints to prevent them from buckling during temperature changes.

LEARNING CHECK 2.3

DESCRIBING

1 Joule and calorie. Joule is the SI unit.

2 Heat is the transfer of thermal energy. As particles gain thermal energy, this becomes kinetic energy and they move faster. The greater kinetic energy can be seen in a higher temperature.

3 Temperature does not flow between objects. Rather, heat flows from the hotter object to the colder object, resulting in a decrease in temperature of the hotter object and an increase in temperature of the colder object

APPLYING

4 When electricity flows through the resistors in the heater, the kinetic energy of the particles in the resistor increases and therefore temperature increases. The particles collide with air particles and transfer their kinetic energy through conduction. After the collisions, the air particles have more kinetic energy than before the collision and the resistor particles have less kinetic energy than before. The air particles then undergo convection and collide with other air particles to increase their kinetic energy.

5 The cool air particles coming out of the air conditioner collide with the warmer air particles in the room. After this collision, the kinetic energy of the cooler air particles increases and the kinetic energy of the warmer particles decreases. In this way, the average kinetic energy and therefore the temperature of the air particles in the room decreases.

6 Apply conversion factor (1 cal = 4.186 J):

$$\text{Energy (J)} = 150\ \text{cal} \times \frac{4.186\ \text{J}}{1\ \text{cal}}$$

Calculate answer:

Energy (J) = 627.9 J

Give answer to correct number of significant figures.

Energy (J) = 630 J

7 Apply conversion factor (1 cal = 4.186 J):

$$\text{Energy (cal)} = 1400\ \text{J} \times \frac{1\ \text{cal}}{4.186\ \text{J}}$$

Calculate answer:

Energy (cal) = 334.4 cal

Give answer to correct number of significant figures.

Energy (cal) = 330 cal

8 Apply power formula:

$$\text{Power} = \frac{\text{energy}}{\text{time}}$$

Rearrange formula for required value of energy:

Energy = power × time

Insert known values:

Energy = 200 W × 2 min

Change watts to base units ($1\ \text{W} = 1\ \text{J s}^{-1}$):

$\text{Energy} = 200\ \text{J s}^{-1} \times 2\ \text{min}$

Apply conversion factor (1 min = 60 s) to change time to SI units:

$\text{Energy} = 200\ \text{J s}^{-1} \times 120\ \text{s}$

Calculate answer:

Energy = 24 000 J

Give answer to correct number of significant figures.

Energy = 20 000 J

LEARNING CHECK 2.4

DESCRIBING

1 1 kg of iron requires 450 J of heat to be added to it to increase its temperature by 1°C.

2 Since the change in temperature of an object is proportional to the amount of heat added to it when the mass is kept the same, a doubling of the amount of heat will increase its temperature by twice as much. Therefore, the object will have a temperature increase of 2°C.

3 Since the amount of heat required to increase the temperature of an object is proportional to the mass, a halving in the mass will require half as much heat to increase its temperature by the same amount. Therefore, 200 J of heat will be required for the temperature of the substance to increase by 1°C.

4 Apply the specific heat equation:

$Q = mc\Delta T$

Rearrange the formula to make c the subject:

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

Insert the units:

$$c = \frac{\text{J}}{\text{kg °C}}$$

The units of the specific heat capacity are therefore:
$\text{J kg}^{-1}\ °\text{C}^{-1}$

APPLYING

5 Steam: $2000\ \text{J kg}^{-1}\ \text{K}^{-1}$

Ice: $2100\ \text{J kg}^{-1}\ \text{K}^{-1}$

Water: $4180\ \text{J kg}^{-1}\ \text{K}^{-1}$

6 Water has a high specific heat capacity, meaning that it requires a large amount of heat for its temperature to increase by 1°C. This means that it is useful as a heat sink to absorb significant amount of heat to be transported in or out of an area needing cooling or heating.

LEARNING CHECK 2.5

DESCRIBING

1 A calorimeter is a highly insulated container that prevents heat energy being lost to the environment and enables the measurement of a heat change.

2 **a** J

b kg

c $\text{J kg}^{-1}\ °\text{C}^{-1}$ or $\text{J kg}^{-1}\ \text{K}^{-1}$

d K or °C

3 Apply the specific heat equation:

$$Q = mc\Delta T$$

Rearrange the formula to make ΔT the subject:

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

Expand ΔT to $T_f - T_i$:

$$T_f - T_i = \frac{Q}{mc}$$

Add T_i to both sides.

$$T_f = \frac{Q}{mc} + T_i$$

APPLYING

4 Since the power of a heating element is proportional to the voltage ($P = VI$), a doubling of the current will result in a doubling of the power.

5 Apply the specific heat equation:

$$Q = mc\Delta T$$

Insert known values in SI units:

$$Q = 0.3\ \text{kg} \times 2400\ \text{J kg °C}^{-1} \times 15°\text{C}$$

Calculate the answer to the correct number of significant figures.

$$Q = 10\,800\ \text{J}$$

6 Apply the specific heat equation:

$$Q = mc\Delta T$$

Rearrange the formula to make ΔT the subject:

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

Expand ΔT to $T_f - T_i$:

$$T_f - T_i = \frac{Q}{mc}$$

Add T_i to both sides:

$$T_f = \frac{Q}{mc} + T_i$$

Insert known values:

$$T_f = \frac{2500\ \text{J}}{2\ \text{kg} \times 800\ \text{J kg}^{-1}\ °\text{C}} + 25°\text{C}$$

Calculate the answer:
$T_f = 26.5625°\text{C}$

Give the answer to the correct number of significant figures.
$T_f = 27°\text{C}$

7 Apply the specific heat equation:

$$Q = mc\Delta T$$

Rearrange the formula to make ΔT the subject:

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

Expand ΔT to $T_f - T_i$:

$$T_f - T_i = \frac{Q}{mc}$$

Add T_i to both sides.

$$T_f = \frac{Q}{mc} + T_i \qquad (1)$$

Call this equation (1).
Apply the power equation:

$$P = \frac{Q}{t}$$

Rearrange the equation to make Q the subject:

$$Q = P \times t$$

Insert the power as a function of voltage and current equation $P = IV$ to the equation:

$$Q = (IV) \times t$$

Insert known values in standard SI form:

$$Q = 5\ \text{A} \times 1.5\ \text{V} \times 30\,\text{min} \times \frac{60\ \text{s}}{\text{min}}$$

Calculate the amount of heat added and call this equation (2).

$$Q = 13\,500\ \text{J} \qquad (2)$$

Insert equation (2) into equation (1):

$$T_f = \frac{13\,500\,\text{J}}{mc} + T_i$$

Insert known values:

$$T_f = \frac{13\ 500\ \text{J}}{0.2\ \text{kg} \times 130\ \text{J kg}^{-1}\text{°C}^{-1}} + 25°\text{C}$$

Calculate the answer:

$T_f = 544.230\,7692°C$

Give the answer to the correct number of significant figures

$T_f = 540°C$

CHAPTER EXAM

MULTIPLE CHOICE

1 D **2** D **3** B **4** D **5** C

6 B **7** B **8** B **9** B **10** D

SHORT RESPONSE

11 Apply the specific heat equation:

$Q = mc\Delta T$

Insert known values in SI units:

$Q = 0.45\text{ kg} \times 670\text{ J kg}^{-1}\ °C^{-1} \times (25°C - 465°C)$

Calculate the answer:

$Q = -132\,660\text{ J}$

Give the answer to the correct number of significant figures noting that a negative value for Q indicates a heat loss.

The heat lost is equal to 1.3×10^5 J

12 Apply the specific heat equation:

$Q = mc\Delta T$

Rearrange the formula to make ΔT the subject:

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

Expand ΔT to $T_f - T_i$:

$$T_f - T_i = \frac{Q}{mc}$$

Add T_i to both sides:

$$T_f = \frac{Q}{mc} + T_i$$

Insert known values:

$$T_f = \frac{49\,000\text{ J}}{0.25\text{ kg} \times 2800\text{ J kg}^{-1}\ °C^{-1}} + 25°C$$

Calculate the answer to the correct number of significant figures.

$T_f = 95°C$

13 Apply the specific heat equation:

$Q = mc\Delta T$

Rearrange the formula to make c the subject:

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

Insert known values

$$c = \frac{51\,094\text{ J}}{1.8\text{ kg} \times 33°C}$$

Calculate the answer to the correct number of significant figures.

$c = 860\text{ J kg}^{-1}\,°C^{-1}$

DATA ANALYSIS

14 Since the formula relating temperature and heat added is linear $T_f = \frac{Q}{mc} + T_i$, with gradient equal to $\frac{1}{mc}$, a graph of temperature vs heat added should also have a gradient of $\frac{1}{mc}$.

From the graph:

$$\text{Gradient} = \frac{\Delta T}{\Delta Q} = \frac{28°C - 26°C}{700\text{ J} - 250\text{ J}} = \frac{1°C}{225\text{ J}}$$

Since:

$$\text{Gradient} = \frac{1}{mc}$$

Gradient from the formula $T_f = \frac{Q}{mc} + T_i$

$$c = \frac{1}{m \times \text{gradient}}$$

Rearrange the formula for c:

$$c = \frac{1}{0.5\text{ kg} \times \frac{1°C}{225\text{ J}}}$$

Insert known values:

$c = 450\text{ J kg}^{-1}\,°C^{-1}$

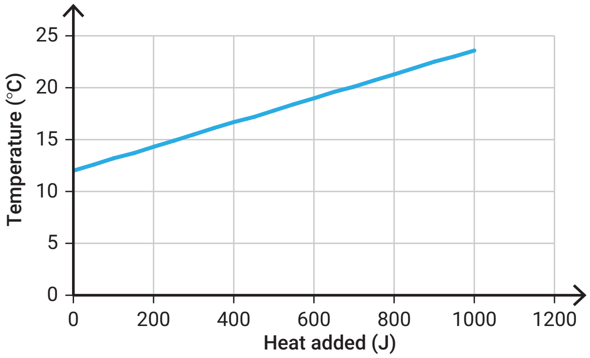
Calculate the answer.

From Table 2.5.1, it is likely the substance is iron since it has a specific heat capacity of 450 J kg^{-1} °C^{-1}.

15 The first step is to calculate the heat added at each time step. This can be done by rearranging the power formula $\left(P = \frac{Q}{t}\right)$ to give $Q = Pt$. This is included as the extra column of the table:

Time (s)	Heat added (J)	Temperature (°C)
0	0	12
10	50	12.6
20	100	13.2
30	150	13.7
40	200	14.3
50	250	14.9
60	300	15.5
70	350	16.1
80	400	16.7
90	450	17.2
100	500	17.8
110	550	18.4
120	600	19
130	650	19.6
140	700	20.1
150	750	20.7
160	800	21.3
170	850	21.9
180	900	22.5
190	950	23
200	1000	23.6

The next step involves graphing temperature vs heat added:



As can be seen in the graph, this is linear with a gradient of 0.0116°C J^{-1}.

This graph can be related to the formula $T_f = \frac{Q}{mc} + T_i$, with gradient equal to $\frac{1}{mc}$.

Therefore:

$$\text{Gradient} = \frac{1}{mc}$$

Rearrange formula for c:

$$c = \frac{1}{m \times \text{gradient}}$$

Insert known values:

$$c = \frac{1}{0.25\ \text{kg} \times 0.0116°\text{C J}^{-1}}$$

Calculate the answer:

$c = 345\ \text{J kg}^{-1}\ °\text{C}^{-1}$

CHAPTER 3 PHASE CHANGES AND LATENT HEAT

LEARNING CHECK 3.1

DESCRIBING

1 Vaporisation is the phase change from liquid to gas at its boiling point, whereas evaporation is the process in which some of the particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point. Vaporisation does not involve any change in temperature, whereas during evaporation, the loss of the most energetic particles results in a decrease in the average kinetic energy and therefore the temperature of the substance.

2 II, IV, III, I

APPLYING

3 During any phase change, the addition of heat results in energy being stored as potential energy by the movement of particles away from the mean position of their intermolecular bonds.

4 The constant linear slope of a heating curve in between phase changes indicates a constant rate of heat energy input.

5 The horizontal lines on a heating curve during a phase change indicate that there is no change in temperature.

ANALYSING

6 **a** 1500°C **b** 2800°C

LEARNING CHECK 3.2

DESCRIBING

1 **a** Latent heat is the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: J kg^{-1}

b The specific latent heat of fusion is the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

c The specific latent heat of vaporisation is the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

APPLYING

2 Alcohol, lead, water, silver, copper, iron, aluminium. This table suggests that 2260 kJ of heat would be required to vaporise 1 kg of water and more than 4.5 times more heat, 10 500 kJ, to vaporise 1 kg of aluminium.

3 Since the amount of heat released is directly proportional to the mass of a substance, there would be three times as much heat, or 615 kJ released when 3.0 kg of liquid copper solidifies.

LEARNING CHECK 3.3

DESCRIBING

1 **a** Joules, J

b Kilograms, kg

c Joules per kilogram or kilojoules per kilogram, J kg^{-1} or kJ kg^{-1}

2 **a** Latent heat of fusion

b Latent heat of vaporisation

c Latent heat of fusion

d Latent heat of vaporisation

APPLYING

3 Apply the latent heat of fusion formula:

$Q = mL_f$

Insert known values:

$Q = 0.33\ \text{kg} \times\ 105\ \text{kJ kg}^{-1}$

Calculate the answer:

$Q = 34.65\ \text{kJ}$

Give the answer to the correct number of significant figures.

$Q = 35\ \text{kJ}$

4 Apply the latent heat of vaporisation formula:

$Q = mL_v$

Rearrange to make L_v the subject:

$$L_v = \frac{Q}{m}.$$

Insert known values:

$$L_v = \frac{52.8\text{kcal}}{160\text{g}}$$

$$L_v = \frac{52.8\text{kcal} \times \dfrac{4.18\text{kJ}}{\text{kcal}}}{0.16\text{kg}}$$

Apply conversion factors to get units into SI format:

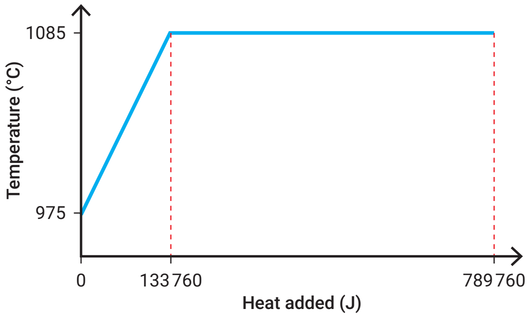
Calculate the answer:

$$L_v = 1379.4 \text{ kJ kg}^{-1}$$

Give the answer to the correct number of significant figures.

$$L_v = 1.4 \times 10^3 \text{ kJ kg}^{-1}$$

5



6 The total heat released is equal to the sum of the heat released during both phases.

$$Q_{\text{total}} = Q_{\text{gas}} + - Q_f$$

Apply the specific heat and latent heat of fusion formulas:

$$Q_{\text{total}} = mc_{\text{gas}} \Delta T + - mL_f$$

Insert known values in correct SI format:

$$Q_{\text{total}} = 2.5 \text{ kg} \times 0.248 \text{ kcal kg}^{-1} {}^\circ\text{C}^{-1} \times \left(\frac{4.18 \text{ kJ}}{\text{kcal}}\right) \times \left(-210^\circ\text{C} - 25^\circ\text{C}\right) - 2.5 \text{ kg} \times 199 \text{ kJ kg}^{-1}$$

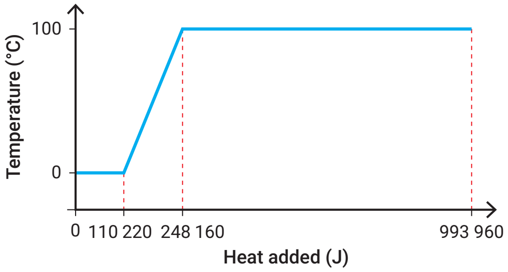
Calculate the answer:

$$Q_{\text{total}} = -1109.44 \text{ kJ}$$

Give the answer to the correct number of significant figures.

$$Q_{\text{total}} = -1100 \text{ kJ}$$

7 **a**



b The total heat added is equal to the sum of the heat added during all three stages:

$$Q_{\text{total}} = Q_f + Q_{\text{water}} + Q_v$$

Apply the specific heat and latent heat formulas:

$$Q_{\text{total}} = mL_f + mc_{\text{water}} \Delta T + mL_v$$

Insert known values:

$$Q_{\text{total}} = \left(0.33 \text{ kg} \times 334 \text{ kJ kg}^{-1}\right) + \left(0.33 \times 4.18 \text{ kJ kg}^{-1} {}^\circ\text{C}^{-1} \times 100^\circ\text{C}\right) + \left(0.33 \text{ kg} \times 2260 \text{ kJ kg}^{-1}\right)$$

Calculate the answer. Give the answer to the correct number of significant figures.

$$Q_{\text{total}} = 993.960 \text{ kJ}$$

$$Q_{\text{total}} = 990 \text{ kJ}$$

CHAPTER EXAM

MULTIPLE CHOICE

1	A	**2**	C	**3**	A	**4**	C	**5**	C
6	D	**7**	A	**8**	A	**9**	A	**10**	B

SHORT RESPONSE

11 Apply latent heat of vaporisation formula:

$$Q = mL_v$$

Rearrange equation to make the mass the subject:

$$m = \frac{Q}{L_v}$$

Insert known values:

$$m = \frac{135 \text{ kJ}}{205 \text{ kJ kg}^{-1}}$$

Calculate the answer:

$$m = 0.65854 \text{ kg}$$

Give answer to correct number of significant figures.

$$m = 0.659 \text{ kg}$$

12 The total heat added is equal to the sum of the heat added for both stages:

$$Q_{\text{total}} = Q_{\text{ice}} + Q_f + Q_{\text{liquid}}$$

Apply the specific heat capacity and specific latent heat of fusion formulas:

$$Q_{\text{total}} = mc_{\text{ice}} \Delta T + mL_f + mc_{\text{liquid}} \Delta T$$

Factorise the common mass:

$$Q_{\text{total}} = m\left(c_{\text{ice}} \Delta T + L_f + c_{\text{liquid}} \Delta T\right)$$

Make mass the subject:

$$m = \frac{Q_{\text{total}}}{c_{\text{ice}} \Delta T + L_f + c_{\text{liquid}} \Delta T}$$

Insert known values. Calculate the answer:

$$m = \frac{380 \text{ kJ}}{2.1 \text{ kJ kg}^{-1} {}^\circ\text{C}^{-1} \times \left(0^\circ\text{C} - -12^\circ\text{C}\right) + 334 \text{ kJ} + 4.2 \text{ kJ kg}^{-1} {}^\circ\text{C}^{-1} \times \left(56^\circ\text{C} - 0^\circ\text{C}\right)}$$

$$m = 0.6393 \text{ kg}$$

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Give the answer to the correct number of significant figures.

$m = 0.64$ kg

CROSS-CHAPTER QUESTION

13 **a** Boiling point 95°C

b Melting point –85°C

c In the solid state, use the first section of the graph to determine the specific heat capacity:

$\Delta Q = mc\Delta T$

Rearrange to make c the subject:

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

Substitute in known values read off the graph. Ensure that $\Delta T = T_f - T_i$.

$$c = \frac{1500 - 0}{0.01 \times (-85 - -145)}$$

Calculate the answer:

$c = 2500\,\text{J kg}^{-1}{}^{\circ}\text{C}^{-1}$

d In the liquid state, use the third section of the graph to determine the specific heat capacity.

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

Substitute in known values read off the graph:

$$c = \frac{11\,750 - 7000}{0.01 \times (95 - -85)}$$

Calculate the answer:

$c = 2638.9\,\text{J kg}^{-1}{}^{\circ}\text{C}^{-1}$

e In gaseous state, use the fifth section of the graph to determine the specific heat capacity.

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

Substitute in known values read off the graph:

$$c = \frac{20\,000 - 18\,500}{0.01 \times (220 - 95)}$$

Calculate the answer:

$c = 1200\ \text{J kg}^{-1}\,{}^{\circ}\text{C}^{-1}$

f **i** For calculating latent heat of fusion, use the flat section between solid and liquid states:

$\Delta Q_f = mL_f$

Rearrange to make L_f the subject:

$$L_f = \frac{\Delta Q_f}{m} = \frac{7000 - 1500}{10} = 550\ \text{J g}^{-1}$$

ii To convert from J g^{-1} to J kg^{-1}:

$550 \times 1000 = 550\,000\ \text{J kg}^{-1}$

g **i** For calculating latent heat of vaporisation, use the flat section between liquid and gaseous states.

$\Delta Q_v = mL_v$

Rearrange to make L_v the subject:

$$L_v = \frac{\Delta Q_f}{m} = \frac{18\,500 - 11\,750}{10} = 675\ \text{J g}^{-1}$$

ii To convert from J g^{-1} to J kg^{-1}:

$675 \times 1000 = 675\,000\ \text{J kg}^{-1}$

14 **a** Boiling point 280 K

b Melting point 175 K

c In the solid state, use the first section of the graph to determine the specific heat capacity.

$\Delta Q = mc\Delta T$

Rearrange to make c the subject:

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

Substitute in known values read off the graph. Ensure that $\Delta T = T_f - T_i$

$$c = \frac{80 - 0}{0.02 \times (175 - 135)}$$

Calculate the answer:

$c = 100\,\text{J kg}^{-1}\ \text{K}^{-1}$

d In the liquid state, use the third section ofthe graph to determine the specific heat capacity.

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

Substitute in known values read off the graph:

$$c = \frac{280 - 130}{0.02 \times (280 - 175)}$$

Calculate the answer:

$c = 71.43\ \text{J kg}^{-1}\,\text{K}^{-1}$

e In the gaseous state, use the fifth section of the graph to determine the specific heat capacity.

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

Substitute in known values read off the graph:

$$c = \frac{450 - 380}{0.02 \times (385 - 280)}$$

Calculate the answer:

$c = 33.33\ \text{J kg}^{-1}\ \text{K}^{-1}$

f **i** For calculating latent heat of fusion, use the flat section between solid and liquid states:

$\Delta Q_f = mL_f$

Rearrange to make L_f the subject:

$$L_f = \frac{\Delta Q_f}{m}$$
$$= \frac{130 - 80}{20}$$
$$= 2.5 \text{ J g}^{-1}$$

ii To convert from J g^{-1} to J kg^{-1}:
$2.5 \times 1000 = 2500 \text{ J kg}^{-1}$

g **i** For calculating latent heat of vaporisation, use the flat section between liquid and gaseous states:
$\Delta Q_v = mL_v$
Rearrange to make L_v the subject:

$$L_v = \frac{\Delta Q_f}{m}$$
$$= \frac{380 - 280}{20}$$
$$= 5 \text{ J g}^{-1}$$

ii To convert from J g^{-1} to J kg^{-1}:
$5 \times 1000 = 5000 \text{ J kg}^{-1}$

DATA ANALYSIS

15 **a** The gradient of the graph can be used to determine the experimental value of L_f.

Gradient of graph $= 0.2107 \text{ kJ g}^{-1}$

Convert from kJ g^{-1} to kJ kg^{-1}:

$0.2107 \text{ kJ g}^{-1} \times 1000 = 210.7 \text{ kJ kg}^{-1}$

b Melting uses the latent heat of fusion:

$Q = mL_f$

Substitute in values from the question:

$Q = 6 \text{ kg} \times 210.7 \text{ kJ kg}^{-1}$

Solve for Q:
$Q = 1264.2 \text{ kJ}$

CHAPTER 4 ENERGY CONSERVATION IN CALORIMETRY

LEARNING CHECK 4.1

DESCRIBING

1 Two objects in thermal equilibrium have the same temperature.

2 The particles of two objects in thermal equilibrium have an equal average kinetic energy.

APPLYING

3 Heat flows out of the warmer liquid water into the colder air in the freezer compartment until the two are at thermal equilibrium. This will involve a phase change of the water to ice.

4 Heat flows from the warmer air in the room into the solid ice until the two are at thermal equilibrium. This will involve a phase change of the ice to liquid water.

LEARNING CHECK 4.2

DESCRIBING

1 The particles of two objects at thermal equilibrium have the same average kinetic energy, so collisions between the two objects are just as likely to transfer heat in either direction. Therefore, the flow in both directions is equal and the net heat flow is equal to zero, meaning that the temperature of neither object will increase or decrease and they will maintain thermal equilibrium.

APPLYING

2 The particles of air that collide with the surface particles of the ice will transfer some of their kinetic energy to them. These ice particles then transfer this higher kinetic energy to other ice particles through collisions, whereas air particles, which have lost kinetic energy, will gain more kinetic energy through collisions with other air particles. In this way, the average kinetic energy of the ice is increased and the average kinetic energy of the air is decreased. This will continue until the melting point of the ice, at which point the kinetic energy imparted by the air particles will be stored as potential energy in the intermolecular bonds. After the phase change, the kinetic energy of the air particles will be transferred to the newly formed water particles until the average kinetic energy of the air particles is equal to the average kinetic energy of the water particles.

3 The particles on the stove element will transfer their high average kinetic energy through conduction to the particles of the saucepan that are in contact with them. The particles in the stovetop, which have lost kinetic energy, will gain more kinetic energy by colliding with other particles in the stovetop. The particles in the saucepan, which have gained kinetic energy, will collide with other particles in the saucepan and transfer heat throughout. This process will continue until the particles in the saucepan, which are in contact with the water, will have a higher average kinetic energy than the water particles in contact with them and a net heat flow will pass from the saucepan into the water due to this difference. This process will continue until the particles of the stovetop, the saucepan and the water have the same average kinetic energy and are therefore at thermal equilibrium.

4 Since temperature is defined as the average kinetic energy of a substance, if all three objects are at thermal equilibrium with each other, they must have equal average kinetic energies.

LEARNING CHECK 4.3

DESCRIBING

1 A calorimeter is a device that is highly insulated and is designed to prevent heat loss from the internal cavity to the surroundings. It consists of an internal cavity surrounded by aluminium walls and an insulating material and/or a vacuum between the internal and the external walls. The internal cavity is said to be thermodynamically isolated.

2 The principle of conservation of energy states that energy can never be created or destroyed, and the equation

$Q_{\text{lost}} = -Q_{\text{gained}}$ simply states that the heat lost by one object is equal in magnitude to the heat gained by another.

3 **a** Both energy and mass can be transferred from the system to the surroundings.

b Energy but not mass can be transferred from the system to its surroundings.

c Neither energy nor mass can be transferred from the system to its surroundings.

APPLYING

4 **a** Isolated
- **b** Closed
- **c** Open
- **d** Open
- **e** Isolated
- **f** Closed

5 $Q_{\text{lost}} = -Q_{\text{gained}}$

Apply the conservation of energy formula:

$$m_{\text{hot}} c \Delta T_{\text{hot}} = -m_{\text{cold}} c \Delta T_{\text{cold}}$$

Apply the specific heat capacity formula:

$$m_{\text{hot}} \Delta T_{\text{hot}} = -m_{\text{cold}} \Delta T_{\text{cold}}$$

Cancel *c*, the specific heat capacity of water from both sides:

$$m_{\text{hot}}\left(T_{\text{f}} - T_{\text{i,hot}}\right) = -m_{\text{cold}}\left(T_{\text{f}} - T_{\text{i,cold}}\right)$$

Expand ΔT:

$$m_{\text{hot}} T_{\text{f}} + m_{\text{cold}} T_{\text{f}} = m_{\text{hot}} T_{\text{i,hot}} + m_{\text{cold}} T_{\text{i,cold}}$$

Gather like terms:

$$\left(m_{\text{hot}} + m_{\text{cold}}\right) T_{\text{f}} = m_{\text{hot}} T_{\text{i,hot}} + m_{\text{cold}} T_{\text{i,cold}}$$

Factorise the common T_{f} from the expression on the left-hand side:

$$T_{\text{f}} = \frac{m_{\text{hot}} T_{\text{i,hot}} + m_{\text{cold}} T_{\text{i,cold}}}{m_{\text{ho}} + m_{\text{cold}}}$$

Isolate T_{f} on the left-hand side of the equation:

$$T_{\text{f}} = \frac{2\,\text{kg} \times 65°\text{C} + 1\,\text{kg} \times 10°\text{C}}{2\,\text{kg} + 1\,\text{kg}}$$

Insert known values recalling that 1 L of water = 1 kg:

$$T_{\text{f}} = 46.666\,666\,67°\text{C}$$

Calculate the answer:

$$T_{\text{f}} = 47°\text{C}$$

Give the answer to the correct number of significant figures.

6 $Q_{\text{lost}} = -Q_{\text{gained}}$

Apply the conservation of energy formula:

$$m_{\text{hot}} c \Delta\ T_{\text{hot}} = -m_{\text{cold}} c \Delta T_{\text{cold}}$$

Apply the specific heat capacity formula:

$$m_{\text{hot}} \Delta\ T_{\text{hot}} = -m_{\text{cold}} \Delta T_{\text{cold}}$$

Cancel *c*, the specific heat capacity of water from both sides:

$$m_{\text{hot}} T_{\text{f}} - m_{\text{hot}} T_{\text{i,hot}} = -m_{\text{cold}}\left(T_{\text{f}} - T_{\text{i,cold}}\right)$$

Expand the brackets:

$$m_{\text{hot}} T_{\text{i,hot}} = m_{\text{hot}} T_{\text{f}} + m_{\text{cold}}\left(T_{\text{f}} - T_{\text{i,cold}}\right)$$

Isolate the term containing the required $T_{\text{i,hot}}$ on the left-hand side:

$$T_{\text{i,hot}} = \frac{m_{\text{hot}} T_{\text{f}} + m_{\text{cold}}\left(T_{\text{f}} - T_{\text{i,cold}}\right)}{m_{\text{hot}}}$$

Isolate $T_{\text{i,hot}}$ on the left-hand side:

$$T_{\text{i,hot}} = \frac{2\,\text{kg} \times 26°\text{C} + 3\,\text{kg} \times \left(26°\text{C} - 23°\text{C}\right)}{2\,\text{kg}}$$

Insert known values, recalling that 1 L of water = 1 kg:

$$T_{\text{i,hot}} = 30.5°\text{C}$$

Calculate the answer:

$$T_{\text{i,hot}} = 31°\text{C}$$

Give the answer to the correct number of significant figures.

7 $Q_{\text{lost}} = -\ Q_{\text{gained}}$

Apply the conservation of energy formula assuming it is an isolated system due to the blanket:

$$m_{\text{tea}} c_{\text{tea}} \Delta\ T_{\text{tea}} = -m_{\text{body}} c_{\text{body}} \Delta T_{\text{body}}$$

Apply the specific heat capacity formula:

$$m_{\text{tea}} c_{\text{tea}}\left(T_{\text{f}} - T_{\text{i,tea}}\right) = -m_{\text{body}} c_{\text{body}}\left(T_{\text{f}} - T_{\text{i,body}}\right)$$

Expand ΔT:

$$m_{\text{tea}} c_{\text{tea}} T_{\text{f}} - m_{\text{tea}} c_{\text{tea}} T_{\text{i,tea}} = -m_{\text{body}} c_{\text{body}} T_{\text{f}} + m_{\text{body}} c_{\text{body}} T_{\text{i,body}}$$

Expand the brackets:

$$m_{\text{tea}} c_{\text{tea}} T_{\text{f}} + m_{\text{body}} c_{\text{body}} T_{\text{f}} = m_{\text{tea}} c_{\text{tea}} T_{\text{i,tea}} + m_{\text{body}} c_{\text{body}} T_{\text{i,body}}$$

Gather terms containing T_{f} on the left-hand side:

$$\left(m_{\text{tea}} c_{\text{tea}} + m_{\text{body}} c_{\text{body}}\right) T_{\text{f}} = m_{\text{tea}} c_{\text{tea}} T_{\text{i,tea}} + m_{\text{body}} c_{\text{body}} T_{\text{i,body}}$$

Factorise T_{f} on the left-hand side:

$$T_{\text{f}} = \frac{m_{\text{tea}} c_{\text{tea}} T_{\text{i,tea}} + m_{\text{body}} c_{\text{body}} T_{\text{i,body}}}{\left(m_{\text{tea}} c_{\text{tea}} + m_{\text{body}} c_{\text{body}}\right)}$$

Isolate T_{f} on the left-hand side:

$$T_{\text{f}} = \frac{\begin{array}{c} 0.62\,\text{kg} \times 4200\,\text{J}\,\text{kg}^{-1}\,°\text{C}^{-1} \times 60°\,\text{C} \\ + 60\,\text{kg} \times 3500\,\text{J}\,\text{kg}^{-1}\,°\text{C}^{-1} \times 33.5°\text{C} \end{array}}{\begin{pmatrix} 0.62\,\text{kg} \times 4200\,\text{J}\,\text{kg}^{-1}\,°\text{C}^{-1} \\ + 60\,\text{kg} \times 3500\,\text{J}\,\text{kg}^{-1}\,°\text{C}^{-1} \end{pmatrix}}$$

Insert known values assuming the tea has a specific heat capacity equal to water:

$$T_{\text{f}} = 33.824\,575°\text{C}$$

Calculate the final temperature:

$$\Delta T_{\text{body}} = T_{\text{f}} - T_{\text{i,body}}$$

The question asks for the *change* in temperature:

$$\Delta T_{\text{body}} = 33.824\,575°\text{C} - 33.5\ °\text{C}$$

Insert initial and final temperatures:

$$\Delta T_{\text{body}} = 0.324\,575°\text{C}$$

Calculate the answer:

$$\Delta T_{\text{body}} = 0.3°\text{C}$$

Give the answer to the correct number of significant figures.

8 $-Q_{\text{lost}} = Q_{\text{gained}}$

Apply the conservation of energy formula since it is in a calorimeter:

$-m_{\text{sample}}c_{\text{sample}}\Delta T_{\text{sample}} = m_{\text{cal}}c_{\text{cal}}\Delta T_{\text{cal}} + m_{\text{water}}c_{\text{water}}\Delta T_{\text{water}}$

Apply the specific heat capacity formula:

$$c_{\text{sample}} = \frac{m_{\text{cal}}c_{\text{cal}}\Delta\ T_{\text{cal}} + m_{\text{water}}c_{\text{water}}\Delta T_{\text{water}}}{-\ m_{\text{sample}}\Delta T_{\text{sample}}}$$

Isolate the required c_{sample} on the left-hand side:

$$c_{\text{sample}} = \frac{0.15\text{ kg} \times 900\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}\left(38^\circ\text{C} - 10^\circ\text{C}\right) + 0.25\text{ kg} \times 4200\text{ J kg}^{-1}\,{}^\circ\text{C}^{-1}\left(38^\circ\text{C} - 10^\circ\text{C}\right)}{-\ 1.23\text{ kg} \times \left(38^\circ\text{C} -\ 98^\circ\text{C}\right)}$$

Insert known values, assuming that the calorimeter is made of aluminium:

$c_{\text{sample}} = 449.5935\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}$

Calculate the answer:

$c_{\text{sample}} = 450\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}$

Give the answer to the correct number of significant figures.

From Table 2.4.1, the specific heat capacity of the sample is similar to that of iron.

9 $-Q_{\text{lost}} = Q_{\text{gained}}$

Apply the conservation of energy formula, assuming it is an isolated system:

$-m_{\text{iron}}c_{\text{iron}}\Delta\ T_{\text{iron}} = m_{\text{water}}c_{\text{water}}\Delta\ T_{\text{water}} + m_{\text{water}}L_{\text{v,water}}$

Apply the specific heat capacity and latent heat of fusion formulas:

$$\Delta\ T_{\text{iron}} = \frac{m_{\text{water}}c_{\text{water}}\Delta\ T_{\text{water}} + m_{\text{water}}L_{\text{v,water}}}{-\ m_{\text{iron}}c_{\text{iron}}}$$

Isolate the ΔT_{iron} on the left-hand side:

$$\Delta\ T_{\text{f,iron}} = \frac{m_{\text{water}}c_{\text{water}}\Delta\ T_{\text{water}} + m_{\text{water}}L_{\text{v,water}}}{-\ m_{\text{iron}}c_{\text{iron}}}$$

Isolate the required $T_{\text{f,iron}}$ on the left-hand side:

$$\Delta T_{\text{f,iron}} = \frac{0.1\text{ kg} \times 4200\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1} \times \left(100^\circ\text{C} - 65^\circ\text{C}\right) + 0.1\text{ kg} \times 2\,260\,000\text{ J kg}^{-1}}{-\ 5\text{ kg} \times 450\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}}$$

$\Delta T_{\text{f,iron}} = -106.9^\circ\text{C}$

Calculate the answer:

$T_{\text{f,iron}} = T_{\text{i}} + \Delta T_{\text{i,iron}}$

$T_{\text{f,iron}} = 140^\circ\text{C} + -106.9^\circ\text{C}$

$\Delta T_{\text{f,iron}} = 33.1^\circ\text{C}$

Give the answer to the correct number of significant figures.

10 $-Q_{\text{lost}} = Q_{\text{gained}}$

Apply the conservation of energy formula, assuming it is an isolated system:

$-m_{\text{steam}}L_{\text{v}} + m_{\text{steam}}c_{\text{water}}\Delta T_{\text{hot}}$
$= -\left(m_{\text{ice}}L_{\text{f}} + m_{\text{ice}}c_{\text{water}}\Delta T_{\text{cold}}\right)$

Apply the specific heat capacity and latent heat formulas:

$m_{\text{steam}}\left(-L_{\text{v}} + c_{\text{water}}\Delta T_{\text{hot}}\right) = -\left(m_{\text{ice}}L_{\text{f}} + m_{\text{ice}}c_{\text{water}}\Delta T_{\text{cold}}\right)$

Factorise the required m_{steam} on the left-hand side:

$$m_{\text{steam}} = \frac{-\left(m_{\text{ice}}L_{\text{f}} + m_{\text{ice}}c_{\text{water}}\Delta T_{\text{cold}}\right)}{\left(-L_{\text{v}} + c_{\text{water}}\Delta T_{\text{hot}}\right)}$$

Isolate the m_{steam} on the left-hand side:

$$m_{\text{steam}} = \frac{-\left(1\text{ kg} \times 334\,000\text{ J kg}^{-1} + 1\text{ kg} \times 4200\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1} \times \left(22^\circ\text{C} - 0^\circ\text{C}\right)\right)}{\left(-2\,260\,000\text{ J kg}^{-1} + 4200\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}\left(22^\circ\text{C} - 100^\circ\text{C}\right)\right)}$$

Insert known values:

$m_{\text{steam}} = 0.6349\text{ kg}$

Calculate the answer:

$m_{\text{steam}} = 0.6\text{ kg}$

Give the answer to the correct number of significant figures.

CHAPTER EXAM

MULTIPLE CHOICE

1	B	**2**	A	**3**	B	**4**	D	**5**	D
6	D	**7**	D	**8**	D	**9**	D	**10**	C

SHORT RESPONSE

11 $-Q_{\text{lost}} = Q_{\text{gained}}$

Apply the conservation of energy formula:

$-m_{\text{iron}}c_{\text{iron}}\Delta T_{\text{iron}} = m_{\text{water}}L_{\text{v,water}}$

Apply the specific heat capacity and latent heat of vaporisation formula:

$$\Delta T_{\text{iron}} = \frac{m_{\text{water}}L_{\text{v,water}}}{-m_{\text{iron}}c_{\text{iron}}}$$

Isolate ΔT_{iron} on the left-hand side:

$$T_{\text{f,iron}} = \frac{m_{\text{water}}L_{\text{v,water}}}{-m_{\text{iron}}c_{\text{iron}}} + T_{\text{i,iron}}$$

Isolate the required T_{f} of the left-hand side:

$$T_{\text{f,iron}} = \frac{0.2\text{ kg} \times 334\,000\text{ J kg}^{-1}}{-3\text{ kg} \times 450\text{ J kg}^{-1}\ {}^\circ\text{C}^{-1}} + 180^\circ\text{C}$$

Insert known values:

$T_{\text{f,iron}} = 130.5185^\circ\text{C}$

Calculate the answer:

$T_{\text{f,iron}} = 131^\circ\text{C}$

Give the answer to the correct number of significant figures.

12 Apply the conservation of energy formula:

$Q_{\text{gained}} = -Q_{\text{lost}}$

Apply the specific heat capacity formulas:

$m_{\text{copper}}c_{\text{copper}}\left(T_{\text{f}} - T_{\text{i}}\right) + m_{\text{water}}c_{\text{water}}\left(T_{\text{f}} - T_{\text{i}}\right) = -m_{\text{lead}}c_{\text{lead}}\left(T_{\text{f}} - T_{\text{i}}\right)$

Substitute in values from the question:

$\left(0.03 \times 380 \times \left(T_{\text{f}} - 18\right)\right) + (0.18 \times 4.18 \times 10^3 \times \left(T_{\text{f}} - 18\right)$

$= -(0.12 \times 130 \times \left(T_{\text{f}} - 98\right)$

Expand brackets:

$11.4T_{\text{f}} - 207.9 + 752.4T_{\text{f}} - 13543.2 = -15.6\ T_{\text{f}} + 1528.8$

Collect like terms and solve for T_f:

$779.4T_f = 15279.9$

$T_f = 19.6\ ^\circ\text{C}$

CROSS-CHAPTER QUESTION

13 Apply the conservation of energy formula:

$Q_{water} = -Q_{steam}$

Apply the specific heat capacity and latent heat formulas assuming 1 kg of steam:

$Q_{water} = -(Q_{steam} + -mL_v + Q_{water\ from\ steam})$

Expand formulas using $Q = mc\Delta T$:

$$mc_{water}(T_f - T_i) = -\begin{bmatrix} (-m_{steam} \times c_{steam} \times (T_f - T_i)) + (-m_{steam} \times L_v) \\ +(m_{steam} \times m_{water} \times (T_f - T_i)) \end{bmatrix}$$

Substitute in values from question:

$$(m \times 4.18 \times 10^3 \times 20) = -\begin{bmatrix} (1 \times 2.00 \times 10^3 \times -20) + (-1 \times 2.26 \times 10^6) \\ +(1 \times 4.18 \times 10^3 \times -50) \end{bmatrix}$$

Collect like terms:

$83\,600m = 2\,309\,000$

Solve for m:

$m = 27.62$ kg of cooling water

DATA ANALYSIS

14 a Calculate the mass of water:

$$\begin{aligned} m_{water} &= m_{cup+water} - m_{cup} \\ &= 210.4 - 158.0 \\ &= 52.4\ \text{g} \end{aligned}$$

Apply the conservation of energy formula:

$Q_{gained} = -Q_{lost}$

Apply the specific heat capacity formulas:

$mc\Delta T_{water} + mc\Delta T_{cup} = -mc\Delta T_{cube}$

Substitute in values from the question. assuming that the cube reaches thermal equilibrium with boiling water:

$$(0.0524 \times 4.18 \times 10^3 \times (28.6 - 26.9)) \\ +(0.1580 \times 387 \times (28.6 - 26.9)) \\ = -(0.010 \times c_{cube} \times (28.6 - 100))$$

Expand brackets:

$372.3544 + 103.9482 = 0.714c_{cube}$

Solve for c_{cube}:

$$\begin{aligned} c_{cube} &= \frac{372.3544 + 103.9482}{0.714} \\ &= 667.09\ \text{J kg}^{-1}\ \text{K}^{-1} \end{aligned}$$

b Most likely metal is nickel $(c = 500\ \text{J kg}^{-1}\ \text{K}^{-1})$.

15 Apply the conservation of energy formula:

$Q_{gained} = -Q_{lost}$

As it is a closed system, $\Delta Q = 0J$.

$Q_{gained} + Q_{lost} = 0$

Apply the specific heat capacity equations:

$mc\Delta T_{copper} + mc\Delta T_{lead} + mc\Delta T_{water} = 0$

Substitute in values from the question:

$$(0.05 \times 380 \times (T_f - 10)) + (0.400 \times 130 \times (T_f - 100)) \\ +(0.200 \times 4.18 \times 10^3 \times (T_f - 20))$$

Expand brackets:

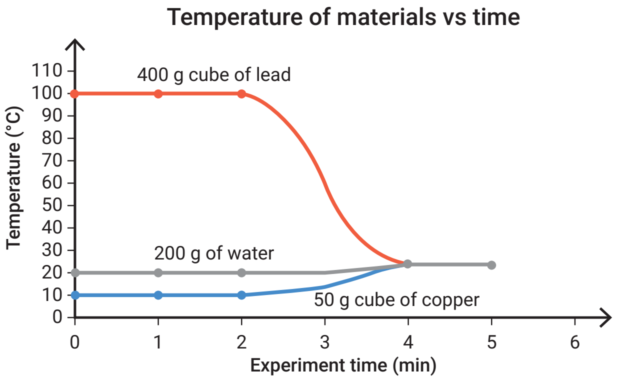
$19T_f - 190 + 52T_f - 5200 + 836\ T_f - 16\,720 = 0$

Solve for T_f:

$907T_f = 22110$

$T_f = 24^\circ\text{C}$

This will be the final temperature of all three materials at thermal equilibrium (4 minutes).



CHAPTER 5 ENERGY IN SYSTEMS – MECHANICAL WORK AND EFFICIENCY

LEARNING CHECK 5.1

DESCRIBING

1 A thermodynamic system can lose energy in the form of heat or work.

2 Work is the energy transferred due to the action of a force over a distance.

3 Power is the amount of energy transferred per unit time.

4 Apply the power formula:

$$P = \frac{E_{transferred}}{t}$$

$$P = \frac{W}{t}$$

$E_{transferred} =$ work for a thermodynamic system:

Apply the work formula: $W = F \times s$. Work is equal to a force applied over a distance:

$$P = \frac{F \times s}{t}$$

Put in the units for force, distance and time.

$$P = \frac{\text{N} \times \text{m}}{\text{s}}$$

It can therefore be seen that power can have the units of N m s^{-1}.

APPLYING

5 Heat from the combustion chamber is used to turn water to steam in the boiler. This steam expands onto the pistons, which turn crankshafts to cause the wheels to turn and ultimately do work on the carriages by pulling them.

6 Apply the work formula:

$$P = \frac{W}{t}$$

Insert known values:

$$P = \frac{3000\ \text{J}}{15\ \text{s}}$$

Calculate the answer:

$P = 200\ \text{J s}^{-1}$

Give the answer to the correct number of significant figures and use the correct unit.

$P = 2.0 \times 10^2\ \text{W}$

7 Apply the work formula:

$$P = \frac{W}{t}$$

Rearrange to make the required W the subject:

$W = P \times t$

Insert known values in the correct SI units:

$$W = 5.0 \times 10^3\ \text{W} \times 2.5\ \text{min} \times \frac{60\ \text{s}}{1\,\text{min}}$$

Calculate the answer with the correct number of significant figures.

$W = 750\,000\ \text{J}$

8 Apply the work formula:

$$P = \frac{W}{t}$$

Rearrange to make the required t the subject:

$$t = \frac{W}{P}$$

Replace W with $F \times s$:

$$t = \frac{F \times s}{P}$$

Insert known values:

$$t = \frac{120\ \text{N} \times 225\ \text{m}}{150\ \text{W}}$$

Calculate the answer with the correct number of significant figures.

$t = 180\,\text{s}$

LEARNING CHECK 5.2

DESCRIBING

1 The work–energy principle states that the change in internal energy of a system is equal to the net heat added to it minus the work done by it.

2 A heat engine is a device that turns heat energy into work.

3 The stable operating temperature of a heat engine occurs when the net heat in and the work done are equal.

4 Positive

5 Negative

6 Negative

7 Positive

APPLYING

8 Apply the work–energy principle:

$\Delta U = Q - W$

Insert known values:

$\Delta U = 2500\ \text{J} - 1200\ \text{J}$

Calculate the answer to the correct number of significant figures.

$\Delta U = 1300\ \text{J}$

9 Apply the work–energy principle:

$\Delta U = Q - W$

Include heat lost in the equation:

$\Delta U = Q_{\text{in}} - Q_{\text{out}} - W$

Insert known values:

$\Delta U = 5\,\text{kJ} - 1.5\,\text{kJ} - 3.0\,\text{kJ}$

Calculate the answer to the correct number of significant figures.

$\Delta U = 0.50\,\text{kJ}$

10 Apply the work–energy principle:

$\Delta U = Q - W$

Include heat lost in the equation:

$\Delta U = Q_{\text{in}} - Q_{\text{out}} - W$

Rearrange for Q_{out}:

$Q_{\text{out}} = Q_{\text{in}} - \Delta\ U - W$

Insert known values remembering that $\Delta U = 0$ at the stable operating temperature:

$Q_{\text{out}} = 440\,\text{kJ} - 0 - 323\,\text{kJ}$

Calculate the answer:

$Q_{\text{out}} = 117\,\text{kJ}$

Give the answer to the correct number of significant figures.

$Q_{\text{out}} = 120\ \text{kJ}$

LEARNING CHECK 5.3

DESCRIBING

1 Usable energy is the energy that can be utilised to perform some desired result, usually in the form of energy to do work.

2 A heat-exchange system is any system that transfers heat from a warmer to a cooler place.

3 A heat-exchange system transfers energy while a heat-conversion system transforms energy.

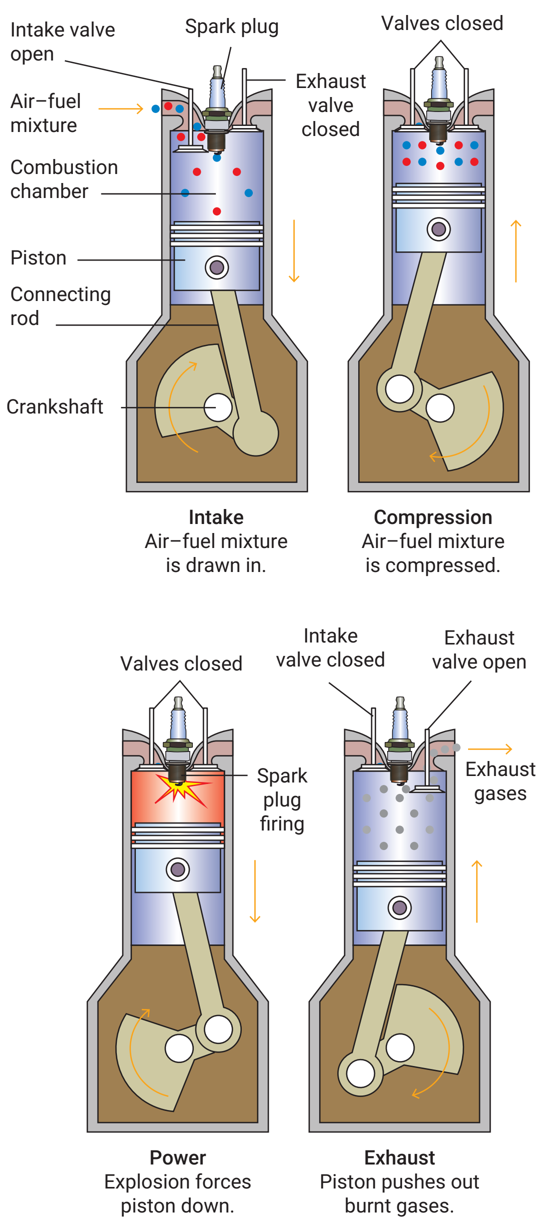
4 In an internal combustion system, the combustion which is used to convert heat energy to work takes place inside of the system, whereas in an external combustion system the combustion takes place outside of the system and the heat is transferred into it.

APPLYING

5 A refrigerator will not cool the room it is in because the design of the system is that it removes heat from inside the fridge to its surroundings. Therefore, any heat removed from the room if the refrigerator door is left open will immediately be transferred back into the room.

6

Four-stroke cycle



Intake
Air–fuel mixture is drawn in.

Compression
Air–fuel mixture is compressed.

Power
Explosion forces piston down.

Exhaust
Piston pushes out burnt gases.

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LEARNING CHECK 5.4

DESCRIBING

1 The efficiency of a system is the fraction of input energy that is converted in a thermodynamic process to useful output energy.

APPLYING

2 a Apply the efficiency formula:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Insert known values:

$$\eta = \frac{35\text{ kJ}}{105\text{ kJ}} \times \frac{100\%}{1}$$

Calculate the answer with the correct number of significant figures.

$\eta = 33\%$

b The remaining 70 kJ of energy would have been lost as heat to the external environment.

3 Apply the efficiency formula:

$$\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Rearrange the equation to make the required energy output the subject:

$$\text{Energy output} = \text{energy input} \times \frac{\eta}{100\%}$$

Insert known values:

$$\text{Energy output} = 900\text{ J} \times \frac{25\%}{100\%}$$

Calculate the answer:

Energy output = 225 J

Give the answer to the correct number of significant figures.

Energy output = 200 J

4 Apply the efficiency formula:

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

Insert known values:

$$\eta = \frac{350\text{ kJ}}{1700\text{ kJ}} \times \frac{100\%}{1}$$

Calculate the answer:

$\eta = 20.5882\%$

Give the answer to the correct number of significant figures.

$\eta = 21\%$

5 a Apply the efficiency formula:

$$\eta = \frac{Q_{in} - Q_{out}}{Q_{in}} \times \frac{100\%}{1}$$

Multiply both sides of the equation by $\frac{Q_{in}}{100\%}$:

$$\frac{\eta}{100\%} \times Q_{in} = Q_{in} - Q_{out}$$

Gather the terms containing the required Q_{in} on the left-hand side:

$$Q_{in} - \frac{\eta}{100\%} \times Q_{in} = Q_{out}$$

Factorise Q_{in} out of the left-hand side:

$$Q_{in}\left(1 - \frac{\eta}{100\%}\right) = Q_{out}$$

Rearrange the equation to make the required Q_{in} the subject:

$$Q_{in} = \frac{Q_{out}}{\left(1 - \frac{\eta}{100\%}\right)}$$

Insert known values:

$$Q_{in} = \frac{115 \text{ kJ}}{\left(1 - \frac{19\%}{100\%}\right)}$$

Calculate the answer:

$Q_{in} = 141.975 \text{ kJ}$

Give the answer to the correct number of significant figures.

$Q_{in} = 140 \text{ kJ}$

b Apply the work–energy principle:

$\Delta U = Q_{in} - Q_{out} - W$

Rearrange the equation to make the required W the subject:

$W = Q_{in} - Q_{out} - \Delta U$

Insert known values, remembering that $\Delta U = 0$ at the stable operating temperature:

$W = 141.975 \text{ kJ} - 115 \text{ kJ} - 0$

Calculate the answer:

$W = 26.9753 \text{ kJ}$

Give the answer to the correct number of significant figures.

$W = 27 \text{ kJ}$

CHAPTER EXAM

MULTIPLE CHOICE

1	C	**2**	A	**3**	D	**4**	B	**5**	D
6	B	**7**	A	**8**	C	**9**	C	**10**	C

SHORT RESPONSE

11 Apply the efficiency formula:

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

Insert known values:

$$\eta = \frac{1.6 \text{ kJ}}{8.5 \text{ kJ}} \times \frac{100\%}{1}$$

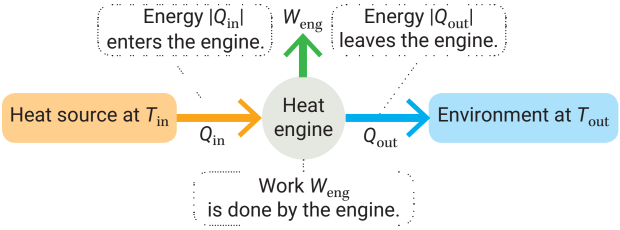
Calculate the answer:

$\eta = 18.8235\%$

Give the answer to the correct number of significant figures.

$\eta = 19\%$

12 The steam engine converts heat to work by combusting a fuel to create heat, which is then used to turn water to steam. This expanding steam then does work on the pistons of the engine that can transfer this work energy to the required place.



$\Delta U = Q - W$

$\Delta U = Q_{in} - Q_{out} - W$

$$\begin{aligned} W &= Q_{in} - Q_{out} - \Delta U \\ &= 5 \text{ kJ} - 1.2 \text{ kJ} - 0 \\ &= 3.8 \text{ kJ} \end{aligned}$$

$$\eta = \frac{W}{Q_{in}} \times \frac{100\%}{1}$$

$$Q_{in} = \frac{W}{\eta} \times \frac{100\%}{1}$$

$$P = \frac{W}{t}$$

$$\begin{aligned} W &= P \times t \\ &= 12\ 000 \text{ W} \times 1 \text{ min} \times \frac{60 \text{ s}}{1 \text{ min}} \\ &= 720 \text{ kJ} \end{aligned}$$

$$\begin{aligned} Q_{in} &= \frac{720 \text{ kJ}}{15\%} \times \frac{100\%}{1} \\ &= 4800 \text{ kJ} \end{aligned}$$

$$\begin{aligned} \Delta U &= Q - W \\ &= Q_{in} - Q_{out} - W \end{aligned}$$

$Q_{out} = Q_{in} - W - \Delta U$

$$\begin{aligned} Q_{in} &= 4800 \text{ kJ} \times \frac{1}{60 \text{ s}} \\ &= 80 \text{ kJ} \end{aligned}$$

$$\begin{aligned} W &= 720 \text{ kJ} \times \frac{1}{60 \text{ s}} \\ &= 12 \text{ kJ} \end{aligned}$$

$$\begin{aligned} Q_{out} &= 80 \text{ kJ} - 12 \text{ kJ} - 0 \\ &= 68 \text{ kJ} \end{aligned}$$

9780170483629

13 Energy efficiency $\eta = \frac{\text{useful output energy}}{\text{input energy}}$

In this case, the useful output energy is the heat transferred from the refrigerator to the surroundings, and the input energy is the energy consumed by the refrigerator.

Substitute values into the equation:

$$\eta = \frac{2000}{5000}$$

$\eta = 0.4$

Percentage energy efficiency $= \eta \times \frac{100\%}{1}$

$0.4 \times = 40\%$

DATA ANALYSIS

14 **a** The heater is not 100% efficient in terms of delivering the energy it consumes to the water it is heating.

b As $P = \frac{E}{t}$, the gradient of an energy vs time graph is the power.

$\frac{\text{rise}}{\text{run}} = \frac{E}{t}$

$P = 1499.2$ W

c

$$\begin{aligned}\sigma_{\text{gradient}} &= \frac{\text{maximum gradient} - \text{minimum gradient}}{2}\\ &= \frac{1572.4 - 1451.7}{2}\\ &= 60.4\end{aligned}$$

Input power = 1499.2 W ± 60.4 W

d As $P = \frac{E}{t}$, the gradient of an energy vs time graph is the power.

$\frac{\text{rise}}{\text{run}} = \frac{E}{t}$

P = 1124.5 W

e

$$\begin{aligned}\sigma_{\text{gradient}} &= \frac{\text{maximum gradient} - \text{minimum gradient}}{2}\\ &= \frac{1165.5\ -\ 1089.7}{2}\\ &= 37.9\end{aligned}$$

Input power = 1124.5 W ± 37.9 W

f

$$\begin{aligned}\eta &= \frac{\text{output}}{\text{input}} \times \frac{100\%}{1}\\ &= \frac{1124.5}{1499.2} \times \frac{100\%}{1}\\ &= 75.0\%\end{aligned}$$

Uncertainty needs to be considered.

The minimum efficiency considering the measurement error can be calculated using the maximum heater output and the minimum absorption value.

$$\eta = \frac{1089.5}{1572.4} \times \frac{100\%}{1}$$

$\eta_{\text{minimum}} = 69.3\%$

Maximum efficiency can be calculated using the minimum heater output and maximum absorption value.

$$\eta = \frac{1165.5}{1451.7} \times \frac{100\%}{1}$$

$\eta_{\text{maximum}} = 80.3\%$

$$\begin{aligned}\sigma &= \frac{\eta_{\text{maximum}} - \eta_{\text{minimum}}}{2}\\ &= \frac{80.3 - 69.3}{2}\\ &= 5.5\end{aligned}$$

Efficiency of water heater $= 75.0\% \pm 5.5\%$

15 **a** Heat or thermal energy

b Energy must be conserved:

$Q_{\text{in}} = Q_{\text{out}}$

According to the diagram:

$Q_{\text{out}} = Q_{\text{light}} + Q_{\text{waste}}$

Substitute the expression for Q_{out} into the first equation:

$Q_{\text{in}} = Q_{\text{light}} + Q_{\text{waste}}$

Rearrange for Q_{waste}:

$Q_{\text{waste}} = Q_{\text{in}} - Q_{\text{light}}$

Substitute in values from the question:

$$\begin{aligned}Q_{\text{waste}} &= 480 - 360\\ &= 120 \text{ J}\end{aligned}$$

c Incandescent bulb:

$$\%\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Substitute in values from the question:

$$\begin{aligned}\%\eta &= \frac{360}{1800} \times \frac{100\%}{1}\\ &= 20\%\end{aligned}$$

LED bulb:

$$\%\eta = \frac{\text{energy output}}{\text{energy input}} \times \frac{100\%}{1}$$

Substitute in values from the question:

$$\begin{aligned}\%\eta &= \frac{360}{480} \times \frac{100\%}{1}\\ &= 75\%\end{aligned}$$

LEDs are becoming more widespread as their energy efficiency is much greater than equivalent incandescent bulbs, reducing energy costs and carbon emissions.

d $P = \frac{Q_{\text{in}}}{t}$

Substitute in values from the question:

$$P = \frac{1800}{60\ \text{s}}$$
$$= 30\ \text{W}$$

CHAPTER 6 NUCLEAR MODEL AND STABILITY

LEARNING CHECK 6.1

DESCRIBING

1 Thomson, Rutherford, Bohr

2 New experiences are constantly providing new evidence of the behaviour of atoms and subatomic particles. From this evidence, we can refine our understanding of what the atom is like. Evidence continues to be compiled as technology advances, and models of the atom are refined accordingly.

APPLYING

3 Key differences include the electron configuration and explanation for electron energy levels to explain why electrons don't spiral into the nucleus. Bohr's model accounts for the conservation of energy and momentum while electrons still orbit within given energy states at outer edges of the atom.

LEARNING CHECK 6.2

DESCRIBING

1 *A*: mass (nucleon) number, *Z*: atomic (proton) number, X: element symbol

2 **a** An element is a substance that only has atoms with the same number of protons.

b Isotopes are atoms with the same number of protons, but a different number of neutrons in the nucleus.

c Nuclides are atoms with the same number of protons and neutrons, and with the nucleus in the same energy state.

3 Proton (positive), electron (negative), neutron (neutral)

4 Atomic mass is the total number of protons and neutrons in the nucleus – an integer value – whereas atomic weight is the weighted average of all the masses of the different nuclides of a naturally occurring sample of the element – a non-integer value.

5 No. Electrons do not exist in the nucleus and are used for bonding.

APPLYING

6 $N = A - Z$

$$= 136 - 57$$
$$= 79 \text{ neutrons}$$

7 $153 \times 0.5218 + 151 \times 0.4782 = 152.04$

ANALYSING

8 The 'element' hydrogen could mean hydrogen-1, hydrogen-2 or hydrogen-3, all of which have different masses. This could cause confusion, as different isotopes have different properties even if they are all the same element.

9 Molybdenum-98. If a neutron is absorbed by a nucleus, the same number of protons are present, only the mass number changes.

LEARNING CHECK 6.3

DESCRIBING

1 Strong, electrostatic (electromagnetic), weak, gravitational

2 The line of stability is the force responsible for keeping nuclei, and hence atoms, together. And as atoms and matter make up the universe, it can be considered the most important of all forces.

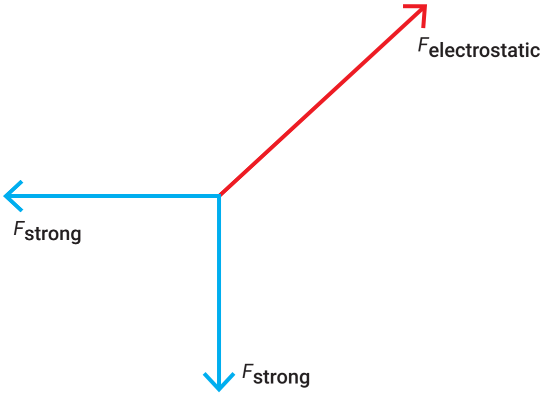
APPLYING

3 The electrostatic force within nuclei will push protons apart, hence atoms would not stay together. If atoms are unable to stay together, matter would not exist as we know it.

4 $F = \frac{kqQ}{r^2}$

$$= \frac{9 \times 10^9 \times (1.6 \times 10^{-19})^2}{(6 \times 10^{-15})^2}$$
$$= \frac{2.304 \times 10^{-28}}{3.6 \times 10^{-29}}$$
$$= 6.4 \text{ N of repulsion}$$

5 Consider the proton in the top right corner. It experiences the following forces:



Notice all forces are balanced so the proton will not move. The gravitational force is so small that it is not labelled in this instance, but would point left, down and towards the other proton.

6 The strong force needs to be exerted on both protons in helium-4 in two directions. Protons exert a repulsive force on each other of 57.6 N (from Worked example 6.3.1). Then we can calculate the magnitude of the strong force on one proton as follows:

$$F_{\text{electrostatic}}^2 = F_{\text{strong}}^2 + F_{\text{strong}}^2$$

$$F_{\text{electrostatic}}^2 = 2 \times F_{\text{strong}}^2$$

$$57.6^2 = 2 \times F_{\text{strong}}^2$$

$$F_{\text{strong}}^2 = 1658.88$$

$$F_{\text{strong}} = 40.73\,\text{N}$$

As the strong force is acting in two directions, on two protons, the total strong force magnitude is $4 \times 40.73 = 162.92$ N.

LEARNING CHECK 6.4

DESCRIBING

1 If a nucleus is stable, it is one of the dots on the line of stability. A stable nucleus has a ratio of protons to neutrons where the interacting forces are balanced.

2 The line of stability, or the stability curve, shows a dot for each isotope of each element that is stable.

APPLYING

3 No, it would not. This ratio is not on the line of stability, and therefore is considered an unstable nuclide.

CHAPTER EXAM

MULTIPLE CHOICE

1 B **2** A **3** C **4** D **5** B

6 B **7** C **8** C **9** A **10** C

SHORT RESPONSE

11 Rubidium-85

12 a Nucleus in the centre of the atom containing protons and neutrons held together by the strong nuclear force. Electrons orbit the nucleus, held in by the electromagnetic force.

b & c Proton: nucleus, +1, 1

Neutron: nucleus, 0, 1

Electron: in orbits around the nucleus, –1, 0

13 a Co (cobalt) **b** Ra (radium) **c** I (iodine)

DATA ANALYSIS

14 An atom with 20 protons and 70 nucleons, will have 50 neutrons.

Reading off the graph, the atom will be much lower than the line of stability. Therefore, it will be unstable.

15 a As *r* increases, *F* decreases non-linearly.

b Due to the shape of the trendline in Graph 1, the experimenter hypothesised that the relationship was inverse-square in nature and thus processed the data to plot *F* vs $\frac{1}{r^2}$. If this relationship is linear, it confirms an inverse-square relationship.

c Using the linear equation from Graph 2:

$$y = 231\,x + \left(1 \times 10^{-14}\right)$$

Substituting in the variables from the graph:

$$F = 231\left(\frac{1}{r^2}\right) + \left(1 \times 10^{-14}\right)$$

d Units for *r* in the data is $\times 10^{-6}$. Therefore, if distance $= 1.5 \times 10^{-5}\text{m}$, r value $= 15$.

From our equation:

$$F = 231\left(\frac{1}{r^2}\right) + 1 \times 10^{-14}$$

Substitute in value for *r*:

$$F = 231 \times \left(\frac{1}{15^2}\right) + 1 \times 10^{-14}$$

$$= 1.03$$

Units for *F* in data $\times 10^{-18}$

$$F = 1.03 \times 10^{-18}\,\text{N}$$

CHAPTER 7 SPONTANEOUS DECAY AND HALF-LIFE

LEARNING CHECK 7.1

DESCRIBING

1 Ionising and non-ionising

2 Terrestrial (from Earth's crust) and cosmic (from space)

3 Ionising radiation and non-ionising radiation are categorised in terms of whether the electron configuration is altered. Ionising radiation can cause electrons to be taken away from atoms, leaving behind ions. Electromagnetic radiation may strip electrons or may simply add energy.

4 Different energy waves serve different purposes, and have different effects on biological organisms. It is important to categorise waves by their energy for both of these reasons.

APPLYING

5 Background radiation needs to be considered so that the radioactivity from a source is not overestimated. The data needs to be calibrated by deducting the original background radiation from the measurements to have a true indication of the measured radiation from a source .

ANALYSING

6 Terrestrial radiation is caused by the decay of nuclei in Earth's crust. This radiation emanates outwards, and then reflects back when it hits the atmosphere. Other planets cannot achieve this because of their lack of atmosphere.

7 Answers will vary but may include radiographer, types of engineers and nuclear power plant workers. Daily monitoring and checks are performed.

LEARNING CHECK 7.2

DESCRIBING

1 Mass number and atomic number

2 Alpha decay: ${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-4}_{Z-2}\mathrm{Y} + {}^{4}_{2}\alpha$, beta-minus decay:

${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\beta + \overline{\nu}$, beta-plus decay: ${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + {}^{0}_{1}\beta + \nu$,

gamma decay: ${}^{A}_{Z}\mathrm{X}^{*} \rightarrow {}^{A}_{Z}\mathrm{X} + \gamma$

3 In nuclear reactions, the nucleus rearranges and new elements are formed. In chemical reactions, bonds rearrange but the nuclei of all atoms have the same configuration.

4 Neon-21

APPLYING

5 ${}^{151}_{67}\mathrm{Ho} \rightarrow {}^{147}_{65}\mathrm{Tb} + {}^{4}_{2}\alpha$, daughter nuclide is terbium-147

6 ${}^{210}_{86}\mathrm{Rn} \rightarrow {}^{206}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$, an alpha particle is emitted

7 **a** ${}^{211}_{87}\mathrm{Fr} \rightarrow {}^{207}_{85}\mathrm{At} + {}^{4}_{2}\alpha$
  b Astatine-207

8 **a** ${}^{213}_{84}\mathrm{Po} \rightarrow {}^{209}_{82}\mathrm{Pb} + {}^{4}_{2}\alpha$
  b Lead-209

9 ${}^{158}_{65}\mathrm{Tb} \rightarrow {}^{154}_{63}\mathrm{Eu} + {}^{4}_{2}\alpha, \rightarrow {}^{154}_{63}\mathrm{Eu} + \gamma^{*}$

10 ${}^{198}_{79}\mathrm{Au} \rightarrow {}^{198}_{80}\mathrm{Hg} + {}^{0}_{-1}\beta$, beta-minus decay

LEARNING CHECK 7.3

DESCRIBING

1 **a** Gamma
  b Alpha
  c All types – depending on the exposure levels

2 Alpha particles and positrons (beta-plus) are both deflected in the same direction in magnetic fields.

3 Gamma radiation, because gamma radiation is a type of electromagnetic radiation with no charge.

4 Alpha radiation; because it is the most massive, it is harder to deflect. Its mass-to-charge ratio is much larger than any other form of radiation.

APPLYING

5 A count rate is how many electric pulses the counter receives in a given time period. This is a measurement of how many nuclei are decaying in a radioactive sample.

6 $\frac{1600}{20} = 80$ counts per second

LEARNING CHECK 7.4

DESCRIBING

1 An element that can only be produced synthetically, and does not exist naturally in the universe

2 By bombarding nuclei with neutrons.

APPLYING

3 The arrow on the line of stability will go directly towards the origin, two spaces down and two spaces left as neutron number and proton number decrease by two each. Daughter nuclide is thorium-234.

4 Vertical arrow upwards by one atomic number increment. Neutron number remains the same. Daughter nuclide is uranium-233.

ANALYSING

5 Answers will vary depending on research conducted. Positives should include that we can harness transuranic elements for obtaining energy; negatives include their high levels of radiation and instability.

LEARNING CHECK 7.5

DESCRIBING

1 ${}^{4}_{2}\mathrm{He}^{2+}$, ${}^{4}_{2}\alpha$

2 ${}^{0}_{-1}\mathrm{e}$, ${}^{0}_{-1}\beta$, ${}^{0}_{1}\mathrm{e}$, ${}^{0}_{1}\beta$

APPLYING

3 **a** ${}^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{13}\mathrm{Al} + {}^{0}_{-1}\beta$, aluminium-23
  b ${}^{81}_{36}\mathrm{Kr} \rightarrow {}^{81}_{37}\mathrm{Rb} + {}^{0}_{-1}\beta$, rubidium-81
  c ${}^{137}_{55}\mathrm{Cs} \rightarrow {}^{137}_{56}\mathrm{Ba} + {}^{0}_{-1}\beta$, barium-137

4 **a** ${}^{11}_{6}\mathrm{C} \rightarrow {}^{11}_{5}\mathrm{B} + {}^{0}_{1}\beta$, boron-11
  b ${}^{121}_{53}\mathrm{I} \rightarrow {}^{121}_{52}\mathrm{Te} + {}^{0}_{1}\beta$, tellurium-121
  c ${}^{15}_{8}\mathrm{O} \rightarrow {}^{15}_{7}\mathrm{N} + {}^{0}_{1}\beta$, nitrogen-15

5 **a** ${}^{233}_{92}\mathrm{U} \rightarrow {}^{229}_{90}\mathrm{Th} + {}^{4}_{2}\alpha$, thorium-229
  b ${}^{240}_{94}\mathrm{Pu} \rightarrow {}^{236}_{92}\mathrm{U} + {}^{4}_{2}\alpha$, uranium-236
  c ${}^{222}_{86}\mathrm{Rn} \rightarrow {}^{218}_{84}\mathrm{Po} + {}^{4}_{2}\alpha$, polonium-218

LEARNING CHECK 7.6

DESCRIBING

1 $N = N_0 e^{-\lambda t}$

2 A measure of the magnitude of radioactive emissions, measured in emissions per second or becquerels (Bq)

APPLYING

3 $N = N_0 e^{-\lambda t}$

$= 1 \times e^{-2 \times 10^{-6} \times 260}$

$= 0.9995$ kg

4 $N = N_0 e^{-\lambda t}$

$N_0 = N \times e^{\lambda t}$

$= 300 \times e^{7.9 \times 10^{-3} \times 27}$

$= 371.33$ g

5 $N = N_0 e^{-\lambda t}$

$\frac{N}{N_0} = e^{-\lambda t}$

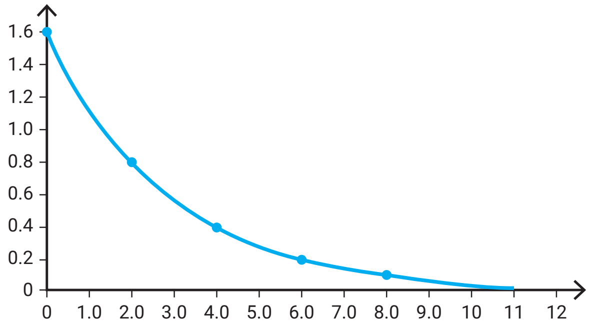
$0.58 = e^{-\lambda \times 1257}$

$\ln 0.58 = -\lambda \times 1257$

$\lambda = \frac{0.5447}{1257}$

$= 4.33 \times 10^{-4}$ year^{-1}

6 Plot of equation $y = 1.6 \times 10^{26} \times e^{-2t}$ for domain $0 \le t \le 12$



LEARNING CHECK 7.7

DESCRIBING

1 Radium, actinium, thorium, neptunium

2 82 for radium, actinium and thorium. 81 for neptunium.

3 Neptunium series

4 This is the atomic number where neutron/proton ratios begin to stabilise.

APPLYING

5 ${}^{230}_{90}\text{Th} \rightarrow {}^{226}_{88}\text{Ra} + {}^{4}_{2}\alpha$

${}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$

${}^{222}_{86}\text{Rn} \rightarrow {}^{218}_{84}\text{Po} + {}^{4}_{2}\alpha$

${}^{218}_{84}\text{Po} \rightarrow {}^{214}_{82}\text{Pb} + {}^{4}_{2}\alpha$

${}^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} + {}^{0}_{-1}\beta$

${}^{214}_{83}\text{Bi} \rightarrow {}^{214}_{84}\text{Po} + {}^{0}_{-1}\beta$

${}^{214}_{84}\text{Po} \rightarrow {}^{210}_{82}\text{Pb} + {}^{4}_{2}\alpha$

${}^{210}_{82}\text{Pb} \rightarrow {}^{210}_{83}\text{Bi} + {}^{0}_{-1}\beta$

${}^{210}_{83}\text{Bi} \rightarrow {}^{210}_{84}\text{Po} + {}^{0}_{-1}\beta$

${}^{210}_{84}\text{Po} \rightarrow {}^{206}_{82}\text{Pb} + {}^{4}_{2}\alpha$

6 **a** ${}^{232}_{90}\text{Th} \rightarrow {}^{228}_{88}\text{Ra} + {}^{4}_{2}\alpha$

${}^{228}_{88}\text{Ra} \rightarrow {}^{228}_{89}\text{Ac} + {}^{0}_{-1}\beta$

b Radium-228 and actinium-228

7 **a** ${}^{238}_{92}\text{U} \rightarrow {}^{234}_{90}\text{Th} + {}^{4}_{2}\alpha$

${}^{234}_{90}\text{Th} \rightarrow {}^{234}_{91}\text{Pa} + {}^{0}_{-1}\beta$

b Thorium-234 and protactinium-234

LEARNING CHECK 7.8

DESCRIBING

1 The time it takes for half of a radioactive substance to decay.

2 $N = N_0 \left(\frac{1}{2}\right)^n$

APPLYING

3 Three decays would have been expected in 9 minutes, but decay is spontaneous, and there is a 50% chance at any point a nucleus will decay. The chance of a nucleus decaying in the first four half-lives (12 minutes) is 1 in 2^4 or 6.25%.

4 $\lambda = \frac{\ln 2}{t_{\frac{1}{2}}}$

$= \frac{\ln 2}{5730}$

$= 1.21 \times 10^{-4}$ year^{-1}

5 **a** $N = N_0 \left(\frac{1}{2}\right)^n$

$= 3 \times 10^{24} \left(\frac{1}{2}\right)$

$= 1.5 \times 10^{24}$ atoms

b 1.5×10^{24} atoms

6 $N = N_0 \left(\frac{1}{2}\right)^n$

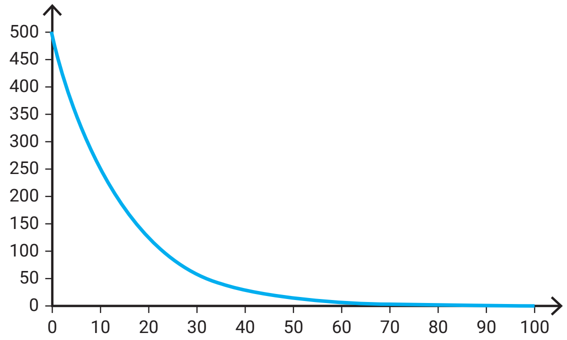
$\frac{N}{N_0} = \left(\frac{1}{2}\right)^n$

$0.3 = \left(\frac{1}{2}\right)^n$

$\log_{\frac{1}{2}} 0.3 = n$

$n = 1.74$ half-lives

7 Plot function $y = 500 \times e^{-0.0693t}$ for domain $0 \le t \le 100$



LEARNING CHECK 7.9

DESCRIBING

1 Nuclear medicine, including PET scans. Radioactive dating to determine the age of fossils.

2 A diagnosis is when the problem is determined.
A treatment works to fix the problem.

3 The half-life needs to be considered for the transportation of the isotope so that it can still be administered to the patient with enough nuclei still ready to decay to be effective.

APPLYING

4 To ensure not too many of the nuclei decay during creation and transportation so it can be administered and used effectively.

5 Carbon-14 decays after a biological organism dies. The ratio of carbon-14 to carbon-12 can be used to find how many half-lives of carbon-14 have passed since the organism died.

ANALYSING

6 No. The half-life of carbon-14 is much too long to be useful for testing the age of carbon-based life forms that are only hundreds of years old.

CHAPTER EXAM

MULTIPLE CHOICE

1 D 2 A 3 A 4 B 5 D
6 A 7 C 8 C 9 C 10 C

SHORT RESPONSE

11 ${}^{60}_{27}\text{Co} \rightarrow {}^{60}_{28}\text{Ni} + {}^{0}_{-1}\beta$, the daughter nuclide is nickel-60

12 a ${}^{234}_{92}\text{U} \rightarrow {}^{230}_{90}\text{Th} + {}^{4}_{2}\text{He}$

b ${}^{214}_{82}\text{Pb} \rightarrow {}^{214}_{83}\text{Bi} + {}^{0}_{-1}\text{e}$

c ${}^{216}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{212}_{82}\text{Pb}$

d ${}^{210}_{82}\text{Pb} \rightarrow {}^{0}_{-1}\text{e} + {}^{210}_{83}\text{Bi}$

e ${}^{218}_{84}\text{Po} \rightarrow {}^{4}_{2}\text{He} + {}^{214}_{82}\text{Pb}$

f ${}^{214}_{83}\text{Bi} \rightarrow {}^{0}_{-1}\text{e} + {}^{214}_{84}\text{Po}$

g ${}^{234}_{91}\text{Pa} \rightarrow {}^{0}_{-1}\text{e} + {}^{234}_{92}\text{U}$

h ${}^{230}_{90}\text{Th} \rightarrow {}^{4}_{2}\text{He} + {}^{226}_{88}\text{Ra}$

i ${}^{91}_{43}\text{Tc} \rightarrow {}^{0}_{+1}\text{e} + {}^{91}_{42}\text{Mo}$

13 a ${}^{107}_{45}\text{Rh} \rightarrow {}^{0}_{-1}\text{e} + {}^{107}_{46}\text{Pd}$

b ${}^{157}_{70}\text{Yb} \rightarrow {}^{4}_{2}\text{He} + {}^{153}_{68}\text{Er}$

c ${}^{121}_{48}\text{Cd}^{*} \rightarrow {}^{121}_{48}\text{Cd} + {}^{0}_{0}\gamma$

d ${}^{156}_{67}\text{Ho} \rightarrow {}^{156}_{66}\text{Dy} + {}^{0}_{1}\beta^{+}$

e ${}^{75}_{31}\text{Ga} \rightarrow {}^{0}_{-1}\text{e} + {}^{75}_{32}\text{Ge}$

f ${}^{179}_{79}\text{Au} \rightarrow {}^{4}_{2}\text{He} + {}^{175}_{77}\text{Ir}$

g ${}^{187}_{80}\text{Hg}^{*} \rightarrow {}^{187}_{80}\text{Hg} + {}^{0}_{0}\gamma$

h ${}^{20}_{11}\text{Na} \rightarrow {}^{0}_{1}\text{e} + {}^{20}_{10}\text{Ne}$

14 a Two β^{-} decays means that two ${}^{0}_{-1}\text{e}$ particles are produced.

Two α decays means that two ${}^{4}_{2}\alpha$ particles are produced.

This can be used to find the starting atom of the actinium series:

$${}^{235}_{91}\text{Pa} \rightarrow 2\,{}^{4}_{2}\text{He} + 2\,{}^{0}_{-1}\text{e} + {}^{227}_{89}\text{Ac}$$

The starting atom is protractinium-235.

b The stable end product will occur after the production of five ${}^{4}_{2}\alpha$ particles and three ${}^{0}_{-1}\text{e}$ particles.

$${}^{227}_{89}\text{Ac} \rightarrow 5\,{}^{4}_{2}\alpha + 3\,{}^{0}_{-1}\text{e} + {}^{207}_{82}\text{Pb}$$

The find end product is lead-207.

DATA ANALYSIS

15 a Initial mass is the mass at $t = 0$ s

$m_0 = 2.5$ g

b Half-life is the time for half the original atoms to decay.

$t_{\frac{1}{2}} = 0.25$ s

c Using the equation to solve for the remaining mass:

$$N = N_0\left(\frac{1}{2}\right)^{n}$$

Determine the number of half-lives passed after 0.2 seconds:

$$n = \frac{t}{t_{\frac{1}{2}}}$$

$$= \frac{0.2}{0.25}$$

$$= 0.8 \text{ half-lives}$$

Substitute back into the original equation:

$$N = 2.5\left(\frac{1}{2}\right)^{0.8}$$

$$= 1.44 \text{ g}$$

d $1\% \text{ of } 2.5 \text{ g} = 0.025 \text{ g}$

Substitute into the equation for half-life:

$$N = N_0\left(\frac{1}{2}\right)^n$$

$$0.025 = 2.5\left(\frac{1}{2}\right)^n$$

Solve for n:

$$0.01 = \left(\frac{1}{2}\right)^n$$

$$\log 0.01 = \log\left(\frac{1}{2}\right)^n$$

$$= n \times \log\left(\frac{1}{2}\right)$$

$$n = \frac{\log 0.01}{\log 0.5}$$

$$= 6.64 \text{ half-lives}$$

Determine the time this would take:

$$n = \frac{t}{t_{\frac{1}{2}}}$$

$$6.64 = \frac{t}{0.25}$$

$$t = 6.64 \times 0.25$$

$$= 1.6 \text{ seconds}$$

e Half-life is dependent on the radionuclide, not on the amount of substance. Therefore, if 4.00 g of the same sample was used, it would take the same amount of time for half of the sample to decay.

$t = 0.25$ seconds

CHAPTER 8 NUCLEAR ENERGY AND MASS DEFECT

LEARNING CHECK 8.1

DESCRIBING

1 E: Energy, the energy released in a nuclear reaction, measured in joules

Δm: Mass defect, the difference between the mass of an atom and that of its constituent parts, measured in kilograms

c: The speed of light, $c = 3.00 \times 10^8 \text{ m s}^{-1}$

2 **a** Electromagnetic force: the force of attraction or repulsion that acts between charged particles

b Strong nuclear force: the force acting to bind nucleons together

c Gravitational force: the force of attraction acting at a distance between masses

d Weak nuclear force: the force acting between subatomic particles within the nucleus; responsible for beta decay

e Nuclear binding energy: the energy required to disassemble a nucleus into its component nucleons

3

	Gravitational force	Weak nuclear force	Electro-magnetic force	Strong nuclear force
Relative magnitude	1	10^{32}	10^{36}	10^{40}
Range (m)	Indefinite	10^{-18} or 1 attometre, 1 am	Infinite	10^{-15} or 1 femtometre, 1 fm

APPLYING

4 **a** Calculate the sum of protons, electrons and neutrons for helium-3 using given values:

2 protons, 1 neutron, 2 electrons

$$2\times1.67208\times10^{-27} + 1\times1.67438\times10^{-27} + 2\times9.11\times10^{-31}$$
$$= 5.0203\times10^{-27}\text{kg}$$

Calculate the mass defect:

$$\Delta m = 5.0204\times10^{-27} - 5.00661\times10^{-27}$$
$$= 1.375\times10^{-29}\text{kg}$$

b Apply Einstein's mass-energy equivalence:

$$E = mc^2$$

Substitute in known values:

$$E = 1.375\times10^{-29}\times\left(3\times10^8\right)^2$$
$$= 1.238\times10^{-12}\text{J}$$

c There are 3 nucleons in a helium-3 atom. Therefore, divide the total binding energy by 3.

$1.238\times10^{-12} \div 3 = 4.127\times10^{-13}\text{J}$ per nucleon

5 **a** Calculate sum of protons, electrons and neutrons for nitrogen-14 using given values:

7 protons, 7 neutrons, 7 electrons

$$7\times1.67208\times10^{-27} + 7\times1.67438\times10^{-27} + 7\times9.11\times10^{-31}$$
$$= 2.3432\times10^{-26}\text{kg}$$

Calculate the mass defect:

$$\Delta m = 2.3432\times10^{-26} - 2.3251\times10^{-26}$$
$$= 1.81\times10^{-28}\text{kg}$$

b Apply Einstein's mass–energy equivalence:

$$E = mc^2$$

Substitute in known values:

$$E = 1.81\times10^{-28}\times\left(3\times10^8\right)^2$$
$$= 1.629\times10^{-11}\text{J}$$

c There are 14 nucleons in a nitrogen-14 atom. Therefore, divide the total binding energy by 14.

$1.629\times10^{-11} \div 14 = 1.164\times10^{-12}\text{J}$ per nucleon

LEARNING CHECK 8.2

DESCRIBING

1 a Natural transmutation

  b Artificial transmutation

APPLYING

2 $^{14}_{7}N + ^{4}_{2}He \rightarrow ^{18}_{9}F^*$

LEARNING CHECK 8.3

DESCRIBING

1 $^{238}_{92}U$

2 a Fission: the process by which a nucleus splits into two or more fragments. Fission may occur naturally or artificially.

  b Fission fragment: a product of a fission reaction with a nucleus smaller than the initial atom.

APPLYING

3 $^{235}_{92}U + ^{1}_{0}n \rightarrow ^{92}_{36}Kr + ^{141}_{56}Ba + 3^{1}_{0}n + \text{energy}$

4 b i Calculate the mass of the reactants using the given information:

$$m_r = 233.044 + 1.01$$
$$= 234.054\ u$$

Calculate the mass of the products using the given information:

$$m_p = 103.91 + 125.91 + 4 \times 1.01$$
$$= 233.86$$

Calculate the mass defect:

$$\Delta m = m_r - m_p$$
$$= 0.194\ u$$

  ii Convert to kilograms:

$$0.194\ u \times 1.66 \times 10^{-27} = 3.2204 \times 10^{-28}\ kg$$

  c Apply Einstein's mass-energy equivalence:

$$E = mc^2$$
$$= 3.2204 \times 10^{-28} \times (3 \times 10^8)^2$$
$$= 2.898 \times 10^{-11}\ J$$

5 a $^{133}_{51}Sb$

  b $^{239}_{94}Pn + ^{1}_{0}n \rightarrow ^{104}_{43}Tc + ^{133}_{51}Sb + 3^{1}_{0}n$

  c Given the mass defect is 0.19 u, convert to kilograms:

$$0.19\ u \times 1.66 \times 10^{-27} = 3.154 \times 10^{-28}\ kg$$

  d Apply Einstein's mass–energy equivalence:

$$E = mc^2$$
$$= 3.154 \times 10^{-28} \times (3 \times 10^8)^2$$
$$= 2.8386 \times 10^{-11} J$$

LEARNING CHECK 8.4

DESCRIBING

1

Nuclear reactor component	Role in the reactor
Moderator	Light elements that slow down fast neutrons, enabling further nuclear reactions
Control rods	Rods of neutron-absorbing materials, such as boron-10, used to reduce the number of free neutrons and to control the rate of a nuclear reaction
Reactor vessel	High nucleon number (dense) material that reflects neutrons back into the reactor sample
Coolant	A temperature control mechanism transferring kinetic heat energy from within the reactor to outside of the reactor

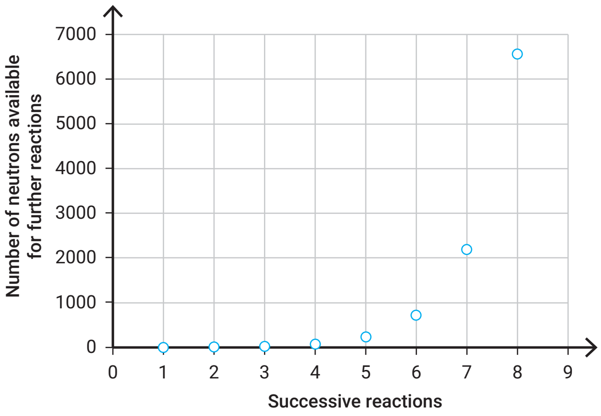
2 Neutrons that have been slowed through collisions with lighter elements (the moderator) to enable their capture within the nucleus of larger fissile elements

APPLYING

3 Control rods contain 'neutron poisons' – elements that absorb neutrons so they cannot take part in successive nuclear reactions. Control rods may be inserted or removed from the reactor vessel to control the rate of nuclear reactions occurring.

4 Nuclear fission reactions typically produce multiple neutrons – each successive reaction enables more reactions to occur. This is shown in the table of successive reactions and the exponential graph of reactions over time.

Successive reactions	Number of neutrons available for further reactions
1	$3^1 = 3$
2	$3^2 = 9$
3	$3^3 = 27$
4	$3^4 = 81$
5	$3^5 = 243$
6	$3^6 = 729$
7	$3^7 = 2187$
8	$3^8 = 6561$



5

Pros	Cons
Environmental – nuclear power plants do not release greenhouse gases and emit fewer radioactive materials into the atmosphere than traditional coal-burning power plants.	Environmental – nuclear disasters, although rare, have catastrophic environmental and public health effects due to dangerous levels of radioactivity.
Economy and efficiency – nuclear power electricity generating plants are in excess of 90% efficient, operate continuously and are cost effective.	Non-renewable – Australia has access to significant renewable energy sources that are not finite and that pose no risk to the environment or climate change.
Abundance of nuclear fuel – Australia has 33% of the world's uranium deposits.	Abundance of alternative fuels – Australia has extensive coal and natural gas resources.

LEARNING CHECK 8.5

DESCRIBING

1 The process of joining two or more nucleons together to form a new atom. Fusion occurs for lighter elements ($Z < 56$) and is accompanied by the release of energy.

2 Nuclear fusion

APPLYING

3 ${}^{2}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + {}^{1}_{0}\text{n} + \text{energy}$

4 Nuclear fusion requires the joining of two or more elements to form a new atom, with an accompanying release of energy.

Nuclear fission requires the splitting of an atom into two or more fission fragments, with an accompanying release of energy.

LEARNING CHECK 8.6

DESCRIBING

1 Nuclear waste examples

High level	Spent fuel rods
Intermediate level	Pipes, gauges, fuel containers
Low level	Protective clothing, water from washing of protective equipment

2 Spent nuclear fuel must be stored in shielded containers and cooled to prevent the escape of radiation and overheating.

LEARNING CHECK 8.7

DESCRIBING

1 $c = 3.00 \times 10^{8}\ \text{m s}^{-1}$

2 $E = \Delta mc^{2}$

E = energy (J)

Δm = mass defect (kg)

c = speed of light (m s^{-1})

APPLYING

3 **a** Iron, mass number 56; 8.7 MeV per nucleon

b Bromine, mass number 80; 8.6 MeV per nucleon

c Oxygen, mass number 16; 8.0 MeV per nucleon

d Uranium, mass number 238; 7.5 MeV per nucleon

e Helium, mass number 4; 7.2 MeV per nucleon

4 The mass defect represents the difference in mass between an atom and its constituent parts. The energy released in a nuclear reaction is determined using the mass defect: $E = \Delta mc^{2}$.

5 Calculate the mass of the reactants:

$$m_r = 3.9039 \times 10^{-25} + 1.67438 \times 10^{-27}$$
$$= 3.921 \times 10^{-25}\ \text{kg}$$

Calculate the mass of the products:

$$m_p = 1.4545 \times 10^{-25} + 2.3727 \times 10^{-25} + 3 \times 1.67438 \times 10^{-27}$$
$$= 3.87743 \times 10^{-25}\ \text{kg}$$

Calculate the mass defect:

$$\Delta m = m_r - m_p$$
$$= 4.3212 \times 10^{-27}\ \text{kg}$$

Calculate the energy using the mass-energy equivalence:

$$E = mc^{2}$$
$$= 4.3212 \times 10^{-27} \times (3 \times 10^{8})^{2}$$
$$= 3.889 \times 10^{-10}\ \text{J}$$

6 Calculate the mass of the reactants:

$$m_r = 3.9039 \times 10^{-25} + 1.67438 \times 10^{-27}$$
$$= 3.921 \times 10^{-25}\ \text{kg}$$

Calculate the mass of the products:

$$m_p = 2.3893 \times 10^{-25} + 1.4926 \times 10^{-25} + 2 \times 1.67438 \times 10^{-27}$$
$$= 3.9154 \times 10^{-25}\ \text{kg}$$

Calculate the mass defect:

$$\Delta m = m_r - m_p$$
$$= 5.2562 \times 10^{-28}\ \text{kg}$$

Calculate the energy using the mass-energy equivalence:

$$E = mc^{2}$$
$$= 5.2562 \times 10^{-27} \times (3 \times 10^{8})^{2}$$
$$= 4.7306 \times 10^{-11}\ \text{J}$$

7 Calculate the mass of the reactants:

$$m_r = 3.34249 \times 10^{-27} \times 2$$
$$= 6.68498 \times 10^{-27}\ \text{kg}$$

Calculate the mass of the products:

$$m_p = 1.673 \times 10^{-27} + 5.00664 \times 10^{-27}$$
$$= 6.67964 \times 10^{-27}\ \text{kg}$$

Calculate the mass defect:

$$\Delta m = m_r - m_p$$
$$= 5.34 \times 10^{-30}\ \text{kg}$$

Calculate the energy using the mass-energy equivalence:

$$E = mc^{2}$$
$$= 5.34 \times 10^{-30} \times (3 \times 10^{8})^{2}$$
$$= 4.806 \times 10^{-13}\ \text{J}$$

8 Calculate the mass of the reactants:

$$m_r = 3.34249 \times 10^{-27} + 5.00664 \times 10^{-27}$$
$$= 8.34913 \times 10^{-27}\ \text{kg}$$

Calculate the mass of the products:

$$m_p = 1.673 \times 10^{-27} + 6.68387 \times 10^{-27}$$
$$= 8.34913 \times 10^{-27} \text{ kg}$$

Calculate the mass defect:

$$\Delta m = m_p - m_r$$
$$= 9.12 \times 10^{-30} \text{ kg}$$

Calculate the energy using the mass–energy equivalence:

$$E = mc^2$$
$$= 9.12 \times 10^{-30} \times (3 \times 10^8)^2$$
$$= 8.208 \times 10^{-13} \text{ J}$$

CHAPTER EXAM

MULTIPLE CHOICE

1 D	**2** C	**3** D	**4** C	**5** C
6 D	**7** C	**8** B	**9** A	**10** B

SHORT RESPONSE

11 **a** Two neutrons

b $\Delta m = 0.1844$ u

$$= 3.0610 \times 10^{-28} \text{ kg}$$

c $E = 2.7549 \times 10^{-11}$ J

12 Convert 361.7 MeV to eV:

$$361.7 \times 10^6 \text{ eV}$$

Convert to joules:

$$361.7 \times 10^6 \times 1.6 \times 10^{-19} = 5.7872 \times 10^{-11} \text{ J}$$

Calculate the atomic mass using the equation:

$$E = mc^2$$

Make mass the subject of the equation:

$$m = \frac{E}{c^2}$$
$$= \frac{5.7872 \times 10^{-11}}{(3 \times 10^8)^2}$$
$$= 6.43 \times 10^{-28} \text{ kg}$$

13 **a** Determine the mass of one atom of ${}^{235}_{92}\text{U}$:

protons = 92, neutrons = 143, electrons = 92

Calculating mass of protons:

$$m_{\text{protons}} = 92 \times 1.6726219 \times 10^{-27} \text{ kg}$$

Calculating mass of neutrons:

$$m_{\text{neutrons}} = 143 \times 1.6749275 \times 10^{-27} \text{ kg}$$

Calculating mass of electrons:

$$m_{\text{electrons}} = 92 \times 9.1093835 \times 10^{-31} \text{ kg}$$

$$m_t = m_{\text{protons}} + m_{\text{neutrons}} + m_{\text{electrons}}$$
$$= 3.934796536282 \times 10^{-25} \text{ kg}$$

Determine the mass defect:

$$\Delta m = 0.1\% \text{ of } m_{\text{total}}$$
$$= 3.934796536282 \times 10^{-28} \text{ kg}$$

Calculate the energy released per fission event:

$$E = \Delta mc^2$$
$$= 3.934796536282 \times (3 \times 10^8)^2$$

$E = 3.541317$ J per fission event (per single atom of ${}^{235}_{92}\text{U}$)

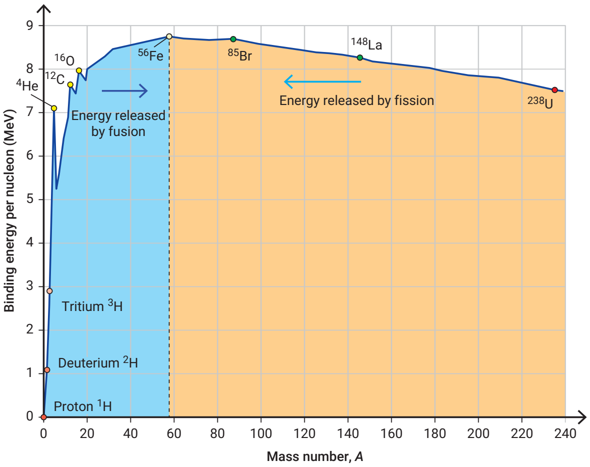
For 10 kg of ${}^{235}\text{U}$:

$$E = \frac{\text{energy released per atom of } {}^{235}\text{U} \times 10 \text{ kg}}{\text{mass of one atom of } {}^{235}\text{U}}$$
$$= \frac{3.541317 \times 10}{3.934796536282 \times 10^{-25}}$$
$$= 9 \times 10^{14} \text{ J}$$

b $$\frac{\text{Energy released by 10 kg uranium}}{\text{energy released by TNT}} = \frac{9 \times 10^{14}}{4 \times 10^9}$$
$$= 2.25 \times 10$$

It takes 2.25×10^5 tonnes of TNT.

14 The most stable nuclide is iron-56. Xenon-140 is bigger than iron, and hence is more likely to take a part in fission.



CROSS-CHAPTER QUESTION

15 Converting mass of neutron to amu:

$$m_n = \frac{1.6749275 \times 10^{-27}}{1.66 \times 10^{-27}} = 1.00899247 \text{ u}$$

Calculating mass defect:

$$\Delta m = m_r - m_p$$
$$= (m_{\text{uranium}} + m_{\text{neutron}}) - (m_{\text{krypton}} + m_{\text{barium}} + 3 \times m_{\text{neutron}})$$
$$= (235.0439299 + 1.00899247)$$
$$+ (91.9261731 + 140.914403 + 3 \times 1.00899247)$$
$$= 236.0529224 - 235.8675535$$
$$= 0.18536889 \text{ u}$$

Convert mass defect from amu to kg:

$$\Delta m = 0.18536889 \times 1.66 \times 10^{-27}$$
$$= 3.077123574 \times 10^{-28} \text{ kg}$$

Calculating the energy released per fission event:

$$E = mc^2$$
$$= 3.077123574 \times 10^{-28} \times \left(3 \times 10^8\right)^2$$
$$= 2.769411217 \times 10^{-11} \text{ J}$$

Calculating the mass of one atom of uUranium-235:

Convert from amu to kg:

$$m_{\text{uranium}} = 235.0439299 \times 1.66 \times 10^{-27}$$
$$= 3.90173 \times 10^{-25} \text{ kg}$$

Calculating the energy released per 0.001 kg (1 g) of uranium-235:

$$E = \frac{\text{energy per atom of } ^{235}\text{U}}{\text{mass of one atom of } ^{235}\text{U}} \times 0.001 \text{ kg}$$
$$= \frac{2.769411217 \times 10^{-4}}{3.90173 \times 10^{-25}} \times 0.001$$
$$= 7.0979 \times 10^{10} \text{ J}$$

The energy released from the fission reaction will be used to heat up the water:

$$Q = mc\Delta T$$

Substitute in known values:

$$7.0979 \times 10^{10} = m_{\text{water}} \times 4.18 \times 10^3 \times 40$$

Solve for mass of water:

$$m_{\text{water}} = \frac{7.0979 \times 10^{10}}{4.18 \times 10^3 \times 40}$$
$$= 4.245 \times 10^5 \text{ kg}$$

CHAPTER 9 CURRENT, POTENTIAL DIFFERENCE AND ENERGY FLOW

LEARNING CHECK 9.1

DESCRIBING

1 a Static electricity is the build-up of electric charge on an object, typically an insulator.

  b Potential energy is stored energy that has the potential to do work, such as gravitational potential, electric potential or chemical potential energy.

  c An insulator is a material that inhibits the flow of electrons, such as plastic or rubber.

  d A conductor is a material that allows the free flow of electrons. Metals are good electrical conductors.

2 D

UNDERSTANDING

3 Proton: $+1.6 \times 10^{-19}$ C

Neutron: no charge

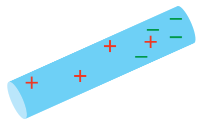
Electron: -1.6×10^{-19} C

4

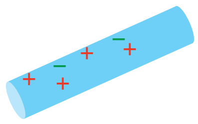
	Proton	Neutron	Electron
Relative mass	1	1	$\frac{1}{10000}$
Position	Nucleus	Nucleus	Electron shell outside nucleus

APPLYING

5 a



Neutral conductor

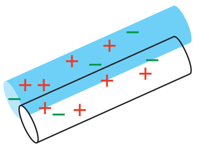


Positively charged conductor

Electrons are attracted to the positively charged conductor.

  b The positively charged conductor will attract the neutral conductor as the negative electrons are able to move within the material to the side closer to the positively charged rod, exerting a greater attractive force than the repulsion of the like charges.

  c



Charges are shared equally across the conductors.

LEARNING CHECK 9.2

DESCRIBING

1 a False

  b True

2 The law of conservation of charge states that the net charge in a system is conserved; that is, the net charge may only be increased or decreased by adding or removing charges from outside of the system.

3 Kirchhoff's current law (first law) states that the total current arriving at a junction within an electric circuit is equal to the total current leaving the junction.

APPLYING

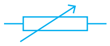
4 a $I_3 = 90$ mA b $I_1 = 2.25$ A

LEARNING CHECK 9.3

DESCRIBING

1 Electromotive force, EMF, is a source of potential energy per charge, or voltage.

2 a



  b

  c

  d

  e

3 An electromotive force (e.g. battery) and typically a load (e.g. lamp, or device to transform electric potential energy into other forms) connected by conducting wires

4 Batteries store energy by increasing the electric potential by placing a large number of electrons near each other at one terminal of the battery. This requires charge to be moved to this terminal.

APPLYING

5 The charging of a phone battery does not introduce more charge – it simply relocates the charge from one terminal to another.

LEARNING CHECK 9.4

DESCRIBING

1 **a** Conventional current is the established convention where electricity is considered as the flow of (hypothetical) positive charge.

b Alternating current, AC, is the flow of charge that changes direction periodically, typically at 50 hertz.

c Potential difference, measured in volts, describes the potential energy available per unit of charge.

d Power is defined as the rate of energy transformation (or work done) per unit of time, $P = \frac{W}{t}$

2 3.6×10^6 J = 1.0 kWh

3 The kWh is a more convenient unit of measurement for household power than the joule.

APPLYING

4 $q = 7.5$ A s or 7.5 C **5** $W = 180$ J

6 **a** $I = 0.94$ A **b** $P = 225$ W

7 **a** $W = 19$ MJ **b** 36.9 kWh

LEARNING CHECK 9.5

DESCRIBING

1 Step 1: Read the question carefully and try to understand the scenario.

Step 2: Organise the information, particularly the values and units provided.

Step 3: Sketch a diagram.

Step 4: Consider what formula may be applied.

Step 5: Verify the units and perform any conversions required.

2 $q = -1.6 \times 10^{-19}$ C

UNDERSTANDING

3 6.25×10^{18}

4 A potential difference leads to an attraction of electrons at the positive terminal of the conducting loop, leading to the flow of electrons.

APPLYING

5 $q = 20$ C **6** 5.0×10^{17} electrons

7 0.1 A

ANALYSING

8 **a** 1920 W **b** 41.5 MJ

9 37.5 C, 2.35×10^{20} electrons **10** 27 J

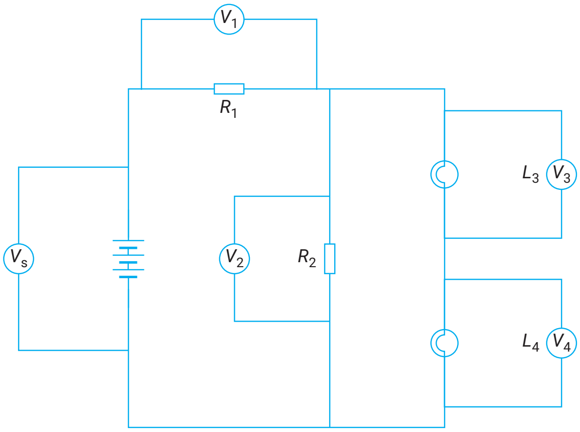
LEARNING CHECK 9.6

DESCRIBING

1 Kirchhoff's voltage law: for any closed loop in an electric circuit, the sum of the potential differences must be zero.

2 The law of conservation of electric charge states that the net charge in a system can only be increased or decreased by adding or removing charges from outside of the system (i.e. all charge is conserved within a closed system).

3



L_3 and L_4 are in series with each other.

R_2 and L_3 and L_4 are in parallel paths.

APPLYING

4 $V_2 = V_3 = 3$ V

5 $V_S = 14$ V

6 $V_2 = 14$ V and $V_3 = V_4 = 7$ V

CHAPTER EXAM

MULTIPLE CHOICE

1 D **2** D **3** C **4** D **5** A

6 D **7** B **8** C **9** C

10 D

SHORT RESPONSE

11 2.0 A away from the junction

12 $V_1 = 0.75$ V

13 Electrons flow from the negative terminal to the positive terminal.

14 Positive charge

15 **a** $q = 20\text{ C}$ **b** $W = 12\text{ J}$ **c** 40 s

CHAPTER 10 RESISTANCE

LEARNING CHECK 10.1

DESCRIBING

1 **a** Metals (e.g. copper) **b** Water
  c Rubber **d** Silicon

2 $R = \frac{\rho \times \ell}{A}$ or $\rho = \frac{R \times A}{\ell}$

3 $R \propto \ell$ as charges moving through a greater length of conductor meet greater opposition to their flow due to the greater length.

4 Resistance is the opposition to flow of electrical charge in a material, measured in ohms, Ω.

APPLYING

5 $\rho = 1.25 \times 10^{-8}\ \Omega\text{m}$

6 $\rho = 1.8 \times 10^{-8}\ \Omega\text{m},\ l = 0.50\text{ m},\ A = 1 \times 10^{-6}\text{ m}^2,\ R = 9.0 \times 10^{-3}\ \Omega$

LEARNING CHECK 10.2

DESCRIBING

1 **a** Ω **b** Ωm **c** A **d** V

2 A line of best fit is adequately modelled using a minimum of five points of data to ascertain the nature of the relationship (linear, quadratic, inverse etc.).

3 Random error: multiple numbers of trials and averaging values

Parallax error: positioning of the observer or device perpendicular to the measuring device

Systematic error: zeroing or calibrating the measuring device

4 Ohmic materials demonstrate a proportional relationship between the current and voltage, that is $V \propto I$. Non-ohmic materials demonstrate a non-linear relationship between the voltage across and current through the material, that is, the resistance varies in non-ohmic materials.

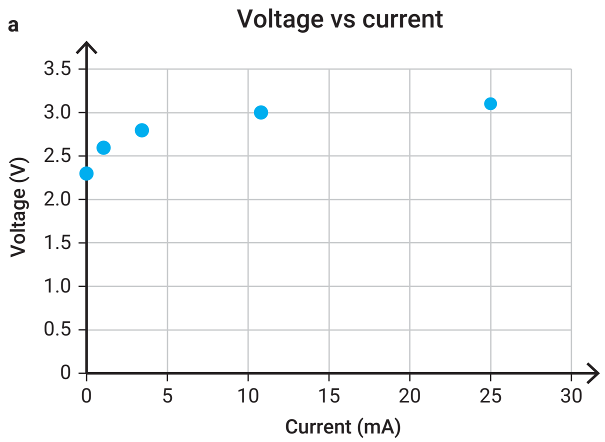
5 $R = \frac{V}{I}$ the law relating the current and voltage through a conductor as directly proportional, $V \propto I$

6 Ohmic device: ceramic resistor; non-ohmic device: light-emitting diode (LED)

7 Ohmic materials display a consistent resistance across a range of voltages. Non-ohmic materials display varying resistances at different voltages.

APPLYING

8 **a**



b The device is non-ohmic. The relationship between current and voltage is non-linear.

c
$$R = \frac{V}{I}$$
$$= \frac{3\text{ V}}{12 \times 10^{-3}\text{ A}}$$
$$= 250\ \Omega$$

LEARNING CHECK 10.3

DESCRIBING

1 Random error: error in timing using a stopwatch

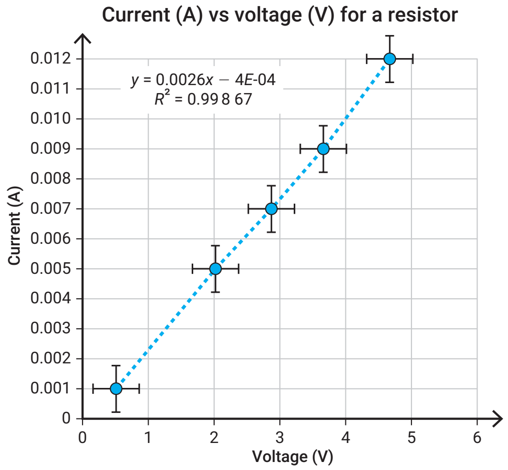
Systematic error: calibration error in electronic mass scales

2 Error bars indicate the uncertainty associated with each measurement and assist in determining if the line of best fit is a precise model of the relationship.

3 A random error is typically seen as values fluctuating on either side of the expected values; that is, as a two-sided error. A systematic error is typically seen as a one-sided error with values either all below or all above the expected values.

ANALYSING

4 **a**



b The device is ohmic, with a linear relationship between the current and voltage.

c $R = 382.5\ \Omega$

This value lies within $390\ \Omega \pm 19.5\ \Omega$ (5%) so is accurate.

CHAPTER EXAM

MULTIPLE CHOICE

1	D	**2**	B	**3**	A	**4**	C	**5**	B
6	A	**7**	C	**8**	B	**9**	C	**10**	A

SHORT RESPONSE

11 **a** Calculate current:

$$I = \frac{V}{R}$$
$$= \frac{6\ \text{V}}{250\ \Omega}$$
$$= 0.024\ \text{A}$$

b Calculate potential difference:

$$V = IR$$
$$= 2.4 \times 10^{-3}\ \text{A} \times 8.4 \times 10^{3}\ \Omega$$
$$= 20.16\ \text{V}$$

c Calculate resistance:

$$R = \frac{V}{I}$$
$$= \frac{4.5\ \text{V}}{3.2 \times 10^{-3}\ \text{A}}$$
$$= 1406.25\ \Omega$$

d Calculate current:

$$I = \frac{V}{R}$$
$$= \frac{3.6\ V}{1.2 \times 10^{-3}\ \Omega}$$
$$= 3 \times 10^{-3}\ \text{A}$$

e Calculate voltage:

$$V = IR$$
$$= 36 \times 10^{-6} \times 6.7 \times 10^{3}$$
$$= 0.24\ \text{V}$$

f Calculate resistance:

$$R = \frac{V}{I}$$
$$= \frac{5.25}{7.25 \times 10^{-3}}$$
$$= 724\ \Omega$$

DATA ANALYSIS

12 $m = \frac{\Delta I}{\Delta V} = 0.002\,59 = \frac{1}{R}$

$R = 388.5\ \Omega$

The resistance falls within the 5% tolerance.

13 **a** The components behave as an ohmic conductor when the potential difference and current remain proportional to each other.

It stops at 20 mA.

b Calculate resistance:

$$R = \frac{V}{I}$$

Substitute in values read from the graph:

$$R = \frac{2.5\ \text{V}}{13\ \text{mA}}$$
$$= \frac{2.5\ \text{V}}{0.013\ \text{A}}$$
$$= 192.3\ \Omega$$

14 This is a linear relationship, indicating that it is an ohmic conductor, one that follows Ohm's law.

$$R = \frac{V}{I}$$

As the graph has V on the *y*-axis and I on the *x*-axis:

$$\frac{V}{I} = \frac{\text{rise}}{\text{run}} = \text{gradient of line}$$

Substitute in values from the graph:

$$\text{Gradient} = \frac{6 - 0}{10.4 \times 10^{-3} - 0}$$
$$= 577\ \Omega$$

15 Given the equation $I = \frac{V}{R}$, expand :

$$I = \frac{1}{R} \times V \quad \text{where} \quad m = \frac{1}{R}$$

Substitute in values from the trend line:

$$2.40 = \frac{1}{R}$$
$$R = 0.417$$

Convert into A from mA:

$$R = \frac{0.417}{10^{-3}}$$
$$= 417\ \Omega$$

Calculate the uncertainty of the gradient:

$$\sigma_{\text{gradient}} = \pm \frac{\text{gradient}_{\text{max}} - \text{gradient}_{\text{min}}}{2}$$
$$= \pm \frac{2.66 - 2.26}{2}$$
$$= \pm 0.2$$

Convert from absolute uncertainty into percentage uncertainty:

$$\text{percentage uncertainty} = \frac{\text{absolute uncertainty}}{\text{measurement}} \times 100\%$$
$$= \frac{0.2}{2.4} \times 100\%$$
$$= 8.33\%$$

Calculate absolute uncertainty of the resistance given the percentage uncertainty above:

$$\sigma = \pm \frac{\text{percentage uncertainty}}{100} \times \text{measurement}$$
$$= \pm \frac{8.33}{100} \times 417$$
$$= \pm 34.7$$

$R = 417 \pm 35\ \Omega$

CHAPTER 11 CIRCUIT ANALYSIS AND DESIGN

LEARNING CHECK 11.1

DESCRIBING

1 Power is a measure of the rate of energy transformation measured in watts, W.

2 Ohm's law is the constant relationship between current and voltage, $V \propto I$, as expressed in the formula $V = I \times R$

3 $P = V \times I$

$P = I^2 \times R$

$P = \frac{V^2}{R}$

APPLYING

4 **a** 130 mA

b 6000 W

c 0.3×10^6 W or 3×10^5 W

5 $P = 38.4$ W

LEARNING CHECK 11.2

APPLYING

1 **a** 72 Ω **b** 3.33 A

c 800 W **d** 960 000 J

2 **a** 0.5 A **b** 480 Ω

c 120 W **d** 43 200 J

3 **a** 0.83 A **b** 288 Ω

c 200 W **d** 96 000 J

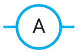
4 **a** 9.17 A **b** 26.2 Ω

c 2200 W **d** 47.5 MJ

LEARNING CHECK 11.3

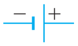
DESCRIBING

1 **a**

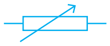


b

c



d



e

2 Lamp

Resistor

Switch

LEARNING CHECK 11.4

DESCRIBING

1 Voltage and electromotive force (EMF)

2 **a** Shared **b** Equivalent

3 A series circuit provides a single path for current to flow. The current is equivalent through all loads and the potential is divided across the loads.

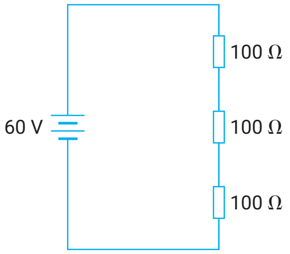
A parallel circuit provides multiple paths for the current to flow. The current splits along the parallel paths and the potential drop is equivalent across each parallel path.

4 $R_t = R_1 + R_2 + R_3$

5 $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

APPLYING

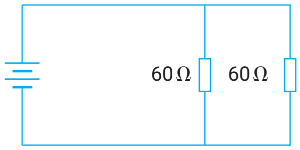
6



$R_t = 300\ \Omega$

$I_t = 0.2$ A

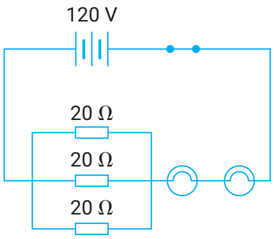
7



$\frac{1}{R_t} = \frac{1}{60} + \frac{1}{60}$

$R_t = 30\ \Omega$

8



REFLECTING

9 Draw the complete, labelled circuit.

Determine parallel and series components.

Calculate the equivalent resistances for series components and parallel components.

Simplify and re-draw the circuit.

Calculate the currents and voltages using Ohm's law.

LEARNING CHECK 11.5

DESCRIBING

1 Kirchhoff's current law states that the total current arriving at a junction within an electric circuit is equal to the total current leaving the junction.

Kirchhoff's voltage law states that for any closed loop in an electric circuit, the sum of the potential differences must be zero.

2 $R = \frac{V}{I}$

3 $V_t = I_t \times R_t$ only applies for the total current and total resistance.

APPLYING

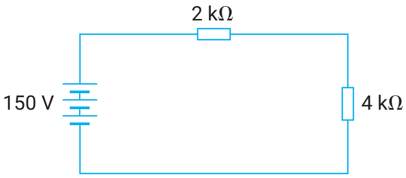
4 **a** 160 Ω **b** 10 Ω

11.6 LEARNING CHECK

ANALYSING

1 **a** 6 kΩ

b



c 0.025 A

d $V_{2\,k\Omega}: 50\,V$

$V_{6\,k\Omega}: 100\,V$

$V_{12\,k\Omega}: 100\,V$

e $I_{2\,k\Omega}: 0.025\,A$

$I_{6\,k\Omega}: 0.017\,A$

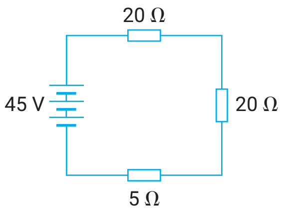
$I_{12\,k\Omega}: 0.0083\,A$

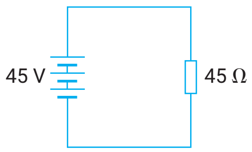
2 **a** $R_{eq} = 20\ \Omega$

b $R_{eq} = 10\ \Omega$

3 **a** $R_{eq} = 45\ \Omega$

b Draw the correct series circuit for the parallel arrangement, then redraw the circuit showing the equivalent circuit for the series arrangement.





c 1.0 A

d $V_{20\,\Omega}: 20\,V$, $V_{30\,\Omega}: 20\,V$, $V_{60\,\Omega}: 20\,V$, $V_{5\,\Omega}: 5\,V$

e $I_{20\,\Omega}: 1.0\,A$, $I_{30\,\Omega}: 0.67\,A$, $I_{60\,\Omega}: 0.33\,A$, $I_{5\,\Omega}: 1.0\,A$

4 $R_1 = 20\ \Omega$, $V_t = 12.8\ V$

5 **a** $R_{eq} = 28.75\ \Omega$

b $V_t = 46\ V$

11.7 LEARNING CHECK

DESCRIBING

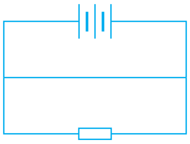
1 240 V, 50 Hz

2 Residual current device – an earth-leakage protection device

Circuit breaker – electromechanical switch that protects from an overload

Fuse – a temperature-dependent safety protection device

3 A short circuit is a bypass within a circuit where the current flows through a less resistive pathway.



APPLYING

4 Electrical circuits have maximum current loads for safety, hence the multiple circuits are required.

CHAPTER EXAM

MULTIPLE CHOICE

1 C **2** B **3** B **4** D **5** C

6 C **7** C **8** B **9** A **10** A

SHORT RESPONSE

11 **a** $3.2\ \Omega$ **b** $2.4\ \Omega$

c $4\ \Omega$ **d** $6\ \Omega$

CROSS-CHAPTER QUESTIONS

12 $R_t = 242.9\ \Omega$

$V_t = 20\text{ V}$

$I_t = 0.082\text{ A}$

$I_{100\ \Omega} = 0.082\text{ A}$

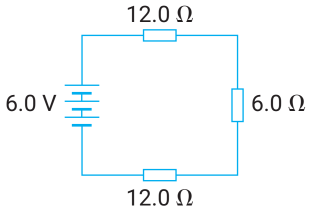
$I_{200\ \Omega} = 0.059\text{ A}$

$I_{500\ \Omega} = 0.023\text{ A}$

$V_{100\ \Omega} = 8.2\text{ V}$

$V_{200\ \Omega} = 11.8\text{ V}$

13 **a**



b $30\ \Omega$

c 0.2 A

d $V_{12\Omega} = 2.4\text{ V}$, $V_{6\Omega} = 1.2\text{ V}$

14 **a** $I = 1.0\text{ A}$ **b** $R_t = 12\ \Omega$

c 2 V **d** 4 V

e 0.5 A

15 **a** First, find R_t:

Calculate the total resistance between the parallel $3\ \Omega$ and 6Ω resistors:

$$R_t = \frac{1}{R_1} + \frac{1}{R_2} + \ldots \frac{1}{R_n}$$

$$\frac{1}{R_{3+6}} = \frac{1}{3\ \Omega} + \frac{1}{6\ \Omega}$$

$$= \frac{2}{6} + \frac{1}{6}$$

$$= \frac{3}{6}$$

$$R_{3+6} = 2\ \Omega$$

Calculate the total resistance between the series 4Ω and $R_{3+6}\Omega$ resistors:

$$R_t = R_1 + R_2 + \ldots R_n$$

$$R_{4+3+6} = 4 + 2$$

$$= 6\ \Omega$$

Calculate the total resistance between the parallel $12\ \Omega$ and $R_{4+3+6}\Omega$ resistors:

$$\frac{1}{R_{12+6}} = \frac{1}{12} + \frac{1}{6}$$

$$= \frac{1}{12} + \frac{2}{12}$$

$$= \frac{3}{12}$$

$$= 4\ \Omega$$

Calculate the total resistance:

$$R_t = 8\ \Omega + R_{12+6}$$

$$= 8\ \Omega + 4\ \Omega$$

$$= 12\ \Omega$$

Calculate the current for the total resistance:

$$I = \frac{V}{R}$$

$$= \frac{24}{12}$$

$$= 2\text{ A}$$

b As current remains constant in series, the current is also 2 A through the $8\ \Omega$ resistor

c Voltage splits in series depending on the resistance:

$$V = IR$$

$$= 2\text{ A} \times 8\ \Omega$$

$$= 16\text{ V}$$

d Remaining potential difference goes to the parallel section:

$$V = V_{\text{battery}} - V_{8\ \Omega}$$

$$= 24 - 16$$

$$= 8\text{ V}$$

e Current splits across parallel depending on the resistance:

$$I = \frac{V}{R}$$

$$= \frac{8\text{ V}}{12\ \Omega}$$

$$= 0.67\text{ A}$$

f Voltage splits in series depending on the resistance:

$$V = IR$$

$$V = 0.67\text{ A} \times 2\Omega = 1.33\text{ V}$$

g $V = 0.67\text{ A} \times 10\Omega = 6.7\text{ V}$

h Current splits across parallel. As part of the current was found in part **e**, the remainder will go through the lower branch.

$$I = 2\text{ A} - 0.67\text{ A}$$

$$= 1.33\text{ A}$$

i Voltage splits in series depending on the resistance:

$$V = 1.33\,\text{A} \times 4\,\Omega$$
$$= 5.3\,\text{V}$$

j The total voltage for this branch = 8 V. If 5.3 V is lost across the 4 Ω resistor, then:

$$V_{\text{remaining}} = 8 - 5.3 = 2.7\ \text{V}\ \text{remaining}$$

k Voltage stays constant across parallel:

$$V = 2.7\,\text{V}$$

l $I = \dfrac{2.7\ \text{V}}{3\ \Omega} = 0.9\ \text{A}$

m $I = \dfrac{2.7\ \text{V}}{6\ \Omega} = 0.45\ \text{A}$

CHAPTER 12 VECTORS AND LINEAR MOTION

LEARNING CHECK 12.1

DESCRIBING

1 Scalar: quantity specified by magnitude only

Vector: quantity that has magnitude and direction (from Greek 'to convey')

2 **a** See Table 12.1.1.

b See Table 12.1.2.

3 **a** Changes magnitude

b Changes magnitude and reverses direction

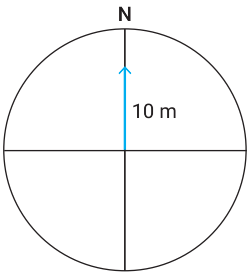
APPLYING

4 Both have magnitude (length); displacement includes length and direction.

5 Distance tells you how far in total; displacement tells you where you are relative to some other position.

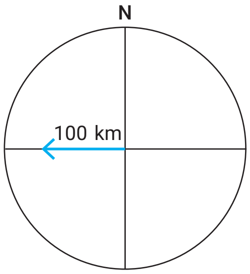
6 Both specify direction using a compass and angles; quadrant angles range from 0° to 90°, true bearings range from 0° to 360°.

7 **a**



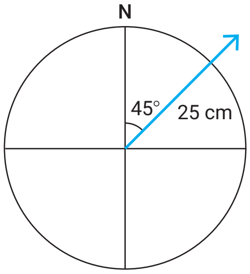
1cm represents 10 m

b



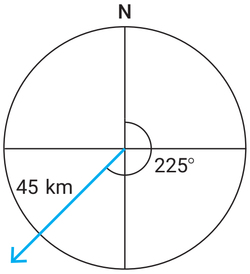
1 cm represents 100 km

c



1 cm represents 10 cm

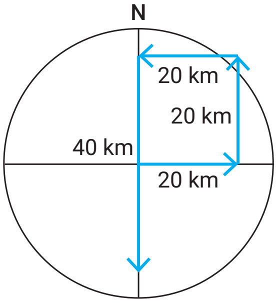
d



1 cm represents 10 km

ANALYSING

8 **a**



1 cm represents 10 km

b 100 km

c 20 km, S

9 Division is multiplication by the inverse of the divisor

LEARNING CHECK 12.2

DESCRIBING

1 **a** $\vec{s} = \vec{d}_2 - \vec{d}_1$

b $s = \left|\vec{d}_2 - \vec{d}_1\right|$

2 Magnitude is the size of the vector displacement

APPLYING

3 **a** ${}^{-}6\text{ km} + 5\text{ km} = {}^{-}1\text{ km}$

  b $4\text{ m} + 5\text{ m} = 9\text{ m}$

  c ${}^{-}8\text{ cm} - 2\text{ cm} = {}^{-}10\text{ cm}$

  d $5\text{ m} - 2\text{ m} = 3\text{ m}$

  e ${}^{-}10\text{ km} - {}^{-}3\text{ km} = {}^{-}7\text{ km}$

  f $2\text{ mm} - {}^{-}3\text{ mm} = 5\text{ mm}$

ANALYSING

4 Each displacement from position to position has a distance as well as a direction. Each distance adds to make the total distance travelled.

EVALUATING

5 Answers will vary.

LEARNING CHECK 12.3

DESCRIBING

1 Distance is the total length of the path of travel when an object moves and is a scalar quantity. In contrast, displacement is the comparative change in position of an an object when it moves and it is a vector quantity.

2 Each time measure assumes an agreed start time or origin of zero.

3 Each displacement measure assumes a start position or origin of zero.

APPLYING

4 **a** $7.0\text{ s} - 3.0\text{ s} = 4.0\text{ s}$

  b $2.45 \times 10^{-2}\text{ s} - 1.37 \times 10^{-2}\text{ s} = 1.08 \times 10^{-2}\text{ s}$

5 **a** $15.1\text{ cm} + {}^{-}4.3\text{ m} = 19.4\text{ m}$

  b ${}^{-}784\text{ mm} + 9.0\text{ mm} = 793\text{ mm}$

LEARNING CHECK 12.4

DESCRIBING

1 Instantaneous speed is the rate of change of distance at a particular moment in time, whereas average speed is the rate of change of distance over a measured time interval.

2 $v = \dfrac{s}{t} = \dfrac{\text{m}}{\text{s}} = \text{ms}^{-1}$

3 A negligibly small time interval is one in which all the instantaneous velocities are so similar to the average as to be considered equal.

APPLYING

4 **a**
$$v_{\text{av}} = \frac{s}{t} = \frac{\left|\vec{d}_2 - \vec{d}_1\right|}{t_2 - t_1}$$
$$= \frac{\left|-90\text{ cm} - {}^{-}60\text{ cm}\right|}{3.0\text{ s}}$$
$$= \frac{30\text{ cm}}{3.0\text{ s}} = 10\text{ cm s}^{-1}$$

  b
$$\vec{v}_{\text{av}} = \frac{\vec{s}}{t} = \frac{\vec{d}_2 - \vec{d}_1}{t_2 - t_1}$$
$$= \frac{{}^{-}90\text{ cm} - {}^{-}60\text{ cm}}{3.0\text{ s}}$$
$$= \frac{{}^{-}30\text{ cm}}{3.0\text{ s}} = {}^{-}10\text{ cm s}^{-1}$$

ANALYSING

5 Speed relates to distance travelled, hence aircraft fuel consumption; velocity relates to displacement interval, that is, where you end up relative to the start.

6 Equivalence of average and instantaneous speed over very small time intervals

LEARNING CHECK 12.5

DESCRIBING

1 Change of velocity, change of displacement over a measurable time interval, rate of change of displacement at a particular time, rate of change of velocity

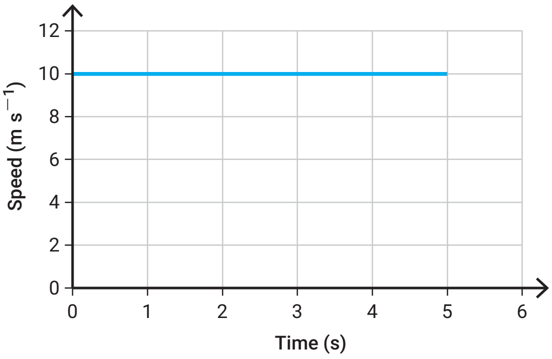
2 Velocity is the change in displacement over time. It can be found by calculating the gradient of a displacement–time graph

3 The area under a velocity–time graph is used to determine a displacement interval.

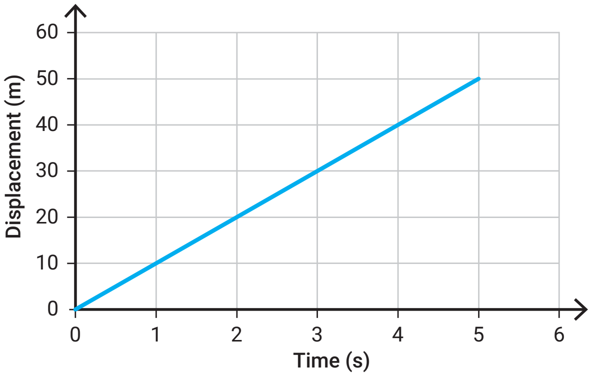
4 Displacement and time data enable velocity to be calculated, which, in turn, enables acceleration to be derived.

APPLYING

5 **a**



b



6 $\Delta v = 6.0\text{ m s}^{-2} \times 3.0\text{ s} = 18\text{ m s}^{-1}$

7 Both graphs are visual ways of representing an object's motion and can be used to mathematically determine quantitative values. A displacement–time graph can be used to determine velocity, whereas a distance–time graph can be used to determine speed.

ANALYSING

8 **a** **i** $s = 80\text{ km h}^{-1} \times 0.5\text{ h} = 40\text{ km}$

ii $s = 40\text{ km} + 100\text{ km h}^{-1} \times 0.75\text{ h}$

$= 40\text{ km} + 75\text{ km}$

$= 115\text{ km}$

b $v_{av} = \dfrac{115\text{ km}}{1.25\text{ h}} = 92\text{ km h}^{-1}$

9 A model represents the real thing. Graphs represent real motion: position, velocity and acceleration of objects as time passes. Each can be used to derive related quantities by reference to gradient and areas: *v* from *s*–*t* (gradient); *s* and *a* from *v*–*t* (area; gradient); *v* from *a*–*t* (area)

LEARNING CHECK 12.6

DESCRIBING

1 **a** $\vec{a}$ = acceleration; $\Delta\vec{v}$ = velocity change;
t = time change

b Direction of velocity change, $\Delta\vec{v}$

2 (metres per second) per second. This unit quantifies how much velocity changes every second.

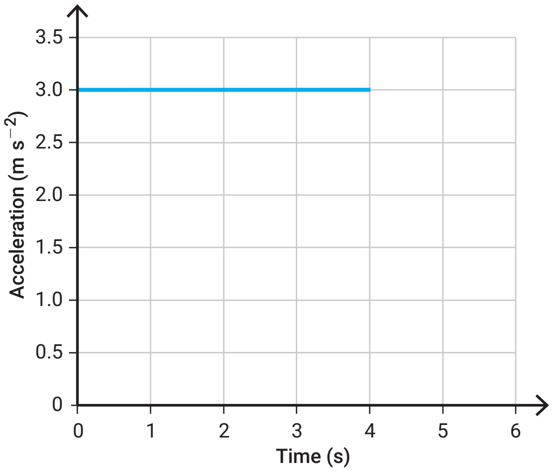
3 Velocity change

4 By its gradient

5 Final velocity is less in magnitude (more negatively directed) than initial velocity.

APPLYING

6 **a**



b $\Delta v = at$

$\Delta v = v_f - v_i$

$v_f - 5.0\text{ m s}^{-1} = 3.0\text{ m s}^{-2} \times 4.0\text{ s}$

$= 5.0\text{ m s}^{-1} + 12\text{ m s}^{-1}$

$= 17\text{ m s}^{-1}$

c In any 1 s time interval, the speed increases by 3.0 m s⁻¹.

ANALYSING

7 The train is travelling in the same positive direction, but slowing from a higher to a lower speed. This makes the velocity interval, hence acceleration, negative.

8 Intervals enable gradients and areas to be calculated.

LEARNING CHECK 12.7

DESCRIBING

1 Type of graph; axis and scale; gradient; area

2

Type of graph	Gradient represents	Area represents
Displacement–time	Velocity	–
Velocity–time	Acceleration	Displacement interval
Acceleration–time	–	Velocity change

3 A gradient is the ratio of intervals: velocity (displacement interval: time interval); acceleration (velocity interval: time interval).

4 An area is the product of two intervals: displacement (velocity interval × time interval); velocity interval (acceleration × time interval).

APPLYING

5 **a** 200 m

b **i** $v=\frac{s}{t}$

$=\frac{600\ \text{m}-200\ \text{m}}{5.0\ \text{min}\times 60\ \text{s min}^{-1}}$

$=1.3\ \text{m s}^{-1}$

ii $\vec{v}=\frac{\vec{s}}{t}$

$=\frac{^{-}300\ \text{m}-600\ \text{m}}{(25.0\ \text{min}-15.0\ \text{min})\times 60\ \text{s min}^{-1}}$

$=\,^{-}1.5\ \text{m s}^{-1}$

c $s=|\vec{d}_2-\vec{d}_1|+|\vec{d}_3-\vec{d}_2|+|\vec{d}_4-\vec{d}_3|$

$s=|600\ \text{m}-200\ \text{m}\ |+|\,^{-}300\ \text{m}-600\ \text{m}|+|0\ \text{m}-\,^{-}300\ \text{m}\ |$

$=1600\ \text{m}$

6 **a** $v_{20\text{s}}=\frac{20}{25}\times 8.0\ \text{m s}^{-1}=6.4\ \text{m s}^{-}$

$s_{20\text{s}}=\frac{1}{2}\times 6.4\ \text{m s}^{-1}\times 20\ \text{s}$

$=64\ \text{m}$

b $s=\text{area}=\frac{1}{2}\times 8.0\ \text{m s}^{-1}\times 25\ \text{s}$

$+8.0\ \text{m s}^{-1}\times(75\ \text{s}-25\ \text{s})+\frac{1}{2}\times 8.0\ \text{m s}^{-1}\times 12\ \text{s}$

$s=548\ \text{m}$

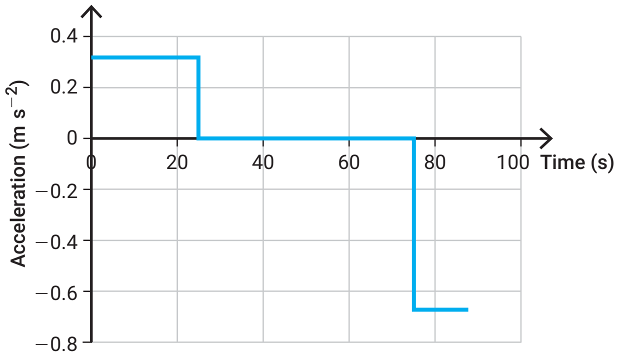
c **i** $a=\frac{8.0\ \text{m s}^{-1}-0\ \text{m s}^{-1}}{25\ \text{s}}$

$=0.32\ \text{m s}^{-2}$

ii $a=\frac{0\ \text{m s}^{-1}-8.0\ \text{m s}^{-1}}{12\ \text{s}}$

$=\,^{-}0.67\ \text{m s}^{-2}$

d



e $s=\text{area}$

$\frac{1}{2}\times 8.0\ \text{m s}^{-1}\times 25\ \text{s}+8.0\ \text{m s}^{-1}\times(t-25\ \text{s})=300\ \text{m}$

$100\ \text{m}+8.0\ \text{m s}^{-1}\times(t-25\ \text{s})=300\ \text{m}$

$8.0\ \text{m s}^{-1}\times(t-25\ \text{s})=200\ \text{m}$

$t-25\ \text{s}=\frac{200\ \text{m}}{8.0\ \text{m s}^{-1}}$

$t-25\ \text{s}=25\ \text{s}$

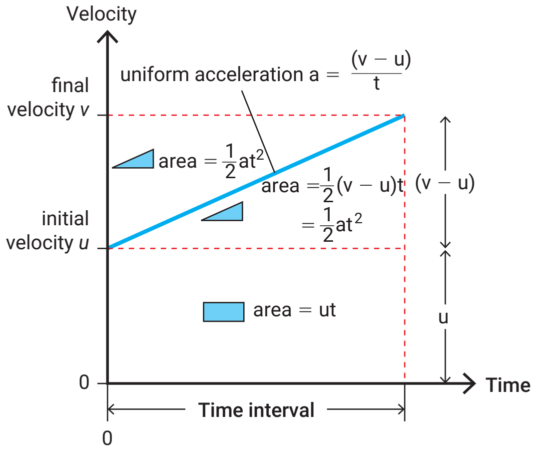
$t=50\ \text{s}$

7 The vehicle has travelled at the greater speed of 80 km h^{-1} for a longer period of time than the slower 70 km h^{-1}, hence it is not a simple average.

LEARNING CHECK 12.8

DESCRIBING

1 **a**



b s = displacement interval; u = initial velocity; v = final velocity; a = acceleration; t = time interval. For equations: see page 317

2 Substitute the three known values into an appropriate equation to calculate the fourth. Select an equation that will readily produce the fifth.

3 Similar: same motion is represented. Different: graphs use visual symbolism; equations use algebraic symbolism

APPLYING

4 **a** $v=u+at$

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

$=\frac{8.0\ \text{m s}^{-1}-5.0\ \text{m s}^{-1}}{15.0\ \text{s}}$

$=0.2\ \text{m s}^{-2}$

b $s = ut + \frac{1}{2}at^2$

$= 5.0\text{ m s}^{-1} \times 15.0\text{ s} + \frac{1}{2} \times 0.2\text{ m s}^{-2} \times (15.0\text{ s})^2$

$= 97.5\text{ m}$

5 **a** $s = ut + \frac{1}{2}at^2$

$a = \frac{2s}{t^2}$ (remember $u = 0\text{ m s}^{-1}$)

$= \frac{2 \times 50\text{ m}}{(2.5\text{ s})^2}$

$= 16\text{ m s}^{-2}$

b $v^2 = u^2 + 2\,as$

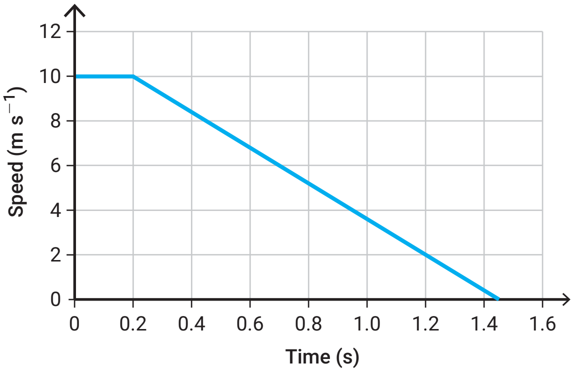
$= \sqrt{u^2 + 2as}$

$= \sqrt{2 \times 16.0\text{ m s}^{-2} \times 50\text{ m}}$

$= 40.0\text{ m s}^{-1}$

ANALYSING

6 **a**



b $s = vt$

$= 10\text{ m s}^{-1} \times 0.2\text{ s}$

$= 2.0\text{ m}$

c $a = \frac{v}{t}$

$t = \frac{v}{a}$

$= \frac{0\text{ m s}^{-1} - 10\text{ m s}^{-1}}{^{-}8.0\text{ m s}^{-2}}$

$= 1.25\text{ s}$

d $s = \frac{1}{2} \times 10\text{ m s}^{-1} \times 1.25\text{ s}$

$= 6.25\text{ m}$

e $s = 2.0\text{ m} + 6.25\text{ m}$

$= 8.25\text{ m}$

7 Make sure to use change in displacement and change in time for s and t, respectively, not instantaneous values.

LEARNING CHECK 12.9

DESCRIBING

1 Gravitational force is the force that arises when a gravitational field acts on mass. It is often calculated as weight. Gravitational acceleration is related to the strength of Earth's gravitational field.

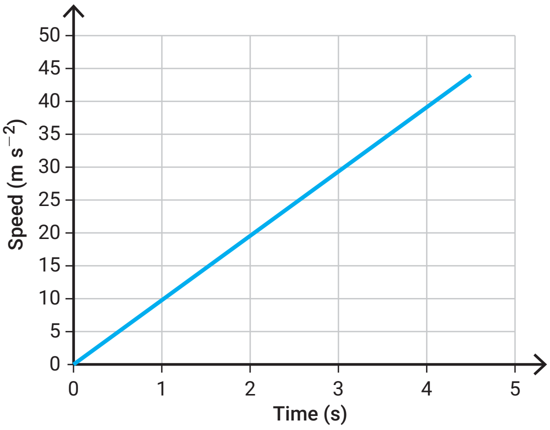
2 $g = 9.8\text{ m s}^{-2}$

3 **a** Initial movement is vertically towards Earth.

b Initial movement is vertically upwards from Earth.

APPLYING

4 **a**



b $a = \text{gradient} = \frac{v}{t}$

$t = \frac{v}{a}$

$= \frac{44.1\text{m s}^{-1} - 0\text{ m s}^{-1}}{9.8\text{ m s}^{-2}}$

$= 4.5\text{ s}$

c $s = \frac{1}{2} \times 44.1\text{m s}^{-1} \times 4.5\text{ s}$

$= 99.2\text{ m}$

d Use *suvat* equations.

5 **a** 1.0 s

b 9.9 m s^{-1}

6 **a** Answers will vary.

b Answers will vary.

CHAPTER EXAM

MULTIPLE CHOICE

1	D	**2**	C	**3**	D	**4**	C	**5**	A
6	A	**7**	B	**8**	D	**9**	B	**10**	D

SHORT RESPONSE

11 **a** $s=\frac{1}{2}(u+v)t$

Make t the subject of the equation:

$$t=\frac{s}{\frac{1}{2}(u+v)}$$

Substitute in values from the question:

$$t=\frac{10}{\frac{1}{2}(0+10)}$$

Solve for *t*:

$t=2.0$ s

b $v=u+at$

Make *a* the subject of the equation:

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

Substitute in values from the question:

$$a=\frac{10-0}{2}$$

Solve for *a*:

$a=5$ m s^{-2}

c Period of acceleration occurred over 10 m and this took 2.0 s. Therefore, there is still 90 m to go at 10 m s^{-1}.

$t=\frac{s}{v}$ as there is no further acceleration

$$=\frac{90}{10}$$

$=9$ s

Total time taken = time to go first 10 m + time for remaining 90 m. 2 s + 9 s = 11 s

12 **a** As the velocity is constant, there is no acceleration.

$$v=\frac{s}{t}$$

Make *s* the subject of the equation:

$s=vt$

Substitute in values from the question:

$s=30$ km h$^{-1}\times 24$ h

$=720$ km

b $v=\frac{s}{t}$

Make *t* the subject of the equation:

$t=\frac{s}{v}$

Substitute in values from the question:

$$t=\frac{500\text{ km}}{30\text{ km h}^{-1}}$$

$=16.67$ h

13 **a** Let up be positive.

$a=-9.8$ m s^{-2}

$s=+20$ m

Calculate how long it takes for the ball to reach the maximum height (when $v=0$):

$$s=vt-\frac{1}{2}at^2$$

Make *t* into the subject of the equation:

$$t=\sqrt{-\frac{2s}{a}}$$

Substitute in values from the question:

$$t=\sqrt{\frac{-2\times 20}{-9.8}}$$

$=2.0$ s

Because of the symmetry of trajectories, it takes the same amount of time to reach the top as it does to fall down to the starting height.

$t_t=2\times 2.02$

$=4.04$ s

b $v=u+at$

Make *u* into the subject of the equation:

$u=v-at$

Substitute in values from the question, assuming only the first half of the trajectory:

$u=0-(-9.8\times 2.02)$

$u=19.80$ m s^{-1}

c Due to the symmetry of the trajectory, the final velocity will be equal to the initial velocity, but in the opposite direction.

$v=-19.80$ m s^{-1}

To calculate from the second half of the trajectory when the ball is falling:

$v=u+at$

Substitute in values from the question:

$v=0+(-9.8\times 2.02)$

$=-19.80$ m s^{-1}

14 Calculating the velocity at the top of the window by considering only the motion in the window.

Assume down is positive.

$s=ut+\frac{1}{2}at^2$, where *u* is the velocity at the top of the window

Make u the subject of the equation:

$$u=\frac{s-\frac{1}{2}at^2}{t}$$

Substitute in values from the question:

$$u=\frac{2.1-\frac{1}{2}\times 9.8\times 0.22^2}{0.22}$$

Solve for u:

$u=8.45\text{ m s}^{-1}$

Calculate the distance from the top of the building to the top of the window:

$v^2=u^2+2as$, where v is the velocity at the top of the window.

Make s the subject of the equation:

$$s=\frac{v^2-u^2}{2a}$$

Substitute in values from the question:

$$s=\frac{8.45^2-0^2}{2\times 9.8}$$

Solve for s:

$s=3.64\text{ m}$

DATA ANALYSIS

15 Assume that north is positive.

- **a** **i** 3 m N
  - **ii** 8 m N
  - **iii** 5 m N
  - **iv** 1.5 m N
- **b** **i** $v_{\text{av}}=\frac{\Delta s}{\Delta t}$
  $=\frac{3\text{ m}}{5\text{ s}}$
  $=0.6\text{ m s}^{-1}\text{ N}$
  - **ii** $\frac{8\text{ m}}{10\text{ s}}=0.8\text{ m s}^{-1}\text{ N}$
  - **iii** $\frac{8\text{ m}}{14\text{ s}}=0.57\text{ m s}^{-1}\text{ N}$
  - **iv** $\frac{4\text{ m}}{20\text{ s}}=0.2\text{ m s}^{-1}\text{ N}$
  - **v** $-\frac{2\text{ m}}{30\text{ s}}=-0.07\text{ m s}^{-1}=0.07\text{ m s}^{-1}\text{ S}$
  - **vi** $-\frac{4\text{ m}}{10\text{ s}}=-0.4\text{ m s}^{-1}=0.4\text{ m s}^{-1}\text{ S}$
  - **vii** $\frac{4\text{ m}}{10\text{ s}}=0.4\text{ m s}^{-1}\text{ N}$
- **c** **i** $0.6\text{ m s}^{-1}\text{ N}$
  - **ii** $0.6\text{ m s}^{-1}\text{ N}$
  - **iii** 0 m s^{-1}
  - **iv** $2\text{ m s}^{-1}\text{ N}$
  - **v** $1\text{ m s}^{-1}\text{ S}$
  - **vi** 0 m s^{-1}
  - **vii** $1.43\text{ m s}^{-1}\text{ S}$
  - **viii** 0 m s^{-1}

CHAPTER 13 FORCES

LEARNING CHECK 13.1

DESCRIBING

1 Change speed; change direction; change both speed and direction simultaneously

2 Responses will vary. Common examples are listed below.

- **a** Forces applied by one object on another when they are close enough to be considered touching (e.g. friction force, tension force, air resistance)
- **b** Forces applied by one object on another when they are far enough apart to not be considered touching (e.g. gravitational force, electrostatic force, magnetic force)
- **c** A force by the gravitational field of a mass on another mass (e.g. the force between the Sun and Earth, or Earth and the Moon)
- **d** A force between two charged particles (e.g. dry hair standing up when being combed, lightning)

3 **a** Applies force to a receiver object

- **b** Object that is subject to a force applied by an agent force

APPLYING

4 Two scales: magnitude and direction

5 Objects apply force externally to other objects. A force is not a property contained inside an object

6 $\vec{F}_{(\text{by B on M})}$ and $\vec{F}_{(\text{by M on B})}$

7 Mass: amount of a substance; weight: gravitational force on mass. $F_{\text{w}}=m\times g$

8 Gravitational force is measured by measuring the normal force; scale is calibrated to read mass.

ANALYSING

9 Moon applies a smaller gravitational force on the box. The scales are read in Earth weights.

LEARNING CHECK 13.2

DESCRIBING

1 Newton's first law: $v=$ constant if $\Sigma F=0$;

Newton's second law: $a=\frac{\Sigma F}{m}$; Newton's third law:

$\vec{F}(\text{by A on B})=\vec{F}(\text{by B on A})$

2 **a** Equal magnitude; opposite direction; same type; act on different objects

- **b** Act on same object

3 **a** Resistance to force applied

- **b** $F_{\text{w}}=mg$

4 Vector sum of forces acting on a single object

5 They act on different objects

APPLYING

6 Since the athlete is maintaining constant velocity, the magnitude of the horizontal force applied is zero.

ANALYSING

7 **a** The ball will not need to be thrown as high.

b The ball will need to be thrown higher.

c The difference in height needs to be accounted for.

8 *F* and *m* are independent variables

9 Action–reaction forces act on different objects. Net forces are the resultant sum of all forces acting on a single object.

LEARNING CHECK 13.3

DESCRIBING

1 Model forces acting on a point particle start at point; directed away from point; length proportional to magnitude.

2 Normal force

3 **a** Force applied by surface on an object in the direction perpendicular to the surface. $N = F(\text{by surface on object})_\perp$

b Force applied by surface on an object in the direction parallel to the surface. $f = F(\text{by surface on object})_\parallel$

APPLYING

4 *N* affects motion perpendicular to the surface; *f* affects motion parallel to the surface.

5 Different type (gravitational/electrostatic); act on same (not different) object

6 Newton's third law:

$1\ \vec{F}(\text{by foot on surface})_\parallel = \vec{F}(\text{by surface on foot})_\parallel$;

friction: $f = \vec{F}(\text{by surface on foot})_\parallel$

7 $\vec{F}(\text{by person on surface})_\perp = \vec{F}(\text{by surface on person})_\perp$

$\vec{F}(\text{by person on surface})_\perp - w > 0$

ANALYSING

8 Friction can act as an opposing force but it can be used to propel runners, walkers and vehicles forwards.

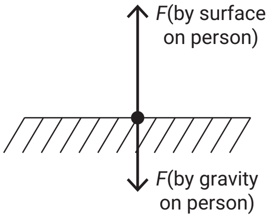
LEARNING CHECK 13.4

DESCRIBING

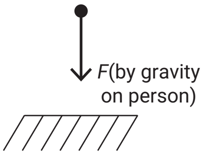
1
- Read the question carefully.
- Visualise or sketch the real situation described.
- Draw a free-body diagram.
- Identify each force acting on the object in question.
- Write each force in the form *F*(by A on B), or use the symbols provided in the question.
- If necessary, write the Newton's third law pair of forces.
- Identify the direction of the net force (or acceleration).
- Add any data provided in the question.
- Consider Newton's laws. Ask:
  - How does Newton's first law apply?
  - How does Newton's second law apply?
  - How does Newton's third apply?
- Set up any equations, using the symbols from the free-body diagram.
- Recall any kinematic formulas that may be useful.
- Solve the equations.
- Check to ensure the answers are those required.

APPLYING

2 **a**



b



3 **a** $\Sigma F = ma$

$F(\text{by kayaker}) - 57\,\text{N} = 0$

$F(\text{by kayaker}) = 57\,\text{N}$

b $a = \dfrac{\Delta v}{\Delta t}$

$= \dfrac{4.0\,\text{m s}^{-1} - 4.0\,\text{m s}^{-1}}{\Delta t}$

$= 0\,\text{m s}^{-2}$

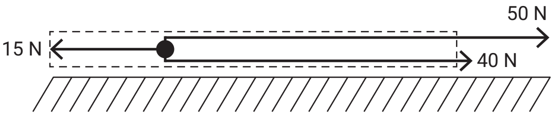
c $\Sigma F = ma$

$F(\text{by seat on kayaker})_\perp - w = 0$

$F(\text{by seat on kayaker})_\perp = 105\,\text{kg} \times 9.8\,\text{m s}^{-2}$

$= 1.03\,\text{kN}$

4 **a**



b $\Sigma F = 50\,\text{N} + 40\,\text{N} - 15\,\text{N} = 75\,\text{N}$

c $a = \frac{\Sigma F}{m}$

$= \frac{75\,\text{N}}{50\,\text{kg}}$

$= 1.5\,\text{m}\,\text{s}^{-2}$

5 $\Sigma F = ma$

$F - 12\,\text{N} = 36\,\text{kg} \times 4.0\,\text{m}\,\text{s}^{-2}$

$F = 156\,\text{N}$

6 **a** $a_{\text{av}} = \frac{\Delta v}{\Delta t}$

$= \frac{2.5\,\text{m}\,\text{s}^{-1} - 0\,\text{m}\,\text{s}^{-1}}{125 \times 10^{-3}\,\text{s}}$

$= 20\,\text{m}\,\text{s}^{-2}$

b $\Sigma F = ma$

$= 70\,\text{kg} \times 20\,\text{m}\,\text{s}^{-2}$

$= 1400\ \text{N}$

c $F(\text{by platform on diver}) - w = 1400\,\text{N}$

$F(\text{by platform on diver}) = 1400\,\text{N} + 70\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2}$

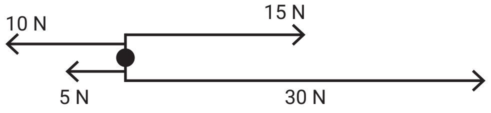
$= 2086\,\text{N}$

By Newton's third law:

$F(\text{by platform on diver}) = F(\text{by diver on platform})$

$F(\text{by diver on platform}) = 2086\,\text{N}$

7 **a**



b $\Sigma F = 15\,\text{N} + 30\,\text{N} - 10\,\text{N} - 5\,\text{N}$

$= 30\,\text{N}$

c $a = \frac{\Sigma F}{m}$

$= \frac{30\,\text{N}}{45\,\text{kg}}$

$= 0.67\,\text{m}\,\text{s}^{-2}$

8 **a** Acceleration:

$v^2 = u^2 + 2as$

$a = \frac{v^2 - u^2}{2s}$

$= \frac{(2.0\,\text{m}\,\text{s}^{-1})^2 - (0\,\text{m}\,\text{s}^{-1})^2}{2 \times 5.0\,\text{m}}$

$= 0.4\,\text{m}\,\text{s}^{-2}$

Newton's second law:

$\Sigma F = ma$

$= 1.5 \times 10^3\,\text{kg} \times 0.4\,\text{m}\,\text{s}^{-2}$

$F(\text{by cable on load}) - w = 600\,\text{N}$

$F(\text{by cable on load}) = 600\,\text{N} + 1.5 \times 10^3\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2}$

$= 1.53 \times 10^4\,\text{N}$

b $\Sigma F = ma$

$\Sigma F = 1.5 \times 10^3\,\text{kg} \times 0\,\text{m}\,\text{s}^{-2}$

$F(\text{by cable on load}) - w = 0\,\text{N}$

$F(\text{by cable on load}) = 1.5 \times 10^3\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2}$

$= 1.47 \times 10^4\,\text{N}$

ANALYSING

9 **a** To stay together, each block must move with the same motion.

b $a = \frac{\Sigma F}{m}$

$a = \frac{20\,\text{N}}{2.0\,\text{kg} + 3.0\,\text{kg}}$

$= 4.0\,\text{m}\,\text{s}^{-2}$

c **i** $\Sigma F = ma$

$F(\text{by A on B}) = m_B a_B$

$= 3.0\,\text{kg} \times 4.0\,\text{m}\,\text{s}^{-2}$

$= 12\,\text{N}$

ii $\Sigma F = ma$

$20\,\text{N} - F(\text{by B on A}) = m_A a_A$

$F(\text{by B on A}) = 20\,\text{N} - 2.0\,\text{kg} \times 4.0\,\text{m}\,\text{s}^{-2}$

$= 12\,\text{N}$

This is the expected result from Newton's third law.

LEARNING CHECK 13.5

DESCRIBING

1 The impulse is the product of a force acting for a time interval.

It is the product of mass and change in velocity.

It is the difference between two momenta.

2 $\vec{F}\Delta\, t = \Delta\, \vec{p} = \Delta\,(m\vec{v})$

3 Impulse

4 In an isolated system, momentum is conserved throughout the time of any and all collisions.

5 The system must be isolated from any external impulses.

6 All impulses are equal and opposite; hence, all momentum changes are equal and opposite.

APPLYING

7 The forces on the receiver are equal in magnitude and opposite in direction to the forces on the agent (Newton's third law). All forces act over the same time interval; hence, all impulses are equal and opposite.

8 The number line can represent force vectors by assigning positive and negative directions. Positive forces are represented with arrows pointing to the right, whereas negative forces are represented with arrows pointing to the left. The length of the arrow shows the magnitude of the force.

9 **a** Area under F–t graph = impulse

b Area under a–b graph = change in velocity multiplying Δv by mass to find impulse.

ANALYSING

10 $P_T(\text{before}) = P_T(\text{after})$

$$p_{\text{Ai}} + p_{\text{Bi}} = p_{\text{Af}} + p_{\text{Bf}}$$
$$p_{\text{Af}} - p_{\text{Ai}} = p_{\text{Bi}} - p_{\text{Bf}}$$
$$p_{\text{Af}} - p_{\text{Ai}} = {}^{-}\left(p_{\text{Bf}} - p_{\text{Bi}}\right)$$
$${}^{+}\Delta\, p_{\text{A}} = {}^{-}\Delta\, p_{\text{B}}$$

LEARNING CHECK 13.6

DESCRIBING

1
- Read the question carefully.
- Visualise the situation described; sketches are essential.
- Divide the page into two columns.
- Label the columns ‘Before’ and ‘After’.
- Sketch a diagram in the ‘Before’ column to show:
  - the situation before the interaction
  - the data provided in the question
  - any missing data.
- Sketch a diagram in the ‘After’ column to show:
  - the situation after the interaction
  - the data provided in the question
  - any missing data (on the diagram show symbol =?).
- In the ‘Before’ column:
  - write an equation for the total momentum before the interaction
  - use symbols for any missing data (on the diagram show symbol =?)
  - complete any calculations that can be completed.
- In the ‘After’ column:
  - write an equation for the total momentum after the interaction
  - use symbols for any missing data
  - complete any calculations that can be completed.
- Equate the equations for the ‘Before’ and ‘After’ situations, then:
  - solve algebraically
  - substitute numerical values
  - calculate the answer.

2 **a** Visualisation makes the situation more real and enables all data to be related to real objects.

b All unknowns can be related algebraically across the entire collision.

3 Newton’s third law states that for every action there is an equal and opposite reaction. Throughout a collision, actions always equal reactions. These take place over the same time interval to produce impulse, hence change in momentum.

APPLYING

4 **a** Take positive as being towards barrier:

$$\Delta p = m\Delta v$$
$$= 1.0 \times 10^3\ \text{kg} \times \left(0\ \text{m s}^{-1} - 20\ \text{m s}^{-1}\right)$$
$$= -2.0 \times 10^4\ \text{kg m s}^{-1}$$

b $J(\text{by barrier on car}) = \Delta p$

$J = -2.0 \times 10^4\ \text{kg m s}^{-1}$

c $F(\text{by barrier on car})\Delta t = \Delta p$

$$F(\text{by barrier on car}) = \frac{\Delta p}{\Delta t}$$
$$= \frac{-2.0 \times 10^4\ \text{kg m s}^{-1}}{2.0\ \text{s}}$$
$$= -1.0 \times 10^4\ \text{N}$$

By Newton’s third law:

$F(\text{by barrier on car}) = F(\text{by car on barrier})$

$F(\text{by car on barrier}) = 1.0 \times 10^4\ \text{N}$

5 **a** The unrestrained toy continues on in its state of uniform motion at 100 km h^{-1} (Newton’s first law) until it hits the windscreen. The toy applies a force on the windscreen, and the windscreen applies a force on the toy (Newton’s third law). The force by the windscreen on the toy causes the toy to decelerate (Newton’s second law: $a = \frac{F}{m}$).

b $F(\text{by windscreen on toy})\Delta t = m\Delta v$

$$F(\text{by windscreen on toy}) = \frac{m\Delta v}{\Delta t}$$
$$= \frac{0.1\text{kg} \times (0\ \text{m s}^{-1} - 27.78\ \text{m s}^{-1})}{0.150\ \text{s}}$$
$$= -18.5\ \text{N}$$

6 $P_{(\text{t before})} = P_{(\text{t after})}$

$$50\ \text{kg} \times 3.0\ \text{m s}^{-1} + 80\ \text{kg} \times 0\ \text{m s}^{-1} = (50\ \text{kg} + 80\ \text{kg}) \times v_{\text{f}}$$
$$v_{\text{f}} = \frac{150\ \text{kg m s}^{-1}}{130\ \text{kg}}$$
$$v_{\text{f}} = 1.2\ \text{m s}^{-1}$$

ANALYSING

7

$$p_{\text{Pi}} = m \times 1.5\ \text{m s}^{-1}$$
$$p_{\text{Pf}} = m \times -0.5\ \text{m s}^{-1}$$
$$p_{\text{Pf}} - p_{\text{Pi}} = m \times -0.5\ \text{m s}^{-1} - m \times 1.5\ \text{m s}^{-1}$$
$$p_{\text{Pf}} - p_{\text{Pi}} = m \times -2.0\ \text{m s}^{-1} \qquad (1)$$
$$p_{\text{Qi}} = m \times -1.5\ \text{m s}^{-1}$$
$$p_{\text{Qf}} = m \times 0.5\ \text{m s}^{-1}$$
$$p_{\text{Qf}} - p_{\text{Qi}} = m \times 0.5\ \text{m s}^{-1} - m \times -1.5\ \text{m s}^{-1}$$
$$p_{\text{Qf}} - p_{\text{Qi}} = m \times 2.0\ \text{m s}^{-1} \qquad (2)$$

Insert equation (1) into equation (2):

$$(p_{\text{Pf}} - p_{\text{Pi}}) + (p_{\text{Qf}} - p_{\text{Qi}}) = m \times -2.0\ \text{m s}^{-1} + m \times 2.0\ \text{m s}^{-1}$$
$$(p_{\text{Pf}} - p_{\text{Pi}}) + (p_{\text{Qf}} - p_{\text{Qi}}) = 0$$

8 $P_{\text{Ti}} = -66.0\,\text{kg m s}^{-1}$

Final momentum:

$P_{\text{Tf}} = p_{\text{Kf}} + p_{\text{Lf}}$

$P_{\text{Tf}} = 6.0\,\text{kg} \times -10\,\text{m s}^{-1} + 12.0\,\text{kg} \times 0.5\,\text{m s}^{-1}$

$P_{\text{Tf}} = -54.0\,\text{kg m s}^{-1}$

Initial momentum ≠ final momentum

This is not possible.

9 Take positive to be in direction of rebound velocity:

a $J = \text{area} \times F - t_{\text{graph}}$

$$= \frac{1}{2} \times 200\,\text{N} \times 0.030\,\text{s}$$

$$= 3.0\,\text{N s}$$

b $J = \Delta p$

$0.058\,\text{kg} \times (v_{\text{f}} - {}^{-}30\,\text{m s}^{-1}) = 3.0\,\text{N s}$

c $v_{\text{f}} + 30\,\text{m s}^{-1} = \dfrac{3.0\,\text{N s}}{0.058\,\text{kg}}$

$v_{\text{f}} = 21.7\,\text{m s}^{-1}$

CHAPTER EXAM

MULTIPLE CHOICE

1	C	**2**	B	**3**	A	**4**	D	**5**	C
6	B	**7**	D	**8**	A	**9**	D	**10**	D

SHORT RESPONSE

11 Impulse = change in momentum:

a $F(\text{by bat on ball})\Delta t = (\Delta p)_{\text{ball}}$

$F(\text{by bat on ball})\Delta t = m_{\text{ball}}\Delta v_{\text{ball}}$

$F(\text{by bat on ball}) = \dfrac{m_{\text{ball}}\Delta v_{\text{ball}}}{\Delta t}$

Take the return direction to be positive:

$$F(\text{by bat on ball}) = \frac{0.15\,\text{kg} \times \left(38\,\text{m s}^{-1} - {}^{-}32\,\text{m s}^{-1}\right)}{0.75 \times 10^{-3}\,\text{s}}$$

$$= 1.4 \times 10^{4}\,\text{N}$$

b By Newton's third law:

$F(\text{by bat on ball}) = F(\text{by ball on bat})$

$= 1.4 \times 10^{4}\,\text{N}$

12 Conservation of momentum:

$\Sigma p_{\text{i}} = \Sigma p_{\text{f}}$

Expand out the equation based on the situation where two objects collide and attach to move off as one mass:

$m_1v_1 + m_2v_2 = (m_1 + m_2)v_3$

Make v_3 the subject of the equation:

$$v_3 = \frac{m_1v_1 + m_2v_2}{m_1 + m_2}$$

Substitute in values from the question:

Assume that right is positive.

$$v_3 = \frac{5\text{ kg} \times 8\text{ m s}^{-1} + 3\text{ kg} \times -3\text{ m s}^{-1}}{5\text{ kg} + 3\text{ kg}}$$

Solve for v_3:

$v_3 = 3.88\text{ m s}^{-1}$ to the right

13 If east is deemed as the positive direction and ignoring friction:

$\Delta p = p_{\text{f}} - p_{\text{i}}$

$= mv - mu$

Substitute in values from the question:

$0 = (67 + 80)v - 67u$

Rearrange the equation:

$67u = 147v$

For this to occur, both *u* and *v* must be positive. Therefore, they both must be in the same direction (east).

CROSS-CHAPTER QUESTION

14 Assume that up is positive.

$I = \Delta p = mv - mu$

Calculate the velocity of ball just before it hits the ground:

$v^2 = u^2 + 2as$

$v = \sqrt{u^2 + 2as}$

Substitute in values from the question:

$v = \sqrt{0^2 + 2 \times -9.8 \times -5}$

$= -9.9\text{ m s}^{-1}$

$= 9.9\text{ m s}^{-1}$ down

Calculate velocity off the ground just after it rebounds.

60% of $5\,\text{m} = 3\,\text{m}$

$v^2 = u^2 + 2as$

Make *u* the subject of the equation:

$u = \sqrt{v^2 - 2as}$

Substitute in values from the question:

$u = \sqrt{0 - 2 \times 9.8 \times 3}$

$= -7.67\text{ m s}^{-1}$ up

Substitute in values into the impulse equation:

$I = mv - mu$

$= (0.1 \times 7.67) - (0.1 \times -9.9)$

$= 1.76\text{ kg m s}^{-1}$ up

DATA ANALYSIS

15 $\vec{J} = \text{area under } F\text{–}t \text{ graph}$

$$= \frac{1}{2} \times 1.0 \times 10^{3}\text{ N} \times 24 \times 10^{-3}\text{ s}$$

$$= 12\,\text{N s}$$

$m\Delta v = 12\,\text{N s}$

$0.15\,\text{kg} \times \left(v_\text{f} - -35\,\text{m s}^{-1}\right) = 12\,\text{N s}$

$v_\text{f} = 45\,\text{m s}^{-1}$

Impulse = momentum change

Take positive to be the outward direction.

CHAPTER 14 NEWTON'S LAWS OF MOTION

LEARNING CHECK 14.1

DESCRIBING

1 **a** A fundamental quantity that can be transferred and transformed.

- **b** The difference between the initial and final energy states
- **c** Energy transfer when force is applied to an object
- **d** The energy of movement
- **e** Energy stored in a system that is available to do work
- **f** Energy stored in a spring or elastic system
- **g** Energy stored in an object due to its position in a gravitational field

2 In a closed system, no energy can come into the system, no energy can leave the system and no energy can be created or destroyed within the system

3 An isolated system is not able to receive energy from or transfer energy to another system.

4 **a** Work done on or by a system is the same as the energy change to or by the system: $\Delta W = \Delta E$.

b Work, $W = \Delta E = F_{\parallel}\Delta s$; $F_{\parallel}$ = component of force parallel to the direction of movement; s = displacement; ΔE = energy transferred

APPLYING

5 Energy is neither created nor destroyed; it is merely transformed. Energy is measured relative to a defined starting value or point. Measures are only made relative to such a given point.

6 Potential energy is stored in a spring when the spring is changed in length; gravitational potential energy is stored in the gravitational field according to the position of a mass in the field.

7 **a**

$$E_\text{k} = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 3.0\,\text{kg} \times \left(8.0\,\text{m s}^{-1}\right)^2$$

$$= 96\,\text{J}$$

b

$$60\,\text{km h}^{-1} = \frac{60\,\text{km h}^{-1} \times 10^3\,\text{m km}^{-1}}{3600\,\text{s h}^{-1}} = 16.7\,\text{m s}^{-1}$$

$$E_\text{k} = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 3.0\,\text{kg} \times \left(16.67\,\text{m s}^{-1}\right)^2$$

$$= 417\,\text{J}$$

8 **a** $W = \Delta E_\text{k} = F_{\parallel}\Delta s$

$$\Delta E_\text{k} = 20\,\text{N} \times 5.0\,\text{m}$$

$$= 100\,\text{J}$$

b

$$\Delta E_\text{k} = \frac{1}{2}mv_\text{f}^2 - \frac{1}{2}mv_\text{i}^2$$

$$\frac{1}{2}mv_\text{f}^2 - \frac{1}{2}mv_\text{i}^2 = 100\,\text{J}$$

$$v_\text{f}^2 - v_\text{i}^2 = 2 \times \frac{100\,\text{J}}{8.0\,\text{kg}}$$

$$v_\text{f}^2 - \left(10\,\text{m s}^{-1}\right)^2 = 25\,\text{J kg}^{-1}$$

$$v_\text{f} = 11.2\,\text{m s}^{-1}$$

ANALYSING

9 Curved path; if the speed is constant, the object describes a circle

The force is always at right angles so there is no component of force parallel to the path (tangent) to do work.

10 Answers will vary.

LEARNING CHECK 14.2

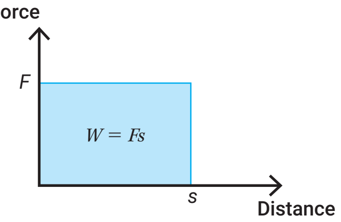
DESCRIBING

1 Work is the force applied to move an object over a distance in the direction of the force: $W = F_{\parallel}\Delta s$.

2 Work is the effort required to transfer energy; $\Delta W = \Delta E$.

3 Work done = area under a force–distance graph

4



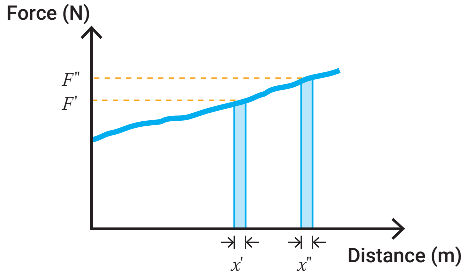
5 **a** $F(\text{by spring}) = k(-x)$

b $F(\text{by spring})$ = force applied by spring

x = change of length of spring

k = stiffness

c i & ii



APPLYING

6 $W = F \Delta s$

$$= 1.5 \times 10^5\,\text{N} \times 5.0 \times 10^{-2}\,\text{m}$$

$$= 7.5 \times 10^3\,\text{N}$$

7 $W = F_{\parallel}s$

$= 30\,\text{N} \times \cos 30° \times 20\,\text{m}$

$= 519.6\,\text{J}$

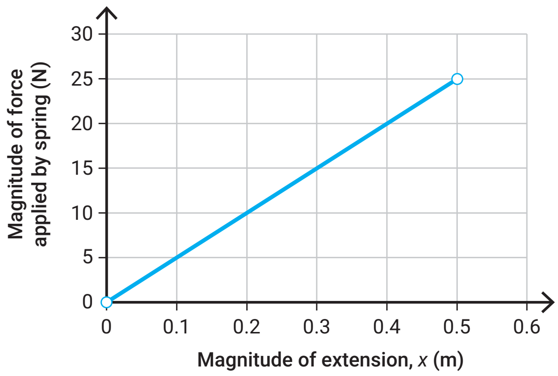
8 $W = F_{\parallel}s$

$= 400\,\text{N} \times 9.0\,\text{m} + (400\,\text{N} + 200\,\text{N}) \times 6.0\,\text{m}$

$= 7.2 \times 10^3\,\text{N}$

ANALYSING

9 **a**



b $E = \frac{1}{2}kx^2$

$x = 50\,\text{cm} - 30\,\text{cm} = 20\,\text{cm}$

$E = \frac{1}{2} \times 50\,\text{N}\,\text{m}^{-1} \times (0.20\,\text{m})^2$

$= 1.0\,\text{J}$

LEARNING CHECK 14.3

DESCRIBING

1 $\Delta E_t = \Delta E_k + \Delta E_p = 0$

2 **a** $\Delta W = mg\Delta h$ $(\Delta h > 0;\ h_2 > h_1)$

b $\Delta W = mg\Delta h$ $(\Delta h < 0;\ h_2 < h_1)$

3 **a** $\frac{1}{2}mv_i^2 = mgh$ **b** $v_i = \sqrt{2gh}$

c $h = \frac{v_i^2}{2gh}$

APPLYING

4 For objects going up, the distance above the surface is positive as the potential energy stored in the system increases.

5 Work is done only when there is a component of the force in the direction of the field. ‘Near Earth’ horizontal motion is at right angles to Earth’s gravitational field.

6 **a** $\Delta E_p = mg\Delta h$

$= 0.160\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2} \times 20.0\,\text{m}$

$= 31.4\,\text{N}$

b $v_i = \sqrt{2gh}$

$= \sqrt{2 \times 9.8\,\text{m}\,\text{s}^{-2} \times 20.0\,\text{m}}$

$= 19.8\,\text{m}\,\text{s}^{-1}$

7

	E_p (J)	E_k (J)	E (J)
a	$E_p = mgh$ $= 50\,\text{kg} \times 9.8\,\text{m}\,\text{s}^{-2} \times 20.0\,\text{m}$ $= 9.8 \times 10^3$	0	9.8×10^3
b	4.9×10^3	4.9×10^3	9.8×10^3
c	0	9.8×10^3	9.8×10^3

ANALYSING

8 If $E_p = 0$ J when $h = 0$ m, then ΔE_p (at H) $= mgH - 0\,\text{J} = mgH$

If $E_p = 100$ J when $h = 0$ then, ΔE_p (at H) $= (100\,\text{J} + mgH) - 100\,\text{J} = mgH$

LEARNING CHECK 14.4

DESCRIBING

1
- Read the question carefully.
- Visualise the situation.
- Check the scales on both axes.
- Convert all scale readings to appropriate SI units.
- Identify the area required as:
  - work done on or by the system
  - kinetic energy increase or decrease
  - potential energy increase or decrease.
- Set up appropriate equations.
- Equate energy changes with areas.
- Substitute values.
- Calculate the answers.
- Check to ensure the results answer the question.

2 A line can be approximated by a series of very small steps. The area under each step is a $\{\text{force} \times \text{distance}\}$ rectangle with units of joule; hence, it is work. The sum of all the very thin rectangles adds up to the area under the graph, and hence is the total work done.

3 $W = \frac{1}{2} \times x \times ks$

$= \frac{1}{2}kx^2$

APPLYING

4 **a** $W = F_{\parallel}s$

$= 250\,\text{N} \times (10\,\text{m} - 0\,\text{m})$

$= 2.5 \times 10^3\,\text{N}$

b $W = F_{\|}s$

$= 250\,\text{N}\times(17\,\text{m}-3\,\text{m})$

$= 3.5\times10^{3}\,\text{N}$

5 **a** **i** $W(\text{by A}) = F(\text{by A})s$

$$\begin{aligned}\Sigma F &= F(\text{by A}) - f\\ F(\text{by A}) &= \Sigma F + f\\ &= 30\,\text{N} + 28\,\text{N}\\ &= 58\,\text{N}\\ W(\text{by A}) &= 58\,\text{N}\times 4.0\,\text{m}\\ &= 232\,\text{J}\end{aligned}$$

ii $W(\text{by A}) = F(\text{by A})s$

$= 58\,\text{N}\times 16\,\text{m}$

$= 928\,\text{J}$

b **i** $W(\text{by B}) = F(\text{by B})s$

$$\begin{aligned}\Sigma F &= F(\text{by B}) + F(\text{by A}) - f\\ F(\text{by B}) &= \Sigma F - F(\text{by A}) + f\\ &= 75\,\text{N} - 58\,\text{N} + 28\,\text{N}\\ &= 45\,\text{N}\\ W(\text{by B}) &= 45\,\text{N}\times(12\,\text{m}-8.0\,\text{m})\\ &= 180\,\text{J}\end{aligned}$$

ii $W(\text{by B}) = F(\text{by B})s$

$= 45\,\text{N}\times(20\,\text{m}-8.0\,\text{m})$

$= 540\,\text{J}$

c $W(\text{by friction}) = F(\text{by friction})s$

$= 28\,\text{N}\times 24\,\text{m}$

$= 672\,\text{J}$

6 **a** $W(\text{by train}) = F(\text{by train})s$

$\Sigma F = F(\text{by train}) - f$

$F(\text{by train}) = \Sigma F + f$

$\Sigma F = ma$

$a = \text{gradient}_{\,v\text{–}t\text{ graph}} = \dfrac{\Delta v}{\Delta t}$

$= \dfrac{10\,\text{m s}^{-1} - 0\,\text{m s}^{-1}}{600\,\text{s} - 0\,\text{s}} = \dfrac{1}{60}\,\text{m s}^{-2}$

$\Sigma F = 5.5\times10^{6}\,\text{kg}\times\dfrac{1}{60}\,\text{m s}^{-2}$

$= 9.2\times10^{4}\,\text{N}$

$s = \text{area under } v\text{–}t \text{ graph}$

$= \dfrac{1}{2}\times 10\,\text{m s}^{-1}\times 600\,\text{s}$

$= 3.0\times10^{3}\,\text{m}$

$F(\text{by train}) = 9.2\times10^{4}\,\text{N} + 1.0\times10^{4}\,\text{N}$

$= 1.02\times10^{5}\,\text{N}$

$W(\text{by train}) = 1.02\times10^{5}\,\text{N}\times 3.0\times10^{3}\,\text{m}$

$= 3.1\times10^{8}\,\text{J}$

b $W(\text{by train}) = F(\text{by train})x$

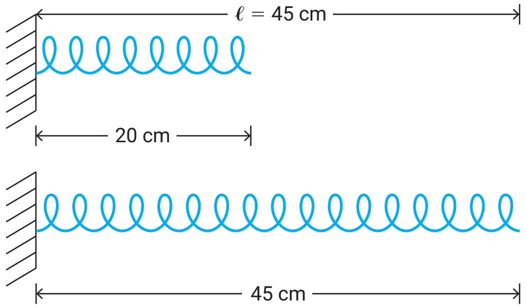
$$\begin{aligned}\Sigma F &= F(\text{by train}) - f\\ F(\text{by train}) &= \Sigma F + f\\ &= 0\,\text{N} + 1.0\times10^{4}\,\text{N}\\ x &= \text{area under}_{\,v\text{–}t\text{ graph}}\\ &= 10\,\text{m s}^{-1}\times(1800\,\text{s} - 1200\,\text{s})\\ &= 6.0\times10^{3}\,\text{m}\\ W(\text{by train}) &= 1.0\times10^{4}\,\text{N}\times 6.0\times10^{3}\,\text{m}\\ &= 6.0\times10^{7}\,\text{J}\end{aligned}$$

ANALYSING

7 $F(\text{by spring}) = k(L-\ell),\ L<\ell$

$F(\text{by spring}) = k(\ell-L),\ \ell<L$

8 **a**



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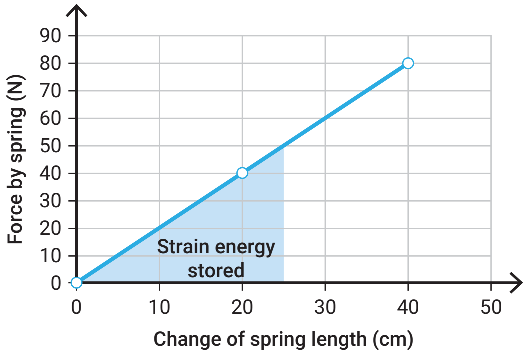


c See graph in part **b**.

d $\dfrac{1}{2}mv^{2} = \dfrac{1}{2}kx^{2}$

$v = \sqrt{\dfrac{k}{m}x^{2}}$

$= \sqrt{\dfrac{200\,\text{N m}^{-1}}{0.200\,\text{kg}}\times(0.45\,\text{m} - 0.20\,\text{m})^{2}}$

$= 7.91\,\text{m s}^{-1}$

LEARNING CHECK 14.5

REMEMBERING

1 **a** Momentum is conserved throughout; the kinetic energy at the start is the same as the kinetic energy at the end.

  b Momentum is conserved throughout; the kinetic energy at the start is different from the kinetic energy at the end.

2 **a** Momentum

  b Kinetic energy

3 **a** Impulse–momentum

  b Work–energy

4 Both momentum and kinetic energy at the start of a collision are conserved in elastic collisions

APPLYING

5 **a** Take right to be positive:

$$P_{\text{t, i}} = P_{\text{t,f}}$$
$$(m_{\text{P}}v_{\text{P}})_{\text{i}} + (m_{\text{Q}}v_{\text{Q}})_{\text{i}} = (m_{\text{P}}v_{\text{P}})_{\text{f}} + (m_{\text{Q}}v_{\text{Q}})_{\text{f}}$$
$$(4.0\,\text{kg} \times 3.0\,\text{m s}^{-1})_{\text{i}} + (5.0\,\text{kg} \times -2.0\,\text{m s}^{-1})_{\text{i}}$$
$$= (4.0\,\text{kg} \times -1.0\,\text{m s}^{-1})_{\text{f}} + (5.0\,\text{kg} \times v_{\text{Q}})_{\text{f}}$$
$$2.0\,\text{kg m s}^{-1} = (5.0\ \text{kg} \times v_{\text{Q}})_{\text{f}} - 4.0\,\text{kg m s}^{-1}$$
$$v_{\text{Q, f}} = \frac{6.0\ \text{kg m s}^{-1}}{5.0\,\text{kg}}$$
$$v_{\text{Q, f}} = 1.2\,\text{m s}^{-1}$$

  b $F(\text{by P on Q})\Delta t = (\Delta p)_{\text{Q}}$

$$= \frac{(m_{\text{Q}}v_{\text{Q}})_{\text{f}} - (m_{\text{Q}}v_{\text{Q}})_{\text{i}}}{\Delta t}$$
$$= \frac{(5.0\,\text{kg} \times 1.2\,\text{m s}^{-1})_{\text{f}} - (5.0\,\text{kg} \times -2.0\,\text{m s}^{-1})_{\text{i}}}{0.4\,\text{s}}$$
$$= 40\,\text{N}$$

  c Compare initial and final kinetic energies:

$$E_{\text{k, i}} = \left(\frac{1}{2}m_{\text{P}}v_{\text{P}}^2\right)_{\text{i}} + \left(\frac{1}{2}m_{\text{Q}}v_{\text{Q}}^2\right)_{\text{i}}$$
$$= \left[\frac{1}{2} \times 4.0\,\text{kg} \times (3.0\,\text{m s}^{-1})^2\right]_{\text{i}} + \left[\frac{1}{2} \times 5.0\,\text{kg} \times (-2.0\,\text{m s}^{-1})^2\right]_{\text{i}}$$
$$= 28\,\text{J}$$
$$E_{\text{k, f}} = \left(\frac{1}{2}m_{\text{P}}v_{\text{P}}^2\right)_{\text{f}} + \left(\frac{1}{2}m_{\text{Q}}v_{\text{Q}}^2\right)_{\text{f}}$$
$$= \left[\frac{1}{2} \times 4.0\,\text{kg} \times (-1.0\,\text{m s}^{-1})^2\right]_{\text{f}} + \left[\frac{1}{2} \times 5.0\,\text{kg} \times (1.2\,\text{m s}^{-1})^2\right]_{\text{f}}$$
$$= 5.6\,\text{J}$$
$$E_{\text{k,i}} \neq E_{\text{k,f}}$$

The collision is inelastic.

6 **a** $F(\text{by seatbelt on person})\ \Delta x = \Delta E_{\text{k, person}}$

$$F(\text{by seatbelt on person}) = \frac{\Delta E_{\text{k, person}}}{\Delta x}$$
$$= \frac{\left(\frac{1}{2}m_{\text{p}}v_{\text{p}}^2\right)_{\text{f}} - \left(\frac{1}{2}m_{\text{p}}v_{\text{p}}^2\right)_{\text{i}}}{\Delta x}$$
$$= \frac{\left[\frac{1}{2} \times 100.0\,\text{kg} \times (0\,\text{m s}^{-1})^2\right] - \left[\frac{1}{2} \times 100.0\,\text{kg} \times (10\,\text{m s}^{-1})^2\right]_i}{1.0\,\text{m}}$$
$$= 5.0 \times 10^3\ \text{N}$$

  b $F(\text{by seatbelt on person})\Delta t = \Delta p_{\text{person}}$

$$\Delta t = \frac{(m_{\text{p}}v_{\text{p}})_{\text{f}} - (m_{\text{p}}v_{\text{p}})_{\text{i}}}{F(\text{by seatbelt on person})}$$
$$= \frac{(100\,\text{kg} \times 0\,\text{m s}^{-1}) - (100\,\text{kg} \times -10\,\text{m s}^{-1})}{5.0 \times 10^3\ \text{N}}$$
$$= 0.20\,\text{s}$$

ANALYSING

7 If $\Delta h_{\text{f}} = \Delta h_{\text{i}},\ v_{\text{f}} = v_{\text{i}}$ and $v_{\text{f}}^2 = v_{\text{i}}^2$

$\Delta P = 0$ and $\Delta E_{\text{k}} = 0$

CHAPTER EXAM

MULTIPLE CHOICE

1 C **2** C **3** C **4** A **5** B

6 C **7** B **8** C **9** A **10** B

SHORT RESPONSE

11 **a** $\Delta E_{\text{p}} = mg\Delta h$

$$= 60\,\text{kg} \times 9.8\,\text{m s}^{-2} \times (1.8\,\text{m} - 0.63\,\text{m})$$
$$= 688\ \text{J}$$

  b $v = \sqrt{2gh}$

$$= \sqrt{2 \times 9.8\,\text{m s}^{-2} \times (1.8\,\text{m} - 0.63\,\text{m})}$$
$$= 4.8\,\text{m s}^{-1}$$

  c $\Delta E_{\text{p}} = mg\Delta h$

$$= 60\,\text{kg} \times 9.8\,\text{m s}^{-2} \times (1.8\,\text{m} - 0.42\,\text{m})$$
$$= 753\ \text{J}$$
$$\Delta E_{\text{k}} = 753\ \text{J}$$

12 **a** $W = Fs$

Substitute in values from the question:

$$W = 85\ \text{N} \times 25\ \text{m}$$
$$= 2125\ \text{J}$$

b $E_p = mg\Delta h$

$= 20 \times 9.8 \times 10$

$= 1960 \text{ J}$

c The difference is due to some work being done against the frictional forces in the pulleys.

13 At the top of the hill, the car will have both kinetic energy and gravitational energy.

Calculate the total amount of energy:

$$E = E_k + E_p$$

$$= \frac{1}{2}mv^2 + mgh$$

Substitute in values from the question:

$$E = \frac{1}{2} \times 800 \times 6^2 + 800 \times 9.8 \times 40$$

$$= 328\,000 \text{ J}$$

At the bottom of the hill, the car will only have kinetic energy.

Calculate the kinetic energy:

$$E_k = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 800 \times 20^2$$

$$= 160\,000 \text{ J}$$

The difference in the energy will have been lost to friction.

$$\Delta E = 328\,000 - 160\,000$$

$$= 168\,000 \text{ J}$$

$$= 168 \text{ kJ}$$

CROSS-CHAPTER QUESTION

14 **a** $W = F\Delta s = \Delta E_k$

$$F = \frac{\Delta E_k}{\Delta x}$$

$$= \frac{\frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2}{\Delta x}$$

$$= \frac{\frac{1}{2} \times 8.0\text{ kg} \times \left[\left(0\text{ m s}^{-1}\right)^2 - \left(20\text{ m s}^{-1}\right)^2\right]}{0.05\text{ m}}$$

$$= 3.2 \times 10^4 \text{ N}$$

b $I = F\Delta t = m\Delta v$

$$\Delta t = \frac{m\Delta v}{F}$$

$$= \frac{8.0\text{ kg} \times (0\text{ m s}^{-1} - 20\text{ m s}^{-1})}{-3.2 \times 10^4 \text{ N}}$$

$$= 5.0 \times 10^{-3} \text{ s}$$

DATA ANALYSIS

15 **a** $W(\text{by net force}) = \Sigma F \times s$

$W = 200\text{ N} \times 12\text{ m}$

$= 2.4 \text{ kJ}$

b $W(\text{by winch}) = F(\text{by winch})s$

$\Sigma F = F(\text{by winch}) - f$

$F(\text{by winch}) = \Sigma F + f$

$$F(\text{by winch})x = \left(\Sigma F_{0\text{–}12\text{m}} + 30\text{ N}\right) \times \left(12\text{ m} - 0\text{ m}\right)$$
$$+ \left(\Sigma F_{12\text{–}24\text{m}} + 30\text{ N}\right) \times \left(36\text{ m} - 12\text{ m}\right)$$

$$W(\text{by winch}) = 230\text{ N} \times 12\text{ m} + 530\text{N} \times 24\text{ m}$$

$$= 15\text{ kJ}$$

CHAPTER 15 WAVE PROPERTIES

LEARNING CHECK 15.1

DESCRIBING

1 All waves transfer energy from one place to another.

2 The intensity of a wave is a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel.

3 Since the intensity of a wave is inversely proportional to the distance from the source squared, doubling the distance results in the intensity becoming one-quarter its original magnitude.

ANALYSING

4 The energy of the stone dropped into a pond does spread as a sphere; however, the interface upon which we view these waves is a slice through the midpoint and as such appears as a circle. The energy that is travelling under the water and through the air is invisible to us.

LEARNING CHECK 15.2

DESCRIBING

1 A wave that requires a physical substance to be able to propagate

2 An imaginary surface joining all points in space reached at the same instant by a wave propagating through a medium

3 The medium is the substance whose particles oscillate in response to the energy of a wave travelling through it.

4 Mechanical waves travel in a medium made of interconnected particles that are progressively disturbed and oscillate about their mean position due to the motion of the energy through them.

5 The ocean waves shown in Figure 15.2.1 are representative of plane wavefronts as the rays that can be drawn perpendicularly to them are parallel to each other.

LEARNING CHECK 15.3

DESCRIBING

1 **a** A single wavefront travelling through a medium

  b A repeating wave passing through a medium

  c A region of high pressure in a mechanical wave

  d A region of lower pressure in a mechanical wave

2 In a transverse wave, the particles of the medium are oscillating in a direction perpendicular to the direction of wave motion, whereas in a longitudinal wave, the particles of the medium are oscillating in a direction parallel to the direction of wave motion.

3 A single disturbance at the end of a string produces a single pulse, whereas a continuous up and down disturbance produces a continuous wave.

LEARNING CHECK 15.4

DESCRIBING

1 **a** Longitudinal **b** Transverse
 c Longitudinal **d** Transverse
 e Transverse

2 **a** A region of high pressure in a mechanical wave
 b A region of lower pressure in a mechanical wave

3 A disturbance on a string will result in a portion of the string being displaced in a direction transverse to the string itself. The displacement of these particles will apply a force on their adjacent particles.

4 In a water wave, the particles of water oscillate in a circular pattern below the surface; however on the surface they are seen to be displaced in a direction transverse to the direction of travel by the wave.

5 In a sound wave, the particles of the medium oscillate parallel to the direction of travel, forming localised high-pressure compressions and low-pressure rarefactions. This pressure differential applies a force on other particles in the medium.

6 Seismic earthquake waves travel through the medium of Earth. The faster P waves are longitudinal compression waves, whereas the slower S waves travel as transverse waves.

ANALYSING

7 Answers will vary but should include:
- a tear in the eardrum preventing the incoming sound waves from sending vibrations onto the small bones of the ear
- a break in one of the small bones preventing the vibration to pass through the ear
- the hairs of the inner ear failing to transmit electrical impulses to the nervous system.

8 Answers will vary but should include:
- discussion of the different speed of travel of the S and P waves in different media
- this resulting in a difference in the time delay between the arrival of the P and S waves at a measuring point depending on the density of the medium.

LEARNING CHECK 15.5

DESCRIBING

1 **a** The positive peak of a wave
 b The negative peak of a wave
 c The straight-line distance between the current position of a particle in a wave and its mean position
 d The maximum displacement of a particle in a wave from its mean position
 e The time it takes before a wave repeats itself
 f The number of whole waves of cycles in one second
 g The distance travelled by a wave before it repeats itself
 h The velocity at which crests move through a medium

2 A displacement–time graph can give information about the amplitude and period of a wave

3 A displacement–distance graph can give information about the amplitude and wavelength of a wave.

4 The properties of the medium through which a wave is travelling has the greatest impact on the velocity of the wave.

5 In this section, displacement refers to the straight-line distance that a particle of the medium through which a wave is passing is displaced from its mean position, whereas the distance is the position of a particle along the axis of wave travel.

APPLYING

6 Apply the frequency equation:

$$f = \frac{1}{T}$$

Rearrange the equation to make the required T the subject:

$$T = \frac{1}{f}$$

Insert known values:

$$T = \frac{1}{23\ \text{Hz}}$$

Calculate the answer:

$$T = 0.043\,478\ \text{s}$$

Give the answer to the correct number of significant figures:

$$T = 4.3 \times 10^{-2}\ \text{s}$$

7 **a** Apply the wave velocity formula:

$$v = \frac{\lambda}{T}$$

Insert known values:

$$v = \frac{0.6\ \text{m}}{0.5\ \text{s}}$$

Calculate the answer to the correct number of significant figures:

$v = 1.2\ \text{m s}^{-1}$

b Apply the frequency equation:

$$f = \frac{1}{T}$$

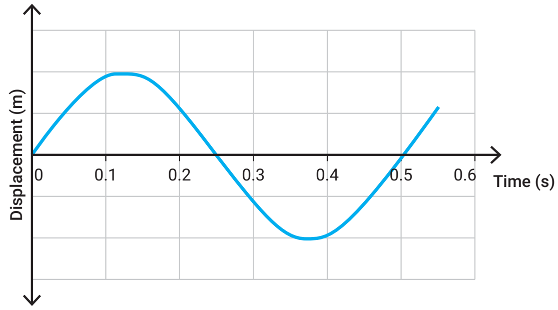
Insert known values:

$$f = \frac{1}{0.5\ \text{s}}$$

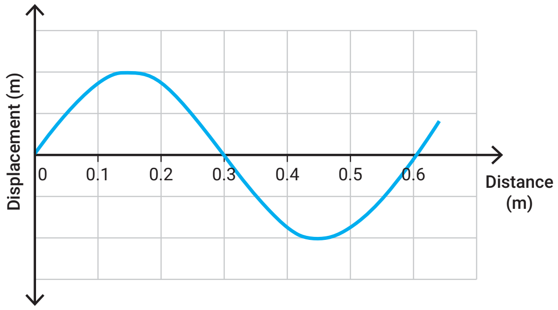
Calculate the answer to the correct number of significant figures:

$f = 2.0\ \text{Hz}$

c



d



8 Apply the velocity equation:

$$v = \frac{\lambda}{T}$$

Rearrange the equation to make the required T the subject:

$$T = \frac{\lambda}{v}$$

$$= \frac{150\ \text{km}}{800\ \text{km h}^{-1}}$$

Insert known values :

$T = 0.1875\ \text{h}$

Calculate the answer:

$$T = 0.1875\ \text{h} \times \frac{3600\ \text{s}}{1\ \text{h}}$$

Apply the conversion factor:

$T = 675\ \text{s}$

Calculate the answer:

$T = 700\ \text{s}$

Give the answer to the correct number of significant figures.

ANALYSING

9 **a** $A = 0.6\ \text{m}$ (from graph)

b $T = 0.125\ \text{s}$ (from graph)

c Apply the frequency equation:

$$f = \frac{1}{T}$$

Insert the known period:

$$f = \frac{1}{0.125\ \text{s}}$$

Calculate the answer.

$f = 8\ \text{Hz}$

d $\lambda = 4\ \text{m}$

e Apply the wave velocity formula:

$v = f\lambda$

Insert known values:

$v = 8\ \text{Hz} \times 4\ \text{m}$

Calculate the answer:

$v = 32\ \text{m s}^{-1}$

LEARNING CHECK 15.6

DESCRIBING

1. The reflection of a wave involves the change in direction of a wavefront at a boundary between two media so that the wavefront continues travelling in the first medium.
2. The wavefront is reflected in an inverted orientation relative to its orientation when it strikes the boundary.
3. The wavefront is reflected in an upright orientation relative to its orientation when it strikes the boundary.
4. When a wave pulse meets a junction with a string of higher density, part of the wave is reflected and part of the wave is transmitted into the new string. The reflected portion travels in an inverted orientation, with a decreased amplitude and an equal velocity relative to its behaviour when it meets the junction. The transmitted portion travels in an upright orientation, with a decreased amplitude and a lower velocity relative to its behaviour when it meets the junction.
5. When a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence.
6. Both reverberation and echoes are caused by the reflection of sound waves at boundaries. A reverberation occurs when too many sound wave reflections arrive at your ear for you to be able to distinguish between them, while an echo is the return to your ear by one sound wave at least 0.15 s after the sound has been transmitted.
7. When waves travel in a tube such as a stethoscope, they can be reflected off the walls of the tube by total internal reflection so that they can be guided along a non-linear path.

APPLYING

8 This would be achieved if the walls of the tube were made from a high-density material and if the angle of incidence was as great as possible.

9 To reduce the impact of echoes and reverberations as much as possible, the walls of a concert hall should be made of a low-density material that will readily allow incident waves to be transmitted through them rather than reflected. This property could be increased by ensuring the angle of incidence is as small as possible by correctly orientating the walls to the source of sound.

LEARNING CHECK 15.7

DESCRIBING

1 The refraction of waves is when waves change direction as they strike an interface with another medium at an angle other than 90°. The speed and wavelength of the wave also change.

2 The apparent position is the position that an object appears to an observer; it may be different from its actual position due to the refraction of its light waves.

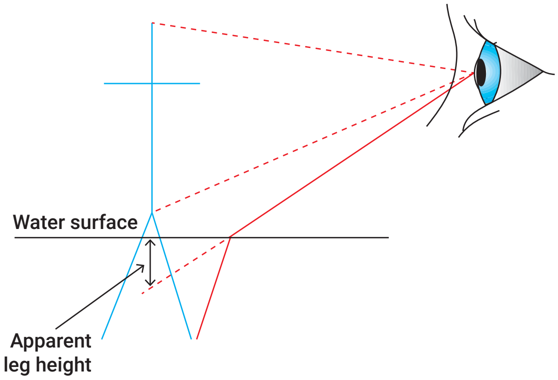
3 Atmospheric refraction is the refraction of light rays as they pass through Earth's atmosphere.

4 Refraction will occur whenever the density of the two media through which the wave travels is different and the angle of incidence is not 90°.

5 When a wave is refracted into a denser material, the wavelength and velocity of the wave will decrease, while the period and frequency remain unchanged.

APPLYING

6 The refraction of light waves coming from the leg causes the apparent position of the feet to be higher than if there was no refraction.



LEARNING CHECK 15.8

DESCRIBING

1 The bending of waves around an obstacle

2 Diffraction is used to create calmer waters in a harbour; the section of incoming water waves that pass through the harbour walls spread in a circular pattern and their energy dissipates.

3 Reflection is the rebounding of waves off a boundary between two media, refraction is the bending of a wave as it passes through the boundary between two media, whereas diffraction is the bending of a wave around an obstacle.

4 The effect of diffraction can be increased by making the wavelength of the incoming wave greater than the width of the obstacle.

APPLYING

5 In the absence of diffraction, the sound would be either reflected or absorbed by the tree and no sound would be heard because there is nothing else for it to rebound back to the observer from. However, if the wavelength of the sound is greater than the width of the tree, the sound waves will diffract around the tree and reach the ears of the observer.

LEARNING CHECK 15.9

DESCRIBING

1 **a** Interference of waves occurs when two or more waves pass through the same space at the same time.

  b Constructive interference occurs when the peaks of two waves overlap to create an overall particle displacement equal to the amplitude of both waves added together.

  c Destructive interference occurs when the peak of one wave overlaps with the trough of another to create an overall particle displacement of less than the amplitude of either wave.

2 Two waves are considered in-phase if they are of the same wavelength and the crests of each wave overlap, whereas they are considered to be out-of-phase if they are of the same wavelength and the crest of one wave does not overlap with the crest of the other.

3 The principle of superposition states that when two waves pass through the same place at the same time, that they will create a particle displacement equal to the sum of the particle displacements of the two individual waves at that point in time.

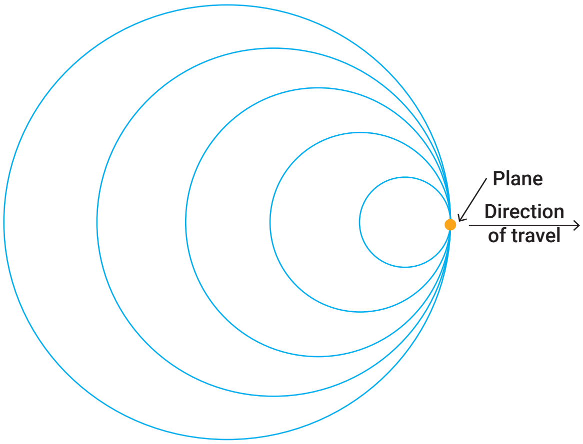
4 The Doppler effect occurs because the velocity of the source of the sound waves can alter the wavelength of the sound as heard by an observer. When the siren is approaching the observer, the wavelength is decreased, which increases the frequency or pitch. As the siren moves away from the observer, the wavelength is increased, which decreases the frequency or pitch.

APPLYING

5 The maximum amplitude occurs when constructive interference or the overlap of the two crests occurs. At this point, the displacement will be equal to the sum of the individual amplitudes, or 6 cm + 9 cm = 15 cm.

6 The minimum amplitude will occur when destructive interference occurs. At this point, the displacement will be equal to the difference between the two amplitudes, or 9.0 cm – 6.0 cm = 3.0 cm.

7



LEARNING CHECK 15.10

DESCRIBING

1 A wave that oscillates in place, without transmitting energy along its extent

2 At a node, the total particle displacement is equal to zero at all times, whereas at an antinode, the particle displacement oscillates between the maximum and minimum values.

3 The distance between a node and an antinode is equal to one-quarter of a wavelength.

4 Node = destructive interference, antinode = constructive interference

5 Each piano string has a different length and/or density, which affects not only the speed of the wave but the wavelength of the standing wave patterns that can form on them. Both of these features affect the frequency of the standing wave that is emitted as a sound wave.

CHAPTER EXAM

MULTIPLE CHOICE

1	D	**2**	A	**3**	D	**4**	C	**5**	D
6	D	**7**	B	**8**	C	**9**	B	**10**	D

SHORT RESPONSE

11 Apply the wave velocity formula:

$$v = \frac{\lambda}{T}$$

Insert known values:

$$v = \frac{5.5\ \text{m}}{5\ \text{s}}$$

Give the answer to the correct number of significant figures.

$$v = 1.1\ \text{m s}^{-1}$$

12 Apply the wave velocity formula:

$$v = f\lambda$$

Rearrange the formula for the required λ:

$$\lambda = \frac{v}{f}$$

Insert known values:

$$\lambda = \frac{343\ \text{m s}^{-1}}{215\ \text{Hz}}$$

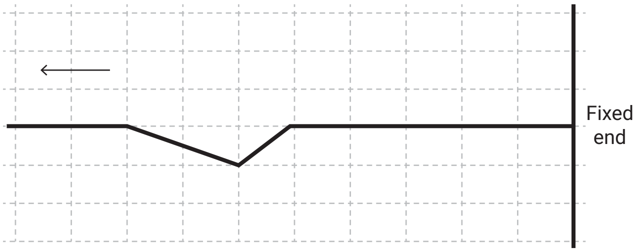
Calculate the answer:

$$\lambda = 1.5953\ \text{m}$$

Give the answer to the correct number of significant figures.

$$\lambda = 1.60\ \text{m}$$

13 **a**



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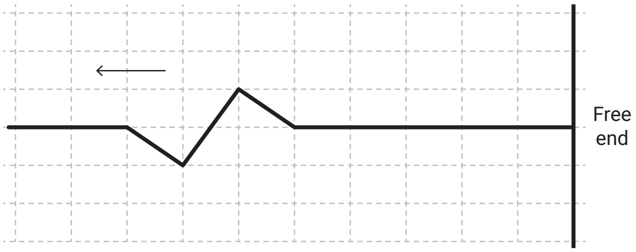

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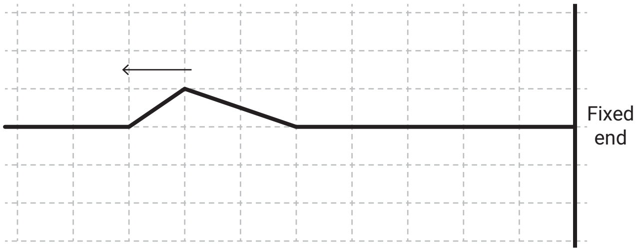

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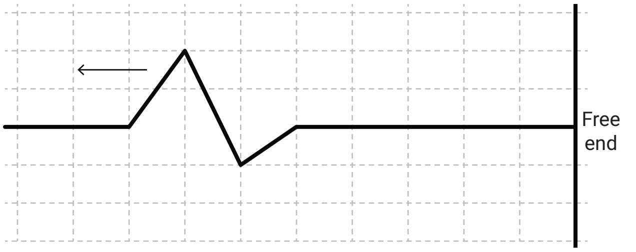
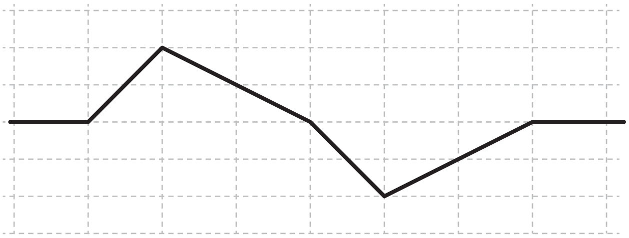


DATA ANALYSIS

14 **a**



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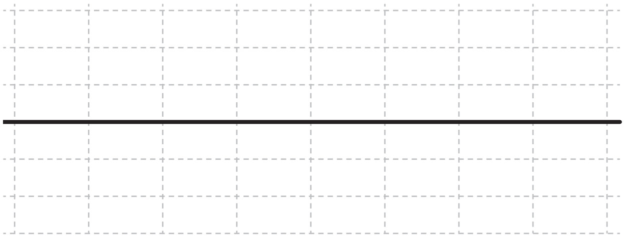

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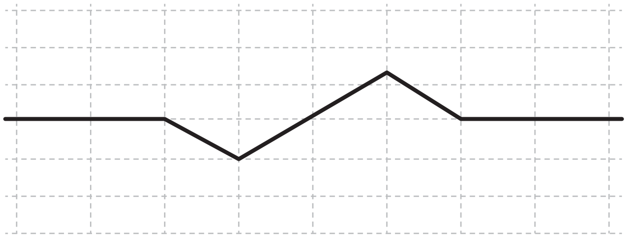


15 **a** $A = 0.6\text{ m}$

b $T = 6.67 \times 10^{-3}\text{ m}$

c $f = \frac{1}{T}$

$= \frac{1}{6.67 \times 10^{-3}\text{ m}}$

$= 150\text{ Hz}$

d $\lambda = 1.5\text{ m}$

e $v = f\lambda$

$= 150\text{ Hz} \times 1.5\text{ m}$

$= 225\text{ m s}^{-1}$

CHAPTER 16 SOUND

LEARNING CHECK 16.1

DESCRIBING

1 **a** The vibration frequency that occurs when the object is displaced from its equilibrium position and then left to vibrate by itself

b The forced vibration of an object in contact with another vibrating object

c When an object is induced to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency

2 A natural vibration is the frequency that an object will vibrate at without interference from any other vibration, whereas a forced vibration is the vibration an object will vibrate at due to the presence of another vibrating object.

3 The driving frequency of a resonating system is the vibration of an object that causes a second object to undergo resonance at the resonant frequency.

4 Blowing across a bottle top provides waves of many frequencies into the bottle and if one of these frequencies coincides with the resonant frequency of the bottle, the bottle will vibrate at this frequency and emit a tone.

5 The condition for resonance to occur is that the driving frequency matches the natural frequency.

6 A standing wave has this name because it appears to ‘stand’; that is, its nodes and antinodes do not appear to travel.

APPLYING

7 A tuning fork will only cause another tuning fork to vibrate at its natural frequency if the first tuning fork is vibrating at the natural frequency of the second and if there is a medium for the vibration to travel through efficiently.

8 If a sound wave with a frequency matching the natural frequency of the glass is played near the glass, the energy of the sound is transmitted very efficiently to the glass, causing it to vibrate with a large amplitude that may overcome the bonds holding the particles of the glass together. If this happens, the glass will shatter,

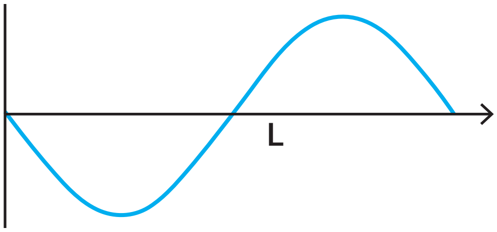
LEARNING CHECK 16.2

DESCRIBING

1 The second mode of vibration has a frequency double that of the fundamental mode. It also has a wavelength half that of the fundamental and has one more node and antinode.

2 The energy of the wave is not destroyed during the formation of a standing wave; rather it results in an altered pattern of propagation. Although the nodes have a displacement of zero at all times, the antinodes will have an increased amplitude compared to that of the original wave.

3



a $\frac{L}{2}$ **b** $\frac{L}{2}$ **c** $\frac{L}{4}$

APPLYING

4 B and C

5 **a** Apply equation:

$$L = n\frac{\lambda_n}{2}$$

Rearrange for the required λ:

$$\lambda_n = \frac{2L}{n}$$

Insert known values:

$$\lambda_1 = \frac{2 \times 0.8\ \text{m}}{1}$$

Calculate the answer to the correct number of significant figures:

$\lambda_1 = 1.6\ \text{m}$

b Apply the wave velocity equation:

$v = f\lambda$

Rearrange for the required f:

$$f = \frac{v}{\lambda}$$

Insert known values:

$$f = \frac{200\ \text{m s}^{-1}}{1.6\ \text{m}}$$

Calculate the answer to the correct number of significant figures:

$f = 125\ \text{Hz}$

c By the equation $f_1 = n\frac{v}{2L}$, it can be seen that decreasing the length of the wire will result in an increase in the fundamental frequency of the standing wave produced.

d Increasing the slotted masses would increase the tension in the string, and thereby increase the frequency as $f \propto \sqrt{r}$.

6 Apply equation:

$$L = n\frac{\lambda_n}{2}$$

Rearrange for the required λ:

$$\lambda_n = \frac{2L}{n}$$

Insert known values:

$$\lambda_1 = \frac{2 \times 0.12\ \text{m}}{1}$$

Calculate the answer to the correct number of significant figures:

$\lambda_1 = 0.24\ \text{m}$

7 From the problem, we can construct two equations:

$f_n = 300\ \text{Hz} = nf_1$ (1)

and

$f_{n+1} = 360\ \text{Hz} = (n+1)f_1$ (2)

Rearrange equation (1) for *n:*

$$n = \frac{300\ \text{Hz}}{f_1}$$

Rearrange equation (2) for *n:*

$$n = \frac{360\ \text{Hz} - f_1}{f_1}$$

Equate the two *n*s:

$$\frac{300\ \text{Hz}}{f_1} = \frac{360\ \text{Hz} - f_1}{f_1}$$

Cancel the denominators on both sides:

$300\ \text{Hz} = 360\ \text{Hz} - f_1$

Rearrange to make the required f_1 the subject:

$f_1 = 360\ \text{Hz} - 300\ \text{Hz}$

Calculate the answer:

$f_1 = 60\ \text{Hz}$

LEARNING CHECK 16.3

DESCRIBING

1 **a** An open pipe has both ends open to the external atmosphere, while a closed pipe has one end open to the external atmosphere and the other end closed.

b The wavelength of the fundamental frequency of an open pipe is two times the length of the pipe, whereas the wavelength of the fundamental frequency of a closed pipe is equal to four times the length of the pipe.

APPLYING

2 D

3 C

4 Apply the closed air pipe frequency formula:

$$f_n = (2n-1)\frac{v}{4L}$$

Rearrange the equation for the required *v:*

$$v = \frac{4f_nL}{(2n-1)}$$

Insert known values:

$$v = \frac{4 \times 256\ \text{Hz} \times 0.31\ \text{m}}{(2 \times 1 - 1)}$$

Calculate the answer:

$v = 317.44\ \text{m s}^{-1}$

Give the answer to the correct number of significant figures:

$v = 320\ \text{m s}^{-1}$

5 Apply the closed air pipe frequency formula:

$$f_n = (2n-1)\frac{v}{4L}$$

Rearrange the equation for the required L:

$$L = (2n-1)\frac{v}{4f_n}$$

Insert known values:

$$L=\left(2\times1-1\right)\frac{340\text{ m s}^{-1}}{4\times5000\text{ Hz}}$$

Calculate the answer:

$L=0.017$ m

CHAPTER EXAM

MULTIPLE CHOICE

1	D	**2**	C	**3**	B	**4**	A	**5**	B
6	B	**7**	B	**8**	B	**9**	A	**10**	B

SHORT RESPONSE

11 **a** Apply the equation:

$f_n=nf_1$

So, the frequencies of the next three harmonics are:

$f_2=2\times f_1=2\times15\text{ Hz}=30\text{ Hz}$

$f_3=3\times f_1=3\times15\text{ Hz}=45\text{ Hz}$

$f_4=4\times f_1=4\times15\text{ Hz}=60\text{ Hz}$

b Apply the equation:

$$f=n\frac{v}{2L}$$

Rearrange for the required v:

$$v=\frac{2Lf_n}{n}$$

Insert known values:

$$v=\frac{2\times3\text{ m}\times15\text{ Hz}}{1}$$

Calculate the answer:

$v=90\text{ m s}^{-1}$

c Apply the equation:

$$L=n\frac{\lambda_n}{2}$$

Rearrange for the required λ:

$$\lambda_n=\frac{2L}{n}$$

Insert known values:

$$\lambda_n=\frac{2\times3\text{ m}}{1}$$

Calculate the answer to the correct number of significant figures:

$\lambda_1=6.0$ m

12 Apply the formula:

$$f_n=n\frac{v}{2L}$$

Rearrange for the required L:

$$L=n\frac{v}{2f_n}$$

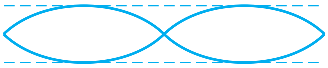
Insert known values:

$$L=1\times\frac{343\text{ m s}^{-1}}{2\times280\text{ Hz}}$$

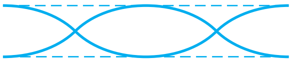
Calculate the answer:

$L=0.61$ m

13 **a** Pressure variation:



b Particle displacement:



14 Apply the equation:

$$f_n=n\frac{v}{2L}$$

Insert known values to calculate the fundamental frequency emitted by the pipe:

$$f_1=1\times\frac{340\text{ m s}^{-1}}{2\times2.2\text{ m}}=77.27\text{ Hz}$$

Since the fundamental frequency is within the range of human hearing, humans will be able to discern the frequency when n = 1.

Rearrange the equation for n:

$$n=\frac{2Lf_n}{v}$$

Insert known values for the highest frequency of human hearing:

$$n=\frac{2\times2.2\text{ m}\times20\,000\text{ Hz}}{340\text{ m s}^{-1}}=258.82$$

This means that the highest harmonic that will be heard is $n=258$.

Therefore, the human ear will be able to hear 258 vibrational modes of the pipe.

CROSS-CHAPTER QUESTION

15 **a** Apply the equation:

$$L=\left(2n-1\right)\frac{\lambda_n}{4}$$

Rearrange for the required λ

$$\lambda_n=\frac{4L}{\left(2n-1\right)}$$

Insert known values and calculate the answers:

$$\lambda_1=\frac{4\times2\text{ m}}{\left(2\times1-1\right)}=8.0\text{ m}$$

$$\lambda_2=\frac{4\times2\text{ m}}{\left(2\times2-1\right)}=2.67\text{ m}$$

$$\lambda_3=\frac{4\times2\text{ m}}{\left(2\times3-1\right)}=1.6\text{ m}$$

b Apply the equation:

$$f_n=\frac{v}{\lambda_n}$$

Calculate the answers:

$$f_1=\frac{340\text{ m s}^{-1}}{\lambda_1}=\frac{340\text{ m s}^{-1}}{8\text{ m}}=42.5\text{ Hz}$$

$$f_2 = \frac{340\ \text{m s}^{-1}}{\lambda_2} = \frac{340\ \text{m s}^{-1}}{2.667\ \text{m}} = 127\ \text{Hz}$$

$$f_3 = \frac{340\ \text{m s}^{-1}}{\lambda_3} = \frac{340\ \text{m s}^{-1}}{1.6\ \text{m}} = 213\ \text{Hz}$$

CHAPTER 17 LIGHT

LEARNING CHECK 17.1

DESCRIBING

1 The wave model of light, the ray model of light and the particle model of light

2 A photon is the particle used to describe some of the behaviour of light.

3 The ray model assumes light travels in straight lines that change direction when they interact with matter; the wave model assumes that light travels as a wave through a medium or a vacuum with a velocity dependent on the properties of the medium; the particle model assumes that light travels in the form of particles that can be absorbed when they interact with matter.

APPLYING

4 'What is light?' is a misleading question because light exhibits wave–particle duality. Instead, the question that should be asked is 'How does light behave?'

LEARNING CHECK 17.2

DESCRIBING

1 The electromagnetic wave model suggests that light is a three-dimensional transverse wave consisting of oscillations in the electric and magnetic fields of its medium.

2 A luminous material emits light while a non-luminous material reflects light.

3 The electromagnetic wave model is very useful in describing the behaviour of light in many situations, including polarisation, reflection, refraction and diffraction.

4 Two adjacent light rays that are emanating from a very distant point source can be considered parallel, as their relative angles of travel are very similar.

5 If light is considered as a wave, the intensity of light as a function of its distance from the source can be modelled using the same concepts as mechanical waves. That is, the intensity of light is indirectly proportional to the square of the distance from the source.

APPLYING

6 Apply the formula:

$c = f\lambda$

Rearrange for the required λ:

$$\lambda = \frac{c}{f}$$

Insert known values:

$$\lambda = \frac{3.0\times10^{8}\ \text{m s}^{-1}}{5.0\times10^{14}\ \text{Hz}}$$

Calculate the answer:

$\lambda = 6.0\times10^{-7}\ \text{m}$

7 Apply the intensity formula at the first point:

$$I_1 = \frac{P}{r_1^2} \qquad (1)$$

Apply the intensity formula at the second point:

$$I_2 = \frac{P}{r_2^2} \qquad (2)$$

Write down the relationship between r_1 and r_2:

$$r_2 = 1.5\times r_1 \qquad (3)$$

Substitute equation (3) into equation (2):

$$I_2 = \frac{P}{(1.5r_1)^2}$$

Expand the brackets:

$$I_2 = \frac{P}{2.25\times r_1^2} = \frac{1}{2.25}\times\frac{P}{r_1^2} \qquad (4)$$

Substitute equation (1) into equation (4):

$$I_2 = \frac{1}{2.25}\times I_1$$

Insert known values:

$$I_2 = \frac{1}{2.25}\times 200\ \text{W m}^{-2}$$

Calculate the answer:

$I_2 = 89\ \text{W m}^{-2}$

8 To calculate the velocity of light in the experiment, both the distance travelled and the time taken need to be known. The distance could be physically measured, and the time taken could be calculated by measuring the rotational velocity of the wheel when it allows a light ray to pass through its teeth.

LEARNING CHECK 17.3

DESCRIBING

1 The orientation in one direction of the electrical part of electromagnetic waves perpendicular to the direction of travel

2 Longitudinal waves cannot be polarised because their oscillations can only be in one direction: parallel to the direction of travel.

3 Both the polariser and the analyser only allow light waves of one polarisation to pass. The polariser selects the orientation of interest and the analyser is used to show the decrease in intensity at all other orientations.

APPLYING

4 Polarised sunglasses reduce the intensity of light reaching the eyes by reflecting all light that is not aligned with the direction of the polariser.

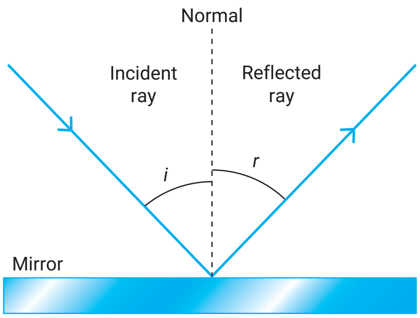
5 This occurs because disturbances in the electric field of the media through which light waves are travelling oscillate in one orientation, so if the analyser starts from dark, it must be orientated perpendicularly to the orientation of the electric field. A quarter turn will make the orientations parallel and light will pass. Another quarter turn will once again cause the orientations to be perpendicular.

LEARNING CHECK 17.4

DESCRIBING

1 The incident ray, the normal to the surface at the point of reflection and the reflected ray all lie in the same plane.

The angle of incidence is equal to the angle of reflection.



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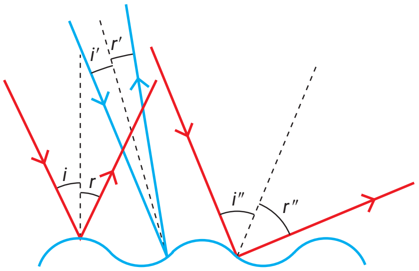
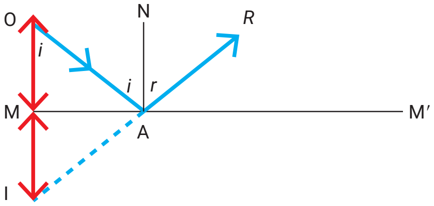
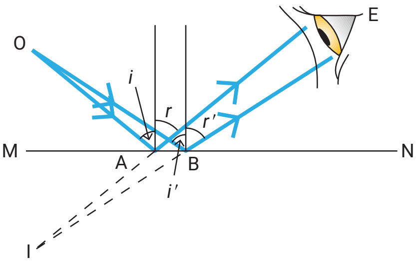


APPLYING

3

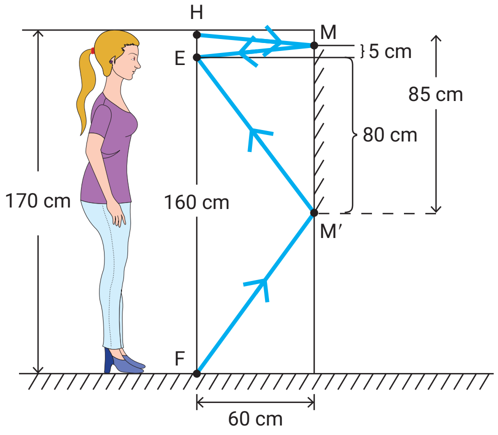


4



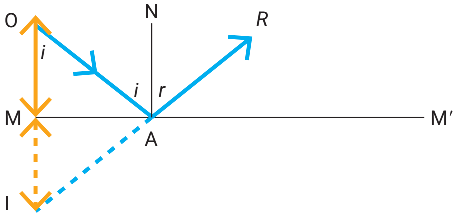
ANALYSING

5



From the image, we see that the minimum height is 85 cm.

6



In ΔAMO:

$\angle AOM = i$ (alternative angle between parallel lines AN and MO)

$\angle OAM = 90° - i$ (complementary angles in right triangle)

along the line IAR:

$\angle MAI + (90° - i) + i + r = 180°$ (angles on a straight line)

$\Rightarrow \angle MAI + 90° + i = 180°$ $(r = i)$

$\Rightarrow \angle MAI = 90° - i$

In ΔAMI:

$\angle MIA = i$ (complementary angles in right triangle)

$\Rightarrow$ ΔAMO and ΔAMI are similar (all angles the same)

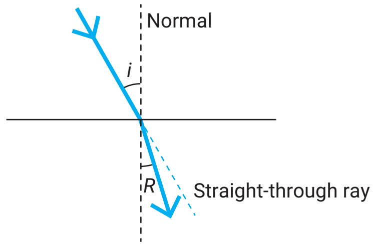
$\Rightarrow$ ΔAMO and ΔAMI are congruent (AM is common)

$\Rightarrow$ MO = MI

LEARNING CHECK 17.5

DESCRIBING

1 **a–c**



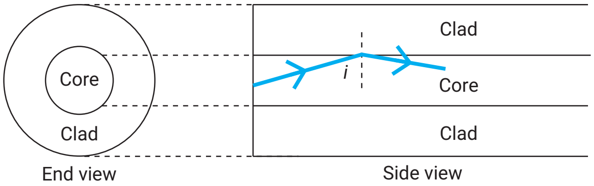
2 Snell's law: $\frac{\sin i}{\sin r} = \text{constant}, n$

3 **a** The absolute refractive index is $\frac{\sin i}{\sin r}$ for light travelling from a vacuum into the medium.

b The refractive index varies slightly with wavelength.

4 The absolute refractive index is relative to a vacuum, taken to be the absolute medium.

5



6 A concave lens is a lens which is thinner in the centre and a convex lens is thicker in the centre. A concave lens diverges incoming parallel rays and a convex lens converges incoming parallel rays.

APPLYING

7 **a** **i** Apply equation:

$c = f\lambda$

Rearrange for the required f:

$f = \frac{c}{\lambda}$

Insert known values:

$f = \frac{3.0 \times 10^{8}\,\text{m s}^{-1}}{981 \times 10^{-9}\,\text{m}}$

Calculate the answer:

$f = 3.06 \times 10^{14}\,\text{Hz}$

ii The frequency remains constant in both media so $f = 3.06 \times 10^{14}$ Hz.

b Apply Snell's law:

$\frac{v_1}{v_2} = \frac{n_2}{n_1}$

Rearrange for the required v_2:

$v_2 = v_1 \frac{n_1}{n_2}$

Insert known values:

$v_2 = 3.0 \times 10^{8}\,\text{m s}^{-1} \times \frac{1.00}{1.39}$

Calculate the answer:

$v_2 = 2.16 \times 10^{8}\,\text{m s}^{-1}$

c Apply Snell's law:

$\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$

Rearrange for the required $\sin r$:

$\sin r = \sin i \frac{n_1}{n_2}$

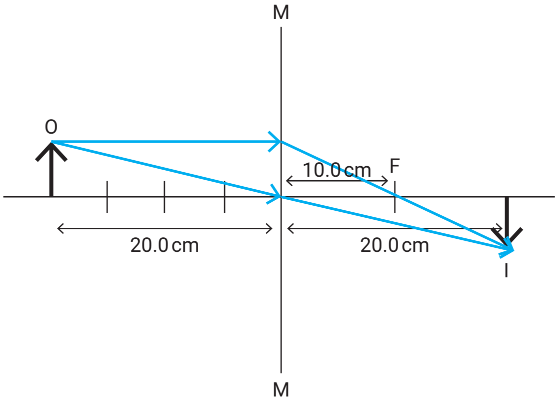
Insert known values:

$\sin r = \sin 25° \times \frac{1.00}{1.39}$

Calculate the answer:

$r = 17.7°$

8



The object lies a distance of 20.0 cm on the opposite side of the lens.

ANALYSING

9 **a** Apply Snell's law for total internal reflection:

$\frac{\sin\theta_c}{\sin 90°} = \frac{n_2}{n_1}$

Rearrange for sin θ_c:

$\sin\theta_c = \sin 90° \times \frac{n_2}{n_1}$

Insert known values:

$\sin\theta_c = \sin 90° \times \frac{1.480}{1.495}$

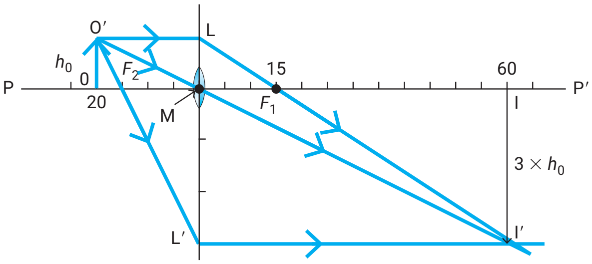
Calculate the answer:

$\theta_c = 81.88°$

b $r = 90° - 81.88°$

$= 8.12°$

10

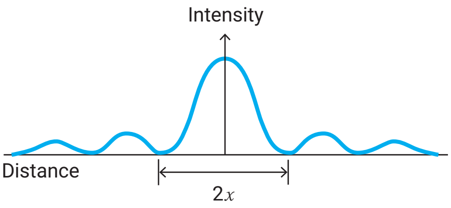


The focal distance of the lens is 15 cm.

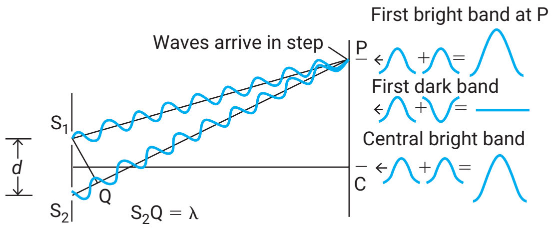
LEARNING CHECK 17.6

DESCRIBING

1 **a**



b



2 **a** Path difference = $n\lambda$ for n values of 1, 2, 3, …

b Path difference = $(n - \frac{1}{2})\lambda$ for n values of 1, 2, 3, …

3 The distance between consecutive bright and dark fringes decreases.

APPLYING

4 The second minimum (destructive interference) corresponds to the path difference associated with $n = 2$.

Apply the destructive interference formula path difference = $(2n - 1)\ \frac{\lambda}{2}$.

Rearrange for the unknown λ:

$$\lambda = \frac{2 \times \text{path difference}}{(2n-1)}$$

Insert known values:

$$\lambda = \frac{2 \times 750\text{ nm}}{(2 \times 2 - 1)}$$

Calculate the answer:

$\lambda = 500$ nm

CHAPTER EXAM

MULTIPLE CHOICE

1	C	**2**	C	**3**	B	**4**	C	**5**	D
6	B	**7**	C	**8**	C	**9**	C	**10**	D

SHORT RESPONSE

11 Apply the intensity formula at the first point:

$$I_1 = \frac{P}{r_1^2} \qquad (1)$$

Apply the intensity formula at the second point:

$$I_2 = \frac{P}{r_2^2} \qquad (2)$$

Write down the relationship between r_1 and $r_{2:}$

$$r_2 = 3 \times r_1 \qquad (3)$$

Substitute equation (3) into equation (2):

$$I_2 = \frac{P}{(3r_1)^2}$$

Expand the brackets:

$$I_2 = \frac{P}{9r_1^2} = \frac{1}{9} \times \frac{P}{r_1^2} \qquad (4)$$

Substitute equation (1) into equation (4):

$$I_2 = \frac{1}{9} \times I_1$$

Insert known values:

$$I_2 = \frac{1}{9} \times 400\text{ W m}^{-2}$$

Calculate the answer:

$I_2 = 44\text{ W m}^{-2}$

12 For angle a:

Apply Snell's law:

$$\frac{\sin i}{\sin r} = \frac{n_{\text{glass}}}{n_{\text{air}}}$$

Substitute in values from the question:

$$\frac{\sin 42}{\sin a} = 1.52$$

Rearrange for a:

$$\sin a = \frac{0.67}{1.52}$$

$a = 26.15°$

For angle b:

angle b = angle a

$\therefore$ angle $b = 26.15°$

For angle c:

Apply Snell's law:

$$\frac{\sin i}{\sin r} = \frac{n_{\text{air}}}{n_{\text{glass}}}$$

Substitute in values from the question:

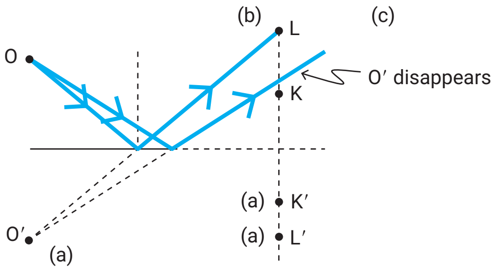
$$\frac{\sin 26.15}{\sin c} = \frac{1}{1.52}$$

Rearrange for c:

$\sin c = \sin 26.15 \times 1.52$

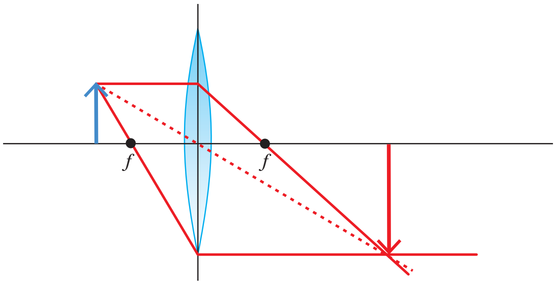
$c = 42°$

13 **a**



b At a point between L and K the image of O disappears.

14 a



b The image is magnified, inverted, real.

CROSS-CHAPTER QUESTION

15 Calculate the distance travelled by light using the distance–velocity formula:

$$s = v \times t$$
$$= 3 \times 10^8 \text{ m s}^{-1} \times 0.01 \text{ s}$$
$$= 3 \times 10^6 \text{ m}$$

Calculate the time that it takes sound to travel this distance by rearranging the distance–velocity formula:

$$t = \frac{s}{v}$$
$$= \frac{3 \times 10^6 \text{ m}}{343 \text{ m s}^{-1}}$$
$$= 8764 \text{ s}$$
$$= 146 \text{ min} = 2.43 \text{ h}$$

GLOSSARY

A

absolute refractive index a measure of the refrangibility of a medium placed in a vacuum and subjected to an incident ray of light

absolute uncertainty the magnitude of the difference between the observed/measured value and the true value

absolute zero the theoretical lowest possible temperature; −273.15°C on the Celsius scale or 0 K on the absolute or kelvin scale

acceleration the rate of change of velocity (vector); magnitude of rate of change of speed (scalar) with respect to time

accepted value the value of a substance or quantity that is universally agreed as being a best estimate due to multiple and highly accurate measurements

accuracy the degree to which the result of a measurement, calculation or specification conforms to the correct value or a standard

action-at-a-distance forces a non-contact force

activity a measure of the magnitude of radioactive emissions; the number of emissions per second, measured in the SI unit Bq

alpha particle a particle made up of two neutrons and two protons; a helium nucleus

alternating current (AC) current that changes direction periodically, typically 50 oscillations per second (50 Hz)

amplitude the maximum displacement of a particle in a wave from its mean position; units: m

analyser material that allows or stops polarised electromagnetic radiation

angle of incidence the angle made between an incident wave and a normal drawn to the surface at the point of incidence

angle of reflection the angle made between a reflected wave and a normal drawn to the surface at the point of incidence

angle of refraction (*r*) the angle that a refracted ray makes with the normal

anthropogenic human-derived; caused by human activity

antineutrino an elementary particle that accompanies β^- decay

antinode a point along a standing wave at which the wave has maximum amplitude; the result of a crest overlapping a crest or a trough overlapping a trough

apparent position the position that an object appears to an observer, which may be different from its actual position due to the refraction of its light waves

artificial transmutation the conversion of one chemical element or isotope into another through a synthetic process, typically through bombarding a nucleus with slow (thermal) neutrons to cause fission events

atmosphere a unit of pressure; 1 atmosphere is the standard pressure at the surface of Earth

atmospheric refraction the refraction of light rays as they pass through Earth's atmosphere

atom a particle; originally thought to be indivisible, but now known to comprise numerous smaller particles

atomic mass number the total number of protons and neutrons in a nucleus (A)

atomic model a series of descriptions relating to the fundamental structure of matter

atomic number the number of protons in a nucleus (Z)

atomic weight (relative atomic mass) the weighted average of all the masses of the different nuclides in a pure, naturally occurring sample of the element

average speed the one (constant) speed that would allow a particle to cover the total of the various distances of a journey in a given time interval

B

body wave a seismic wave that travels through the body of Earth

boiling point the temperature at which a substance undergoes a phase change from liquid to gas (vaporises)

Boltzmann distribution a formula showing the distribution of energy among the particles of a system

bombarding radiation radiation composed of particles, such as alpha particles or neutrons, that are bombarded at the nucleus to force transmutation and radioactive decay

Brownian motion the random motion of small particles suspended in a fluid as a result of being bombarded by the particles of the fluid

C

calorie the amount of heat energy required to raise the temperature of 1 g of water by 1°C; 1 cal = 4.186 J

calorimeter a highly insulated container that prevents heat energy being lost to the environment, used to measure quantities of heat

centre of mass the point in an extended particle where all the mass can be considered to be concentrated

chromatic dispersion the effect of different colours refracting by different amounts in the same medium; colours spreading

circuit breaker an electromechanical switch that trips when there is an overload; safety protection against overload

cladding the outer glass of optical fibre

closed pipe a pipe that is open at one end and closed at the other end

closed system a system that can lose energy but not mass to its surroundings

collision an interaction between two objects subject to action–reaction pairs of forces

combination circuit a circuit that contains both series and parallel components

compression a region of high pressure in a mechanical wave

condensation the phase change from gas to liquid

condenser a vessel that removes heat from a gas by allowing it to turn back into a liquid

conduction the process by which energy is transferred through the collision of particles

conductor a material of low resistance that allows the flow of electrons (e.g. metals)

constructive interference the interference of in-phase waves resulting in an increased displacement at the point of overlap

contact force a force applied by one object on another when they are close enough to appear to be touching

continuous wave repeating waves passing through a medium

controlled chain reaction a chain of nuclear reactions that are controlled to limit the rate at which they occur. In steady state (reaction rate held constant), an average of one neutron from each reaction goes on to cause another reaction. This is the case for a nuclear power reactor running at constant power output

convection the process by which energy is transferred through the bulk motion of a fluid

convection cell the condition that occurs when there are density differences within a fluid; the density differences result in rising and falling currents

convection current fluid circulating as a result of heating at a point or localised region; movement of a fluid because of convection

conventional current the convention to describe electrical current as the flow of positive charge

converging (convex) lens a lens that is thicker in the middle than at the ends

coplanar in the same plane

core the inner glass of optical fibre

Coulomb's law states that the force of attraction or repulsion between two charges is inversely proportional to the square of its distance

crest the positive peak of a wave; unit: m

critical angle the angle of incidence for which the angle of refraction is 90° (total internal reflection occurs); beyond the critical angle, reflection but not refraction occurs

current (*I*) the rate of flow of charge, i.e. charge per unit time; $I = \frac{q}{t}$; unit: ampere (A)

D

daughter nuclide the nuclide formed after a parent nuclide has emitted particles from its nucleus; the daughter nuclide is more stable than the parent nuclide

decay the decrease in amplitude when the vibrating source of a wave is removed

deceleration negative acceleration

delocalised valence electrons the outer electrons of metal atoms that are free to move

dependent variable the variable that changes as a result of a change in the independent or controlled variable

deposition the phase change from gas to solid without becoming a liquid

derive to obtain or create from base principles

destructive interference the interference of out-of-phase waves resulting in a decreased displacement at the point of overlap

diffraction the bending of waves around an obstacle

diffuse reflection (scattering) reflection from a rough surface; rays in a beam reflect in different directions

diffusion the spontaneous movement of substances or energies from areas of high concentration to areas of low concentration

direct current (DC) current that is always in one direction

displacement position relative to another position; the difference between two positions specified with respect to an origin; the straight-line distance between the current position of a particle in a wave and its mean position

distance length, measured in metres (m)

diverging (concave) lens a lens that is thicker at the edges than in the middle

Doppler effect the shift in the wavelength and frequency of waves that results from the relative motion of the source and the receiver

driving frequency the vibration of an object that causes a second object to undergo resonance

E

elastic collision a collision between two or more objects in which there is no loss of kinetic energy

elastic potential energy the energy stored in a spring or elastic system

electrical circuit a complete conducting loop through which charge can flow

electromagnetic force the combined electrical and magnetic force acting between charged particles; the force is attractive for unlike charges, and repulsive for like charges

electromagnetic radiation energy that travels as waves and moves at the speed of light

electromagnetic spectrum the continuous spectrum describing all radiation from high energy to low energy and including visible light

electromagnetic wave model a model that states that light acts like a transverse wave that has electric and magnetic components

electromotive force (EMF) a source of potential energy per charge (voltage)

electron a negatively charged subatomic particle with mass 9.11×10^{-31} kg

electron-volt, eV a small energy unit, equivalent to 1.60×10^{-19} J

element a substance made up of atoms with the same number of protons

EMF electromotive force; source of potential energy per charge; unit: volt (V)

energy a fundamental quantity that can be transformed and transferred; it is defined by source or by the way it is measured

energy change (ΔE) energy transfer or transformation; quantity of energy that can be measured

energy efficiency the fraction of input energy that is converted in a thermodynamic process to useful output energy

enrichment a process of separating out U-235 from a sample and adding it to another sample, increasing the proportion of U-235 in natural uranium

epicentre the point on Earth's surface directly above the seismic focus

error the difference between a measured value and true value

evaporation the process in which some particles with high kinetic energy escape the surface of a liquid at a temperature below its boiling point

external combustion engine a device to produce work through the expansion of a fluid that is heated by the combustion of an external fuel source

extraneous variable any variable that is not directly related to the experiment but could affect the results of the experiment

F

first harmonic the simplest mode of vibration that accounts for the fundamental tone

first law of thermodynamics in the universe, energy can neither be created nor destroyed; however, energy can change form and energy can flow from one place to another. The total energy of an isolated system remains constant

fissile capable of being split or divided (e.g. by undergoing fission) (e.g. U-235, U-238, U-233, Pu-239)

fission the process by which heavy nuclei ($Z > 56$) separate into fragments, with the release of energy; typically, fission fragments have quite different masses

fission fragment a nucleus produced as a result of fission; fission product

focal length the distance from lens to focal point

focal point the point to which light is parallel to the axis of a lens is focused

forced vibration the vibration that occurs in an object when it is forced to vibrate by another vibrating object

frame of reference a system within which measurements are made; point of view

frequency (f) the number of whole waves of cycles in one second; unit: Hz or s^{-1}

friction force the force applied by a surface parallel to the surface

fuse a temperature-dependent wire that melts if an overload occurs; safety protection against overload

fusion the process by which nucleons join to form a new nucleus. Nucleosynthesis is the set of fusion reactions that lead from nucleons to a variety of nuclides. This occurs for light elements ($Z < 56$) and energy is released

G

gamma ray high-energy electromagnetic radiation

gravitational force the manifestation of Newton's universal law of gravitation; a force of attraction acting between every mass throughout the universe

gravitational mass the mass of an object that acts at a distance on other masses via gravitational force

gravitational potential energy the energy stored in a system comprising masses subject to gravitational force

gravity the gravitational force applied by Earth's mass on smaller masses on or near Earth; by extension, the force applied by a large celestial mass, such as a moon or a planet, on nearby masses

ground energy state the state in which a nucleus has absorbed no energy, and requires no additional energy to maintain its state

H

half-life the time it takes for half of a radioactive substance to decay

heat the transfer of thermal energy through a substance or between substances

heat conductor a material that readily allows the transfer of heat

heat-conversion system a system that transforms the internal energy of a system

heat engine a system that converts heat energy to work

heat-exchange system any system that transfers heat from a warmer to a cooler place

heating curve a plot of temperature versus time or heat added

heat insulator a material that is a poor conductor of heat

heat pump a system that moves thermal energy from one place to another

heat sink an object or material that moderates the temperature of its surroundings due to its large specific heat capacity

I

ideal gas a theoretical gas whose particles have no attraction to or repulsion from each other

image a picture of an object

impulse the action of a force over a time interval; $\vec{J} = \vec{F}t$

incident wave an incoming wave

independent variable a variable on which another variable is dependent; also called the controlled variable

inertia, inertial mass the tendency of a body to continue in its state of rest or of uniform motion in a straight line

in phase when two waves of equal wavelength have their crests and troughs aligned

instantaneous time a particular moment on a clock

instrumental uncertainty the inherent limitations and potential errors associated with the measuring instruments or tools used in scientific experiments or observations

insulator a material that inhibits the flow of electrons (e.g. rubber)

intensity a measure of the energy per unit time travelling through a unit area perpendicular to the direction of travel

interference wave overlap

intermolecular force an electrostatic force of attraction or repulsion between neighbouring particles of a substance

internal energy the sum of the kinetic energy of the particles in a system and the potential energy stored in a system

interval a change in a quantity, such as time interval, displacement interval or velocity interval

ionising power the ability to ionise nearby atoms; high ionising power means it is likely that nearby atoms will have their electrons stripped

ionising radiation electromagnetic radiation that does ionise nearby atoms and has high energy

isolated system a system that no matter or energy transfers into or out of and in which no energy is created or destroyed

isotopes elements with the same number of protons, but a different number of neutrons in the nucleus

J

joule the SI unit of energy; $1\,\text{J} = 1\,\text{kg}\,\text{m}^2\,\text{s}^{-2}$

K

kilowatt-hour (kWh) a convenient measure of electrical energy equal to the power consumption of 1 kilowatt in 1 hour: $1.0\,\text{kWh} = 3.6 \times 10^6\,\text{J}$

kinetic energy (E_k) the energy of an object resulting from its motion

kinetic particle model the model that explains the properties of the different states of matter; the particles in solids, liquids and gases have different amounts of energy, are arranged differently and move in different ways

Kirchhoff's current law (first law) in an electrical circuit, the total current arriving at a junction is equal to the total current leaving the junction

Kirchhoff's voltage law (second law) for any closed loop in an electrical circuit, the sum of the potential differences must be zero

L

latent heat the heat required to change the state of a substance at its boiling point or melting point without a change in temperature; unit: $\text{J}\,\text{kg}^{-1}$

law of conservation of charge the net charge within an isolated system is constant

law of reflection when a wave is incident upon a surface, the angle of reflection is equal to the angle of incidence

line of best fit a straight line through data points in a graph that best expresses the relationship shown in a scatterplot

longitudinal wave a wave whose particles oscillate about a mean position in the same line as the direction of travel of the wave

luminiferous aether a non-existent substance that was proposed to exist in early wave models of light as the medium through which light could travel

luminous a source that produces light

M

magnification (M) the ratio of image height to object height

mass defect (Δm) the difference in the mass of an atom and the mass of its constituent parts, as expressed in Einstein's mass–energy equation: $\Delta E = \Delta mc^2$

matter a physical substance

maximum trendline a trendline with the greatest gradient that fits within the data within the uncertainty values

mean the average value of a set of values

mechanical wave a wave that requires a physical substance to be able to propagate

medium a substance that allows the transfer of energy from one place to another

melting the phase change from solid to liquid

melting point the temperature at which a substance undergoes a phase change from solid to liquid (melts)

metallic lattice a regular arrangement of large numbers of metal atoms that allows free electrons to move readily

metastable able to remain in a higher energy state for a certain period

minimum trendline a trendline with the smallest gradient that fits within the data within the uncertainty values

moderator light atoms in a nuclear reactor that slow down fast neutrons to thermal speeds, in order to increase the likelihood of further fission events; often heavy water is used

molecule a collection of atoms bound together by chemical bonds

momentum the quantity of motion calculated by the product of mass and velocity; $\vec{p} = m\vec{v}$

N

natural (or free) frequency the vibration frequency that occurs when an object is displaced from its equilibrium position and then left to vibrate by itself

natural transmutation the conversion of one chemical element or isotope into another through natural radioactive decay

negligible so small it can be ignored; very little

neutrino an elementary particle that accompanies β^+ decay

neutron a neutrally charged subatomic particle within the nucleus of an atom

node a point along a standing wave at which the amplitude is zero; the result of a crest overlapping a trough

non-contact force a force applied by one object on another when they are separated by distance

non-ionising radiation electromagnetic radiation that does not ionise nearby atoms and has low energy

non-luminous a source that reflects light

non-ohmic device a component that does not provide a constant resistance: $R \neq \frac{V}{I}$

normal a line drawn perpendicular to a surface

normal force the force applied by a surface at right angles (normal) to the surface

nuclear binding energy the energy needed to disassemble a nucleus into its component nucleons; a measure of stability of a nuclide

nucleon a proton or neutron; a particle that makes up the nucleus of an atom

nucleus the centre of an atom; comprises most of an atom's mass

nuclides elements with the same number of protons and neutrons with the nucleus in the same energy state

O

ohmic device a component with constant resistance (i.e. a device that exhibits a proportional relationship between current and voltage: $R = \frac{V}{I}$)

Ohm's law the physical law that states that the current flowing through a conductor is directly proportional to the voltage across the conductor; i.e. $\frac{V}{I}$ = a constant, where the constant is the resistance of the conductor

opaque not transparent; not able to be seen through

open pipe a pipe that is open at both ends

open system a system that can lose mass and energy to its surroundings

optical centre the centre of curvature of a lens

optical fibre a transparent light guide making use of total internal reflection at a boundary between materials of similar refractive index

out of phase when the crests of a wave align with the troughs of another wave of equal wavelength

P

parallel circuit a circuit with multiple paths that the current can flow through

parent nuclide the original nuclide before emitting particles from the nucleus

Pearson correlation coefficient (*R*) a statistical measure that quantifies the direction and strength of a relationship between two variables

penetrating power the ability to penetrate air, liquids and solids; radiation with high penetrating power can penetrate highly compacted solids

percentage error the difference between a measurement result and an accepted value, expressed as a percentage of the accepted value

percentage uncertainty a measure of the uncertainty of a measurement compared with the size of the measurement, given as a percentage

period (*T*) the time it takes before a wave repeats itself; unit: s

phase change a change in physical state (e.g. solid to liquid)

photon a particle of light

plane mirror a mirror with a plane (flat) reflecting surface

plasma a collection of free-moving electrons and ions that can be accelerated by magnetic and electric fields

point source a single located source from light transmits equally in all directions

polarisation orientation in one direction of the electrical part of electromagnetic waves

polariser material that selects the direction of polarisation

potential difference (*V*) a measure of the potential energy per unit of charge; potential difference and voltage are measured in volts (V); also called voltage: $V = \frac{W}{q}$

potential energy (E_p) the energy available to do work

power (*P*) a measure of the rate of energy transformation; unit: watt (W)

power the rate at which work is done by a system, or the rate at which energy is being transferred

precision the closeness of several independent measurements of the same quantity to each other

primary data data collected directly by a person or group

principal axis the line through both the focus and the centre and perpendicular to the axis of a curved lens

principle of superposition when two or more waves of the same nature travel past a point in a medium, the medium undergoes a resultant displacement at that point, which is the sum of the individual particle displacements due to the waves at that point

proton a positively charged subatomic particle within the nucleus of an atom

pulse a single wavefront travelling through a medium

P wave (or primary) a longitudinal earthquake compression wave that passes through the body of Earth

Q

qualitative non-numerical data; descriptive information

quantitative numerical data; a specific amount

R

radiation energy transfer across space; the process by which heat is transferred without the need for a medium; energy from radioactive atoms

radioactive decay when a nucleus breaks apart; it can happen naturally or be forced by impact from subatomic particles outside the nucleus

radioactivity particles or rays that come from energy rearrangements in a nucleus

random error a variation that affects a measurement in a random way so that successive measured values may reflect small changes from each other

range the difference between the maximum and minimum values of a measured confidence interval

rarefaction a region of low pressure in a mechanical wave

ray a line drawn at right angles to a wavefront and in the direction of travel

ray diagram a diagram that traces the path taken by light

ray model a model that describes light as travelling in rays that can change direction during interactions with matter

real image an image of an object where the rays of the image do not pass through the image itself; the image can be projected onto a screen

refraction the change in direction of a wave when it passes through a boundary between two media of different densities at an angle other than 90°; speed and wavelength also change, frequency remains constant

refractive index a measure of refrangibility; a measure of the relative change of direction of waves or light rays when travelling from one medium to another

refrangibility a measure of how much refraction occurs when light moves into a particular material from a vacuum

regular (or specular) reflection predictable reflection from a very smooth surface; rays in a beam all reflect in the same direction

relative refractive index the comparative difference in refrangibility between two media with different absolute refractive indices

reliability the extent to which the results of assessments are consistent, replicable and free from error

research question a question that directs the scientific inquiry activity; it focuses the research investigation or student experiment, informing the direction of the research, and guiding all stages of inquiry, analysis, interpretation and evaluation

residual current device (RCD) an earth-leakage protection device; safety protection against overload

resistance the opposition to the flow of electrical charge throughout a given material; and the ratio between potential difference and current; unit: ohm (Ω)

resistivity (ρ) a measure of how much a material opposes the flow of charges; unit: Ω m

resonance when an object is made to oscillate at its natural frequency by the vibration of another object that is also vibrating at that natural frequency

resonant frequencies the possible standing wave frequencies of an object

reverberation the effect that occurs when too many sound wave reflections arrive at your ear for you to distinguish between the sounds

root mean square voltage (V_{rms}) AC voltages may be compared to DC voltages by converting the peak voltage to the root mean square voltage, or $V_{rms} = \frac{V_{peak}}{\sqrt{2}}$

S

scalar a quantity specified by one measurement scale only, such as magnitude

secondary data data that is collected by someone else

second law of thermodynamics the direction of heat flow is always from a hotter object to a colder object

seismic focus the underground point from which earthquake energy is released

seismograph a device that records the amplitude and frequency of seismic waves and yields information about Earth and its subsurface structure

semiconductor a material that conducts electricity less readily than a conductor but more readily than an insulator

series circuit a circuit with only one path that the current can flow through

short circuit a connection between two points that allows current to flow with negligible resistance

sinusoidal pattern a pattern that is similar in shape to that of a sine wave

slow (thermal) neutron neutron with kinetic energy of about 0.1–20 keV

solidification the phase change from liquid to solid

S (or secondary) wave a transverse earthquake waves that shakes Earth in directions which are perpendicular to the direction that the wave is travelling; also known as shear waves

specific heat capacity the amount of energy required to increase the temperature of 1 kg by 1°C (or kelvin) of a substance without a change of phase; unit: $J\,kg^{-1}\,K^{-1}$ or $J\,kg^{-1}\,°C^{-1}$

specific latent heat of fusion the heat required to change the state of 1 kg of a substance from a solid to a liquid without a change in temperature

specific latent heat of vaporisation the heat required to change the state of 1 kg of a substance from a liquid to a gas without a change in temperature

speed the time rate of change of distance; magnitude of velocity (scalar) with respect to time

spontaneous happens without any external action; all radioactive materials decay spontaneously, in a random and unpredictable way, and it is impossible to predict when one atom will decay, if at all, in a given period

standing wave (stationary wave) a wave that oscillates in place, without transmitting energy along its extent; has stable points called nodes, where there is no oscillation

static electricity charges at rest, or stationary; typically produced on insulators by friction between two surfaces

strong nuclear force the force required to hold nucleons together, especially to overcome the electrostatic force of repulsion between protons

subatomic particle a particle within an atom

sublimation the phase change from solid to gas without becoming a liquid

superheated steam steam that is held under high pressure and heated to a temperature above the boiling point of water

system any object or set of objects under investigation

systematic error an error that acts to give a consistent offset in data; for example, consistently above or consistently below

T

temperature a measurement of the average kinetic energy of the particles in a substance

thermal conductivity a measure of how efficiently heat can be conducted through a material

thermal current a rising air column of hotter air caused by the process of convection

thermal energy heat; the form of energy that gives rise to an increase in the kinetic energy of particles

thermal equilibrium the condition in which the particles of two or more objects in physical contact have the same temperature and average kinetic energy as each other

thermistor temperature-dependent resistor; used to detect changes in temperature

thermometer a device that measures temperature or a temperature gradient

time interval the time between two measurements of time

total internal reflection the transport and containment of a wave by coherently reflecting it back and forth often in a tube

transmutation the conversion of one chemical element into another as the result of a nuclear reaction, such as neutron capture, or that occurs in spontaneous radioactive decay, such as alpha decay and beta decay

transuranic element an element with an atomic number of over 92 that can only be produced synthetically, and does not exist naturally in the universe

transverse wave a wave whose particles oscillate about a mean position perpendicular to the direction of travel by the wave

trendline a line that represents the general direction or pattern of data points

trough the negative peak of a wave; unit: m

U

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

unstable describes a nucleus that is likely to decay because the strong nuclear force is not large enough to overcome the electrostatic repulsion force

usable energy energy that can be used to perform a desired result; usually in the form of energy to do work

V

validity the extent to which the experiment measures what it is intended to measure

vaporisation the phase change from liquid to gas

vector a quantity that has magnitude and direction; quantity characterised by two or more scales

velocity the rate of change of displacement; speed with direction (vector) with respect to time

vibration mode or harmonic standing wave pattern

virtual image an image of an object where the rays do not pass through the image; the image cannot be projected onto a screen

voltage divider a device used to vary voltage at the output depending on a control resistor; also called a potential divider

W

watt (W) the unit of power; $1\,\text{W} = 1\,\text{J}\,\text{s}^{-1}$

wavefront an imaginary surface joining all points in space that are reached at the same instant by a wave propagating through a medium

wavelength (λ) the distance travelled by a wave before it repeats itself; unit: m

wave model a model that describes light as travelling as waves

wave–particle duality the need to model light as both a wave and a particle

wave velocity (v) the velocity at which a wave crest moves through a medium

weak nuclear force one of the four fundamental forces; acts between subatomic particles (leptons) and is responsible for beta decay

weight the gravitational force on mass; force exerted by mass of Earth on masses ‘near Earth’; by extension, the force by any large mass in the universe, such as the Moon, on any smaller mass ‘nearby’

work (W) the energy transferred due to the action of a force over a distance

Z

zeroth law of thermodynamics if two systems are in thermal equilibrium with a third system, then they must be in thermal equilibrium with each other

INDEX

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