SACE ONE – AUSTRALIAN CURRICULUM

PHYSICS

WORKBOOK
SECOND EDITION

MARIA CARUSO

Essentials education

ADELAIDE TUITION CENTRE

THE AUTHOR

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PUBLISHING INFORMATION

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Preface

This workbook is designed to cover the core topics of the new Stage 1 SACE Subject Outline in order from topic 1 through to topic 6. However, the topics can be taught in any order, as each topic is treated individually.

The worked examples are designed to help model the use and application of the theoretical concepts. The exercises are designed to help consolidate ideas. There are a variety of question types, which range in difficulty. These question types include recalling facts, describing, graphing and explaining. Clear and detailed solutions are provided. This workbook can be used in class or as a supplement at home.

The workbook also addresses *Science as a human endeavour*, providing examples and ideas for further investigation taken from the Subject Outline. Similarly, Student Practical Investigations are referred to in the body of the workbook and in some of the exercises.

I have tried to cover all aspects of the Subject Outline but recognise that while teachers are expected to teach all six topics they may choose which parts of a topic they would like to address with their class. I trust that you will find this workbook valuable to your teaching of this new course.

All students and teachers should refer to the SACE website – **www.sace.sa.edu.au** – for the most up-to-date version of the Subject Outline.

Maria Caruso

September 2018

Contents

Science as a human endeavour

Communication in science is very important. In early times, different units were being used for the same quantities and this lead to misunderstandings and confusion. The metric system began in France around 1795 and was became France's legal system of measurement in 1840. Several international conferences were held after that and this lead to the International System (a modern version of France's metric system) being established in 1960. Australia officially converted to the SI system as recently as 1982.

Gauss, Webber, Thomson and Maxwell were all scientists that contributed to the development of SI units. Investigate what they did.

Estimating physical quantities

You may need to be able to make reasonable and appropriate estimations of physical quantities throughout this course.

For example you may need to estimate the mass of an apple or the running speed of an athlete. Since many physical constants vary in value, a reasonable and appropriate estimation should fall in a range of acceptable values.

Worked Example

Write estimate values for each of the following:

1. the mass of a 747 aeroplane

   300 – 400 tonne

2. the time taken for a ball to fall 10 m

   1.4 – 1.5 seconds

3. the length of an adult human leg

   55 – 85 cm

4. the mass of a tennis ball

   55 – 60 g

Listed below are the ranges of the smallest and largest values for length, mass and time.

Length – Sub-nuclear particles (diameter of and nucleus) 10^{-15} m to the visible universe 10^{25} m

Mass – the mass of electrons 10^{-30} kg to the mass of the universe 10^{50} kg

Time – time for light to pass across a nucleus 10^{-23} s to the age of the universe 10^{18} s

Significant figures (sf)

The precision of a measurement is limited by the equipment used. For example, a ruler with a millimetre scale can give a more precise measurement for the thickness of a book than a ruler that only has a centimetre scale. The ruler with a millimetre scale can measure the width of the book to two significant figures e.g. 22 mm while the other ruler can only give a value of the width of the book to the nearest centimetre or one significant figure i.e. 2 cm.

The value for the same measurement can have a different level of precision. This is often indicated by the number of significant figures.

Interestingly enough, precise measurements do not always lead to an accurate value for a particular quantity. Accuracy is indicated by how close the final answer is to an accepted value for that quantity.

Rules

1. All non-zero digits are significant e.g. 238.9 (4 sf)
2. All zeros between non-zero digits are significant e.g. 2004.67 (6 sf)
3. For large numbers, the zeros after the non-zero digits are not significant e.g. 4500 (2 sf)
4. For numbers less than one, zeros before the non-zero digits are not significant e.g. 0.0006 (1sf) whereas zeros to the right of the non-zero digits are significant e.g. 0.000600 (3 sf)

   Standard form helps give zeros significance. For example, 3000 has one significant figure but it if it is written as 3.00×10^3, it is considered to have three significant figures.

5. When **adding or subtracting** a series of measurements e.g. 23.55 + 1.2 + 2.766 = 27.516

   The answer can only be as accurate as the value with the least accurate place value i.e. one decimal place

   The answer is therefore rounded off to 27.5

6. When **multiplying or dividing** a series of measurements, the answer is rounded off to the least number of significant figures in the original data e.g. 23.04 × 3.5 = 80.64

   This value is rounded off to 81 (2 sf).

In general try to keep your rounding off to a minimum. Save values in the calculator's memory and round off your final answer.

Topic 1: Linear motion and forces

1.1 Motion under constant acceleration

Science understanding

1. Linear motion with constant velocity is described in terms of relationships between measurable scalar and vector quantities, including displacement, distance, speed, and velocity
    - Solve problems using $v = \frac{s}{t}$
    - Interpret solutions to problems in a variety of contexts.
    - Explain and solve problems involving the instantaneous velocity of an object.
2. Acceleration is a change in motion. Uniformly accelerated motion is described in terms of relationships between measurable scalar and vector quantities, including displacement, speed, velocity, and acceleration.
    - Solve problems using equations for constant acceleration and $a = \frac{\Delta v}{\Delta t}$.
    - Interpret solutions to problems in a variety of contexts.
    - Make reasonable and appropriate estimations of physical quantities in a variety of contexts.
3. Graphical representations can be used qualitatively and quantitatively to describe and predict aspects of linear motion.
    - Use graphical methods to represent linear motion, including the construction of graphs showing:
        - position *versus* time
        - velocity *versus* time
        - acceleration *versus* time.
    - Use graphical representations to determine quantities such as position, displacement, distance, velocity, and acceleration.
    - Use graphical techniques to calculate the instantaneous velocity and instantaneous acceleration of an object.
4. Equations of motion quantitatively describe and predict aspects of linear motion.
    - Solve and interpret problems using the equations of motion:

      $v = v_0 + at$

      $s = v_0 t + \frac{1}{2}at^2$

      $v^2 = v_0^2 + 2as$
5. Vertical motion is analysed by assuming that the acceleration due to gravity is constant near Earth's surface.
6. The constant acceleration due to gravity near the surface of the Earth is approximately $g = 9.80\ ms^{-2}$.
    - Solve problems for objects undergoing vertical motion because of the acceleration due to gravity in the absence of air resistance.
    - Explain the concept of free-falling objects and the conditions under which free-falling motion may be approximated.
    - Describe qualitatively the effects that air resistance has on vertical motion.
7. Use equations of motion and graphical representations to determine the acceleration due to gravity.

Speed

The speed of an object is defined as the distance the object travels per unit time.

The equation for calculating speed is $speed = \frac{distance}{time}$

Using symbols we write $v = \frac{s}{t}$

where v = speed, s = distance or how far the object moves and t = time over which the object moves.

If the distance is in kilometres and the time is in hours, the unit of speed is kmh^{-1}.

If the distance is in metres and the time is in seconds, the unit of speed is ms^{-1}.

Note: It is better to write kmh^{-1} instead of km/h and ms^{-1} instead of m/s.

The standard international (SI) unit of speed is ms^{-1}.

Different types of speed

Average speed

Calculating the speed of an object often involves calculating an average speed. Average speed does not take into account any changes in motion. It involves the total distance travelled and the total time. It doesn't indicate whether the object speeds up, slows down or stops during the journey. For instance, consider a car that travels between two sets of traffic lights. The car speeds up as it takes off from the first set of lights and slows down as it approaches the second set of lights. An average speed does not take these changes of motion into account.

$$v_{av} = \frac{s_{total}}{t_{total}}$$

Constant speed

Constant speed means that an object travels exactly the same distance every unit of time. Light travels with a constant speed of 3.00×10^8 metres every second. Sound waves travel with a constant speed of 330 metres every second in air (this can change depending on the density of the air). If a car is travelling with a constant speed of 60 kmh^{-1}, this means that it travels **exactly** 60 kilometres every hour.

Figure 1.1.1

Figure 1.1.1 illustrates constant motion or speed. The dots are equally spaced, which means the object travels the same distance per unit of time.

Instantaneous speed

Instantaneous speed is the speed of an object at a particular instant in time. It is what the speedometer in a car measures. As the car speeds up or slows down the needle on the speedometer points to the speed of the car at a particular instant of time.

Science as a human endeavour

Laser guns

Laser guns work by sending out pulses of infra-red laser light towards a moving object, such as a car. The time taken for a pulse to return to the gun is recorded. The distance to the car is calculated using:

$$s_1 = vt = 3 \times 10^8 \times \frac{t_1}{2}$$

The object continues moving, and the time taken for a second pulse to return to the laser gun is recorded. The new distance to the car is calculated using:

$$s_2 = vt = 3 \times 10^8 \times \frac{t_2}{2}$$

The distance travelled by the car between the two pulses is the difference between these two values. The speed of the car is calculated using:

$$v_{ave} = \frac{s_{travelled\ between\ pulses}}{t_{between\ pulses}} = \frac{s_1 - s_2}{t_{between\ pulses}}$$

Investigate other ways of calculating the speed of an object, e.g. radar gun, point-to-point cameras. What are the benefits and limitations?

Running with dinosaurs

How did Robert Alexander (1976) develop a method for determining the gait and speed of dinosaurs?

Common Conversions useful to problem solving

km to m	× 1000 or 10^3
cm to m	÷ 100 or × 10^{-2}
minutes to seconds (s)	× 60
hours to s	× 60 × 60 or × 3600
days to s	× 24 × 60 × 60 or × 86400
kmh^{-1} to ms^{-1}	÷ 3.6
ms^{-1} to kmh^{-1}	× 3.6

Worked examples

1. A dog runs 30 m in 4.0 s. Calculate the average speed of the dog.

   $v = \frac{s}{t} = \frac{30}{4} = 7.5\ ms^{-1}$

2. A marble circles the inside rim of a bowl of radius 15.0 cm five times in 20.0 s.

   Determine the average speed of the marble.

   radius = 15.0 cm = 0.15 m

   (The distance covered is the circumference of the bowl. We calculate the circumference using $2\pi r$)

   t = 20.0 s

   $v = \frac{s}{t} = \frac{2\pi r \times 5}{20} = \frac{2\pi \times 0.15 \times 5}{20} = 0.236\ ms^{-1}$

3. A boat travels 10.0 km in 30.0 minutes.

   (a) Calculate the average speed of the boat in kmh^{-1} and ms^{-1}.

   s = 10.0 km

   t = 30.0 minutes = 30 ÷ 60 = 0.5 h

   $v = \frac{s}{t} = \frac{10}{0.5} = 20.0\ kmh^{-1}$

   20 kmh^{-1} = 20 ÷ 3.6 = 5.56 ms^{-1}

   (b) Calculate the distance travelled by the boat in 6.50 hours.

   s = vt = 20 × 6.5 = 130 km

4. Light travels with a speed of $3.00 \times 10^8\ ms^{-1}$. Calculate the time taken for light to travel from the Sun to Earth, a distance of 1.50×10^{11} m.

   $t = \frac{s}{v} = \frac{1.5 \times 10^{11}}{3 \times 10^8} = 500\ s$

Vector and scalar quantities

Quantities that have **size or magnitude only** are called **scalar** quantities. Examples include mass, time, energy and temperature.

Quantities that have both **magnitude and direction** are called **vector** quantities. One example is force (a push or a pull). This is because an object can be pulled or pushed in a given direction e.g. 5 N east.

We will come across many vector quantities throughout this course. We will deal with each as it arises. Some examples of scalar and vector quantities are summarised in the table below.

Scalar quantities	Vector quantities
distance	displacement
speed	velocity
time	acceleration
mass	force
volume	momentum
temperature	electric field
charge	magnetic field
heat	
energy	
power	

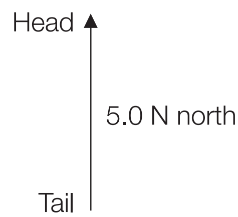
Representing vector quantities

From your Year 10 studies, you will be familiar with a force being a push or pull. Force has magnitude and direction, and is therefore a vector quantity.

A vector quantity is denoted in **bold type** or with an arrow above the symbol.

F = 5.0 N north *or* $\vec{F}$ = 5.0 N north

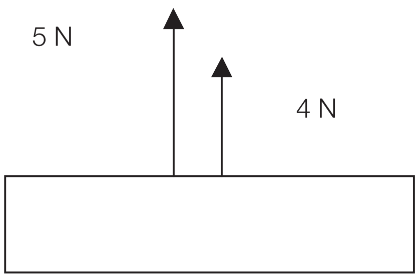
An arrow is used to represent the vector quantity. The **length** of the arrow represents the **magnitude** of the vector and the **arrow head** points in the **direction** of the vector.



Adding vector quantities

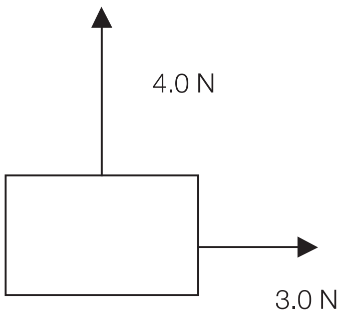
Worked examples

1. 5 N north + 4 N north



9 N north

2. 4.0 N north + 3.0 N east



The total or resultant force is $F_R = 4 \uparrow + 3 \rightarrow$

A ***vector triangle*** is drawn in order to 'add' the two vectors. The vectors are added 'head to tail'. The order doesn't matter.

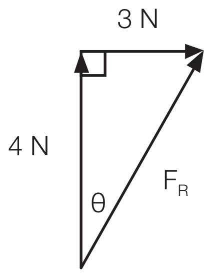
Pythagoras' Theorem is used to find the ***magnitude*** of the resultant force and **trigonometric ratios** are used to find the ***direction.***

$F_R = \sqrt{3^2 + 4^2} = 5N$

$\tan\theta = \frac{opposite}{adjacent} = \frac{3}{4}$

$\theta = \tan^{-1}(\frac{3}{4})$

$\theta = 37^o$



The final answer is expressed with magnitude and direction.

F_R= 5.0 N N37° E

Note: A scale diagram could have been used to solve the above problem.

Displacement and velocity

Distance is how far an object has travelled (or length covered). It is a ***scalar*** quantity because no direction is involved.

Position is the location of a body.

Displacement is the change in position and includes direction. It is a ***vector*** quantity since it involves both magnitude (size) and direction.

Velocity is defined as displacement per unit time. Velocity is a ***vector*** quantity.

Worked examples

1. A man walks 5.0 km in a northerly direction and then 2.0 km in a southerly direction.

(a) State the distance travelled by the man.

7.0 km

(b) State the displacement of the man.

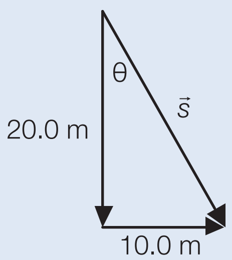
3.0 km North

2. A ferret races 20.0 m south and then 10.0 m east.

(a) Calculate the distance travelled by the ferret.

30.0 m

(b) Calculate the displacement of the ferret.



$$\vec{s} = \sqrt{20^2 + 10^2} = 22.4m$$

$$\tan\theta = \frac{opposite}{adjacent} = \frac{10}{20}$$

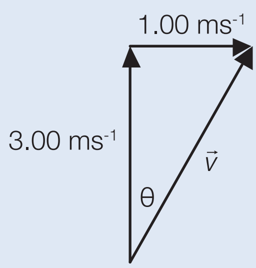
$$\theta = \tan^{-1}(\frac{10}{20})$$

$$\theta = 26.6^o$$

$\vec{s}$ = 22.4 m S26.6°E

3. A boat is rowed with a speed of 3.00 ms^{-1} in a northerly direction. It encounters a water current flowing with a speed of 1.00 ms^{-1} in an easterly direction.

(a) Calculate the resultant velocity of the boat.



$$\vec{v} = \sqrt{3^2 + 1^2} = 3.16ms^{-1}$$

$$\tan\theta = \frac{opposite}{adjacent} = \frac{1}{3}$$

$$\theta = \tan^{-1}(\frac{1}{3})$$

$$\theta = 18.4^o$$

$\vec{v}$ = 3.16 ms^{-1} N18.4°E

(b) Calculate the boat's displacement after 10.0 minutes.

$\vec{s} = \vec{v}t$ = 3.16 × (10 × 60) = 1896m = 1.90 × 10^3 m N18.4°E

(c) Assume that the rower's intention was to row to a destination directly north of his starting point. How far off course is the boat after 10.0 minutes?

$s = vt = 1 \times (10 \times 60) = 600m$ east

(d) How could the rower compensate for the effect of the current?

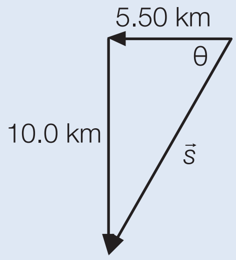
Row into the current with a velocity of 3.16 ms^{-1} N18.4°W

4. A man for his morning fitness routine walks 5.50 km W and then turns and walks 10.0 km S in 3.00 hours and 15.0 minutes. Calculate the

(a) distance travelled by the man.

15.5 km

(b) man's final displacement.



$$\vec{s} = \sqrt{5.5^2 + 10^2} = 11.4km$$

$$\tan\theta = \frac{opposite}{adjacent} = \frac{10}{5.5}$$

$$\theta = \tan^{-1}(\frac{10}{5.5})$$

$$\theta = 61.2°$$

$$\vec{s} = 11.4 \text{ km W}61.2°\text{S}$$

(c) man's average speed for the journey.

$$v = \frac{s}{t} = \frac{15.5}{3.25} = 4.77\ kmh^{-1}$$

(d) man's average velocity for the journey.

$$\vec{v} = \frac{\vec{s}}{t} = \frac{11.4}{3.25} = 3.51\ kmh^{-1}\ \text{W}61.2°\text{S}$$

Subtracting vectors

If 5 N north is represented as $5N\uparrow$, then $-5N\uparrow$ must mean $5N\downarrow$ or 5 N south.

When subtracting a vector, it is added in reverse.

Therefore 5N north – 5 N south = $5N\uparrow -5N\downarrow = 5N\uparrow +5N\uparrow = 10N\uparrow$

Worked Examples

1. $50N\rightarrow -100N\leftarrow = 50N\rightarrow +100N\rightarrow = 150N\rightarrow$
2. $2N\downarrow -3N\downarrow = 2N\downarrow +3N\uparrow = 1N\uparrow$

Acceleration

If an object is not travelling with constant speed (i.e. it is speeding up or slowing down) it is said to be accelerating.

Acceleration is the change in velocity per unit time or the rate of change in velocity.

$$\vec{a} = \frac{\Delta\vec{v}}{\Delta t} = \frac{\vec{v}_f - \vec{v}_i}{\Delta t}$$

where $\Delta\vec{v}$ = change in velocity

$\vec{v}_f$ = final velocity in ms^{-1}

$\vec{v}_i$ = initial velocity in ms^{-1}

Δt = time taken for the change in velocity in seconds

Since velocity is a ***vector*** quantity, then the acceleration will also have a magnitude and direction and is therefore considered a ***vector*** quantity.

Notes:

1. If direction is not involved i.e. only the speed changes, then the acceleration of an object is the change in speed per unit time.
2. Although the speed of an object may be constant, a change in direction constitutes a change in velocity. The object is said to accelerate.
3. A constant acceleration of 3 ms^{-2} means that the object speeds up by 3 ms^{-1} every second i.e. the speed increases as follows after every second:

   0 ms^{-1}, 3 ms^{-1}, 6 ms^{-1} ,9 ms^{-1}, 12 ms^{-1}, 15 ms^{-1}…
4. If an object speeds up, the acceleration is ***positive***.
5. If an object slows down, the acceleration is ***negative***. This is sometimes called a deceleration.
6. The acceleration due to gravity is constant near the surface of the Earth and is g = 9.80 ms^{-2} towards the centre of the Earth.

Worked examples

1. A car accelerates from rest to a speed of 60.0 kmh^{-1} in 5.00 seconds. Calculate the magnitude of the acceleration of the car.

$$a = \frac{v_f - v_i}{\Delta t} = \frac{\frac{60}{3.6} - 0}{5} = 3.33 ms^{-2}$$

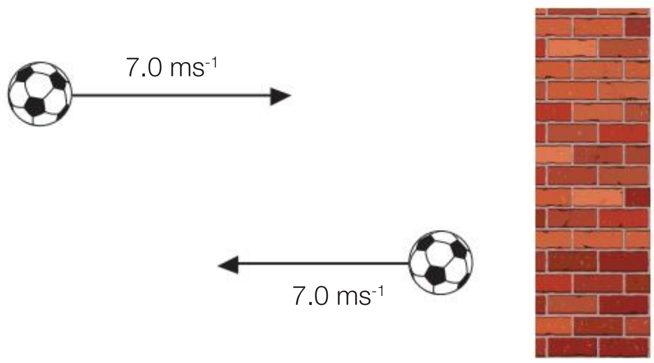
2. A truck can accelerate from rest at a rate of 4.00 ms^{-2}. Calculate its speed after 8.00 seconds. Answer in ms^{-1} and kmh^{-1}.

$$a = \frac{v_f - v_i}{\Delta t} \qquad v_f = v_i + at = 0 + 4 \times 8 = 32.0 ms^{-1} = 115 kmh^{-1}$$

3. A ball is thrown vertically into the air with a speed of 10.0 ms^{-1}. Calculate the time taken to reach its maximum height.

$$a = \frac{v_f - v_i}{\Delta t} \qquad \Delta t = \frac{v_f - v_i}{a} = \frac{0 - 10}{-9.8} = 1.02 s$$

4. A ball collides with a wall as shown.



(a) Calculate the ball's change in velocity.

$\Delta \vec{v} = \vec{v}_f - \vec{v}_i = 7 \leftarrow - 7 \rightarrow = 7 \leftarrow + 7 \leftarrow = 14 ms^{-1} \leftarrow$ (90° away from the wall)

(b) If the collision takes 0.120 s, calculate the acceleration experienced by the ball.

$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \frac{14}{0.12} = 120 ms^{-2} \leftarrow$$

Helpful online resources

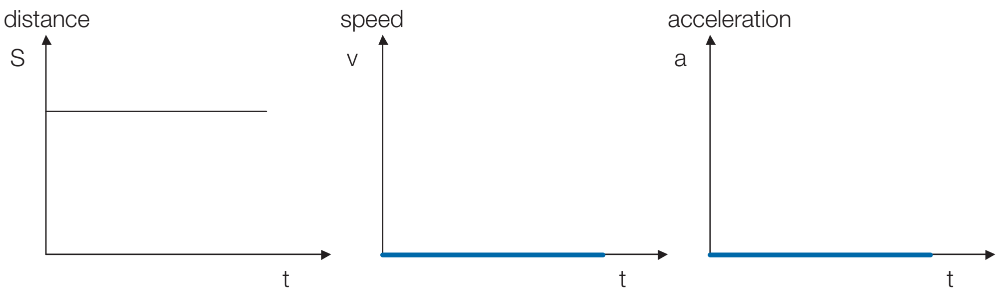
Explore the relationship between velocity and acceleration using the computer interactive 'The Maze Game'.

https://phet.colorado.edu/en/simulation/legacy/maze-game

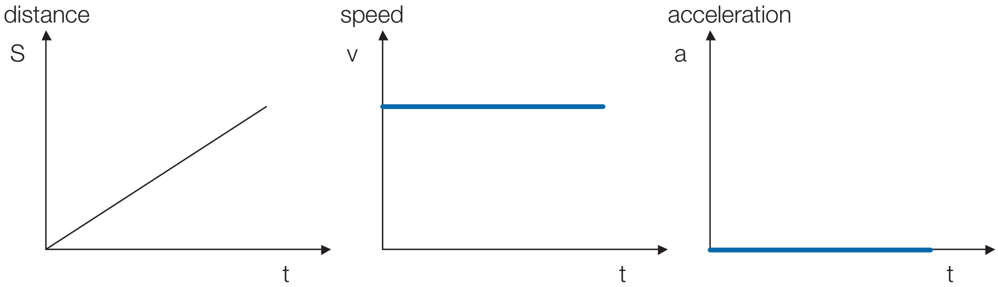
Graphing Motion

Instead of using lengthy descriptions to describe the motion of an object, motion can be represented graphically. In addition, the slope and the area under the graph can have a physical significance. The graphs shown in the section below represent the distance vs time, speed vs time and acceleration vs time graphs for a stationary object, and object travelling with constant speed and an object experiencing a scalar acceleration.

Stationary Motion



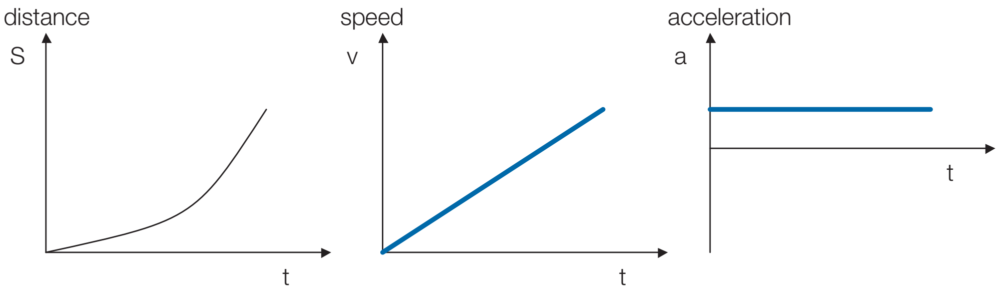
Constant Speed



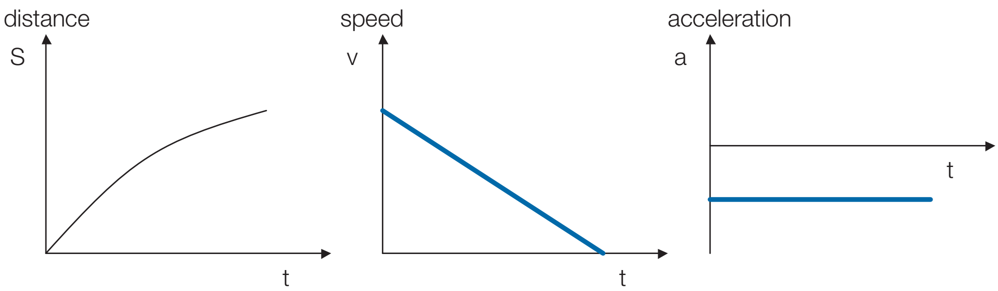
The **gradient** of a distance vs time graph represents **speed**.

$$gradient = \frac{rise}{run} = \frac{\Delta s}{\Delta t}$$

Constant acceleration



The distance vs time graph above indicates that the distance travelled per unit time increases. This represents **accelerated** motion.



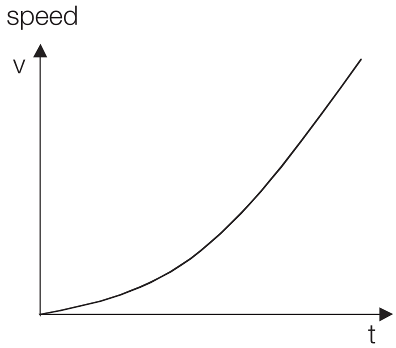
The distance vs time graph above represents a negative acceleration or **decelerated** motion as the distance travelled per unit time is decreasing.

The **gradient of the tangent** of a distance vs time graph at any particular time represents the **instantaneous speed** at that time. We write

$$v = \frac{\Delta s}{\Delta t} \quad as \quad \Delta t \to 0$$

The **area** under of a speed vs time graph represents **distance**.

Non constant acceleration



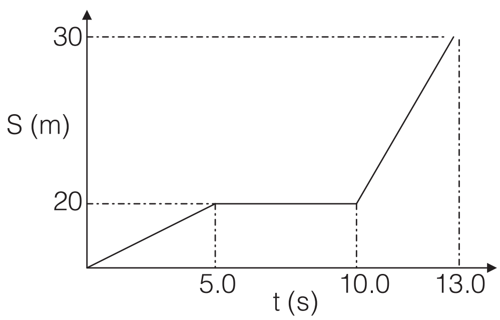
A curved speed vs time graph indicates that the speed is constantly changing.

The **gradient of the tangent** at a given point represents the **instantaneous acceleration**. i.e. the change in speed that takes place over a very short period of time $\Delta t \to 0$. We write

$$a = \frac{\Delta v}{\Delta t} \quad as \quad \Delta t \to 0$$

Worked examples

1. Consider the distance vs time graph below for the motion of a toy car.



Note: This diagram is not to scale

(a) Describe the motion of the toy car.

The toy car travels with constant speed, travelling 20 m in 5 s. The car then remains stationary for 5 s and then travels with a higher constant speed for the remaining 3 seconds.

(b) State the total distance travelled by the toy car.

30 m

(c) Calculate the average speed of the toy car.

$$v = \frac{s}{t} = \frac{30}{13} = 2.3ms^{-1}$$

(d) Determine the toy car's speed at the following times:

(i) t = 4.0 s

$gradient = speed = \frac{20}{5} = 4.0\ ms^{-1}$

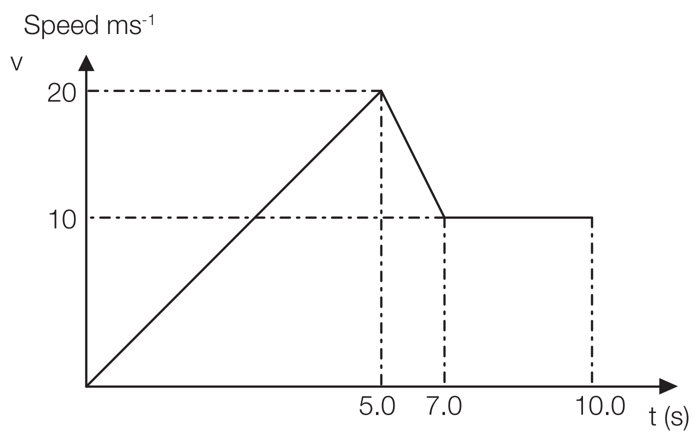
(ii) t = 8.0 s

$gradient = speed = 0\ ms^{-1}$

(iii) t = 11 s

$gradient = speed = \frac{10}{3} = 3.3\ ms^{-1}$

2. Consider the speed vs time graph below.



Note: This diagram is not to scale

(a) Describe the motion depicted by the graph.

The body accelerates at a constant rate from rest for 5 s reaching a speed of 20 ms^{-1}. The body then decelerates at a constant rate for 2 s until it's speed is 10 ms^{-1}. The body then travels with a constant speed of 10 ms^{-1} for its final 3 s of motion.

(b) Determine the greatest acceleration experienced by the body whose motion is illustrated by the graph.

t = 0 s to 5 s: $gradient = acceleration = \frac{20}{5} = 4.0 ms^{-2}$

t = 5 s to 7 s: $gradient = acceleration = \frac{-10}{2} = -5.0 ms^{-2}$

The greatest acceleration is -5.0 ms^{-2} or a deceleration of 5.0 ms^{-2}.

(c) Calculate the distance moved by the body in 10.0 s.

Area under the graph = distance = $\frac{20 \times 5}{2} + 2 \times 10 + \frac{10 \times 2}{2} + 3 \times 10 = 110\ m$

Displacement time graphs

Displacement is a vector quantity, direction is therefore taken into account. Figure 1.1.2 shows the displacement vs time graph for a body.

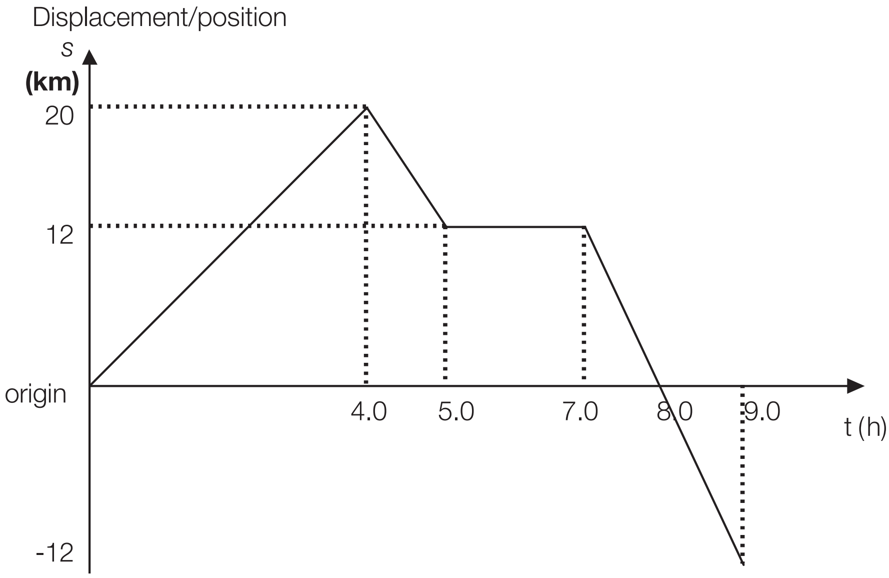


Figure 1.1.2. This diagram is not to scale

The Figure 1.1.2 graph represents a body traveling with constant velocity in a forward direction. The displacement from the origin is 20 km and this took 4.0 h to achieve. The body then turns and travels back towards the origin with constant velocity until its displacement is 12 km. The body then stops and remains stationary for 2.0 h and then continues to travel with constant velocity towards and past the origin. The body's final displacement is 12 km behind the origin.

The forward velocity between t = 0 h and 4.0 h is represented by the gradient = $\frac{rise}{run} = \frac{20}{4} = 5.0\ kmh^{-1}$.

The gradient between t = 4.0 h and 5.0 h is = $\frac{rise}{run} = \frac{-8}{1} = -8.0 kmh^{-1}$.

The negative value means that the object is travelling with a constant velocity of 8.0 kmh^{-1} in a negative direction or back towards the origin. Similarly, the gradient and hence velocity between $t = 9.0\ h$ is –12 kmh^{-1}, which indicates that the object is travelling in a negative direction.

Now consider the two graphs for accelerated motion shown below.

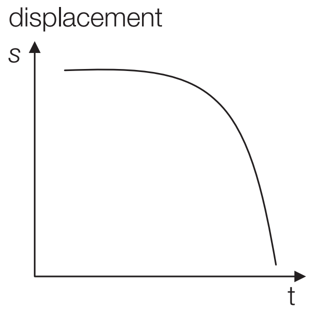


Figure 1.1.3

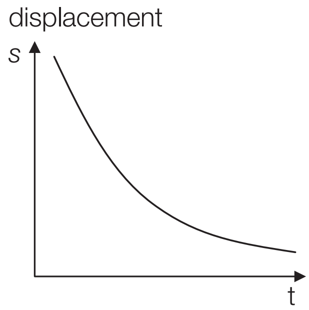


Figure 1.1.4

Understanding rather than memory should be applied when analysing the graphs. Figure 1.1.3 illustrates an acceleration in a negative direction (i.e. towards the origin). This is because instantaneous velocity, which is represented by the slope of the tangent increases with time and is negative. Using the same reasoning, Figure 1.1.4 illustrates a deceleration in a negative direction or towards the origin.

Velocity time graphs

Velocity is a vector quantity, and therefore direction is taken into account. Figure 1.1.5 shows the velocity vs time graph for a body.

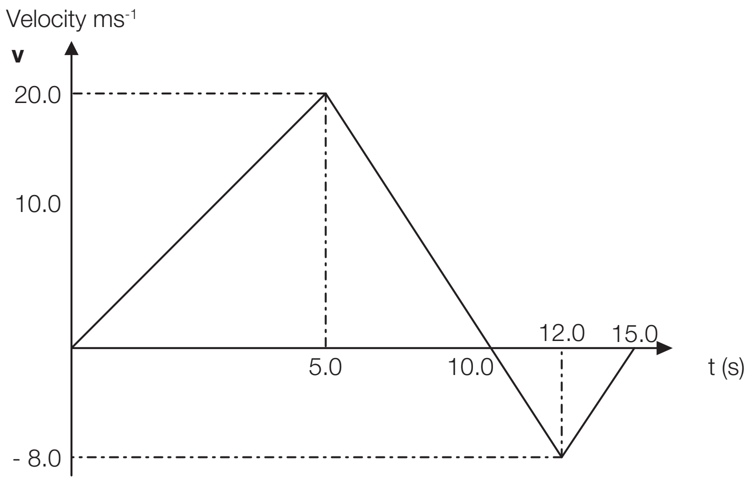


Figure 1.1.5

The **area under the graph** gives the **displacement of the body**. Areas above the time axis represent **positive displacements**, and areas below the time axis, represent **negative displacements**.

The **gradient** of the graph represents **acceleration**.

Figure 1.1.5 represents a constant acceleration from rest in a positive direction. The body reaches a velocity of 20.0 ms^{-1} in 5.0 s. The body then decelerates at a constant rate for 5.0 s coming to rest. The body then turns around and accelerates at a constant rate in a negative direction for 2.0 s reaching a velocity of 8.0 ms^{-1}. The body decelerates at a constant rate for the final 3.0s of its motion once again coming to rest.

When a velocity vs time graph crosses the time axis, a change in direction is indicated.

Worked examples

1. Use Figure 1.1.5 to answer the following questions:

   (a) Determine the distance moved by the body.

   $$\textit{Distance} = \textit{total area under the graph} = \frac{20\times 10}{2} + \frac{5\times 8}{2} = 120m$$

   (b) Calculate the average speed of the body.

   $$v = \frac{s}{t} = \frac{120}{15} = 8.0\ ms^{-1}$$

   (c) Determine the final displacement of the body.

   Displacement = area above time axis – area below the time axis = 80 m in a forward or positive direction

   (d) Calculate the average velocity of the body.

   $$\vec{v} = \frac{\vec{s}}{t} = \frac{80}{15} = 5.3ms^{-1}\ \ \textit{forwards}$$

   (e) Determine the acceleration of the body between t = 10.0 s and t = 12.0 s.

   $$a = \textit{gradient} = \frac{v_f - v_i}{\Delta t} = \frac{-8-0}{2} = -4.0ms^{-2}$$

   This represents an acceleration (speeding up) in the negative direction.

? Science inquiry activities

The following suggested activities are subject to the type of equipment available in your school. You will be guided by your teacher.

1. Construct position *versus* time graphs and velocity *versus* time graphs using trolleys on an inclined plane.
2. Consider the accelerations of different masses. Use motion sensors or other multi-image technology to collect data.

Helpful online resources

Refer to the following computer interactive 'The Moving Man' to further understand position and velocity graphs.

https://phet.colorado.edu/en/simulation/legacy/moving-man

Equations of motion for constant acceleration

Whenever a body experiences a constant acceleration in a straight line, the ***equations of motion*** are used. ***These equations are summarised below.***

$$v = v_0 + at$$

$$s = v_0 t + \frac{1}{2}at^2$$

$$v^2 = v_0^2 + 2as$$

where

v_0 = initial velocity (ms^{-1})

v = final velocity (ms^{-1})

t = time (s)

a = acceleration (ms^{-2})

s = distance (m)

Air resistance

Recall that a free-falling object experiences an acceleration of 9.80 ms^{-2} near the surface of the Earth. This is in the absence of air resistance.

Air resistance is the unbalanced force that acts to oppose the motion of an object moving through the air.

Air resistance is sometimes referred to as drag forces. Air resistance acts in all directions and is caused by the moving object colliding with air particles. The object exerts a force on the air particles and by Newton's Third Law the air exerts an equal and opposite force on the object.

The vertical velocity of an object thrown vertically into the air or falling vertically towards the ground is reduced. As the object rises it decelerates at a rate greater than 9.80 ms^{-2} and comes to rest earlier. The maximum height reached is smaller than if the gravitational acceleration had acted alone. As an object falls, the acceleration is less than 9.80 ms^{-2} and it takes longer to fall. The acceleration is smaller than if the gravitational acceleration had acted alone.

Air resistance is the reason why a feather takes longer to fall to the ground than a compact object such as a stone or ball bearing. The feather experiences a significant amount of air resistance. If air resistance is eliminated, both objects take the same amount of time to fall to the ground. Your teacher may demonstrate this concept in the classroom using a tube containing a feather and a small ball bearing. A vacuum pump can be used to remove most of the air in the tube. You will find that both objects take the same amount of time to fall through the tube.

Helpful online resources

There is no air resistance on the Moon. The following link is to a NASA video clip of a feather and hammer being dropped simultaneously on the surface of the Moon. Both objects reach the surface of the Moon at the same time.

http://apod.nasa.gov/apod/ap111101.html

? Science inquiry practicals

The following are some ideas for science inquiry practicals.

1. Experimentally determine the acceleration due to gravity by recording an object falling against an appropriate scale using a ticker-timer, motion sensor, or other multi-image applications. Use data to construct a velocity vs time graph.
2. Design investigations to determine if mass has any effect on vertical acceleration.

Worked examples

1. A car accelerates from rest to a speed of 120 kmh^{-1} in 7.2 s.

(a) Calculate the acceleration of the car.

120 kmh^{-1}= 33.3 ms^{-1}

$$a = \frac{v - v_0}{t} = \frac{33.3 - 0}{7.2} = 4.6ms^{-2}$$

(b) Calculate the distance travelled by the car during the 7.2 s.

$$s = v_0 t + \frac{1}{2}at^2 = 0 + 0.5 \times 4.6 \times (7.2)^2 = 120m$$

(c) Calculate the time taken for the car to travel 240 m

$$s = v_0 t + \frac{1}{2}at^2 \qquad t = \sqrt{\frac{2s}{a}} = \sqrt{\frac{2 \times 240}{4.6}} = 10.2s = 10s \ \ (2sf)$$

2. A stone is released and dropped down a well. A splash is heard after 3.50 s.

(a) Calculate the depth of the well.

$$s = v_0 t + \frac{1}{2}at^2 = 0 + 0.5 \times 9.8 \times (3.5)^2 = 60.0m$$

(b) Calculate the speed of the stone just before it strikes the water.

$$v^2 = v_0{}^2 + 2as$$

$$v = \sqrt{2as} = \sqrt{2 \times 9.8 \times 60} = 34.3 \ ms^{-1}$$

3. A stone is thrown vertically into the air with a speed of 15.0 ms^{-1}.

(a) Calculate the time taken for the stone to reach maximum height.

$$v = v_0 + at$$

$$t = \frac{v - v_0}{a} = \frac{0 - 15}{-9.8} = 1.53s$$

(b) Calculate the time taken for the stone to return to the person's hand.

1.53 × 2 = 3.06s

(c) Calculate the vertical height reached by the stone.

$$v^2 = v_0{}^2 + 2as$$

$$s = \frac{v^2 - v_0{}^2}{2a} = \frac{0^2 - 15^2}{2 \times -9.8} = 11.5m$$

(d) Determine the stone's ***velocity*** after 2.00 s

The stone is falling from maximum height for a time of 2 – 1.53 =0.47 s

$$v = v_0 + at = 0 + 9.8 \times 0.47 = 4.61ms^{-1} \ \ downwards$$

or $v = v_0 + at = 15 - 9.8 \times 2 = -4.60ms^{-1}$ $\quad$ *i.e.* $4.60ms^{-1}$ *downwards*

(NB: Rounding off has caused a slight discrepancy in the final value)

Extra understanding

Projectile Motion

In the absence of air resistance, an object fired horizontally or at an angle to the ground, will follow a parabolic path or trajectory. The motion is referred to as projectile motion. This section is an introduction to Stage 2 subtopic 1.1.

A multi-image or strobe-light photograph can capture the motion of the projectile. Figure 1.1.6 shows a multi-image photograph of a red ball falling vertically under the action of gravity and a yellow ball with an initial horizontal velocity tracing a parabolic path.

Figure 1.1.6 shows that the vertical positions of both balls are identical as they fall. Both balls are acted upon by the constant gravitational force in the vertical direction and undergo a uniform acceleration of 9.80 ms^{-2} towards the ground.

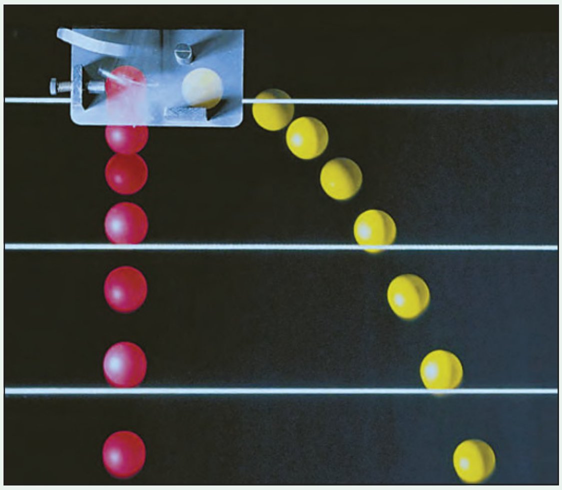


Figure 1.1.6

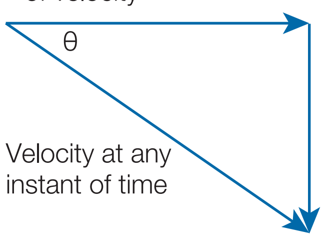
Figure 1.1.6 also shows that the yellow ball travels with constant velocity in the horizontal direction. This is indicated by the fact that the horizontal displacement of the yellow ball is the same between successive images i.e. that there are no unbalanced forces acting in the horizontal direction.

In general, when an object undergoes projectile motion, the horizontal and vertical components of the object's motion can be treated independently. The motion can be analysed using the equation for constant speed in the horizontal direction and the equations of motion in the vertical direction.

HORIZONTAL COMPONENT	VERTICAL COMPONENT
$v = \frac{s}{t}$	$v = v_0 + at$ $s = v_0 t + \frac{1}{2}at^2$ $v^2 = v_0^2 + 2as$

Notes:

1. The two components can be added vectorially to give the velocity vector at any instant of time.



2. The two components can be used independently to calculate the range, time of flight or the height fallen or reached by the projectile.
3. All calculations are based on the assumption that air resistance is negligible.

Analysing Motion

There are three main cases when analysing projectile motion. Each case is described below. Worked examples are used to model the use of the equations in calculating horizontal displacement or range, vertical heights reached, times of flight and velocities at various instances of time.

Case 1: An object launched horizontally to the ground

Figure 1.1.7 shows an object launched horizontally to the ground.

In this case the initial vertical velocity is zero. The equations for analysing the motion of the object are summarized below.

Horizontal component	Vertical component
$v = \frac{s}{t}$	$v = at$
where s is the range or horizontal distance and v is the horizontal launch velocity	$s = \frac{1}{2}at^2$
	$v^2 = 2as$

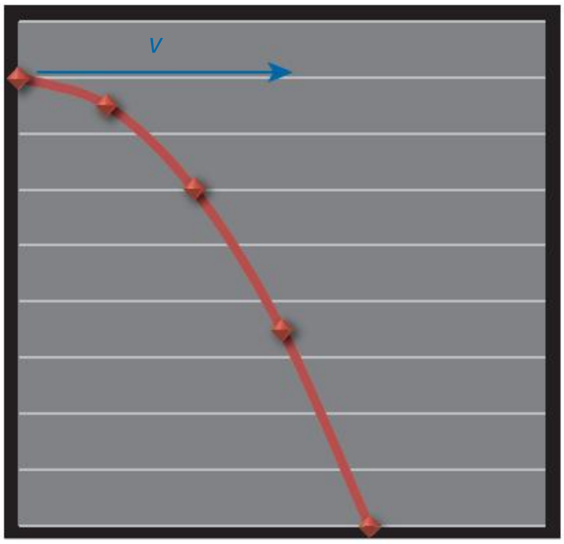


Figure 1.1.7

Case 2: An object launched at an angle above the horizontal that lands at the same height that it is launched.

Figure 1.1.8 shows an object launched at an angle above the horizontal.

The object lands at the same height that it is launched. The initial launch velocity vector v, has two components - the ***horizontal*** v_H ***and vertical*** v_v component. Figure 1.1.9 shows the vector triangle that represents the launch velocity and its horizontal and vertical components. It can be seen that the horizontal component has a magnitude of $v_H = v\cos\theta$ and the vertical component has a magnitude of $v_v = v\sin\theta$. The equations for analysing the motion of the object are summarized below.

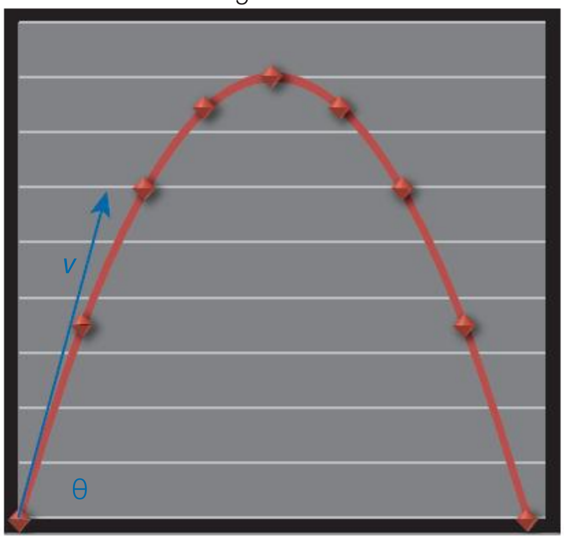


Figure 1.1.8

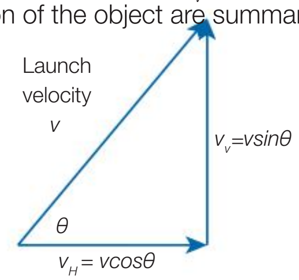


Figure 1.1.9

Horizontal component	Vertical component
	$v = v_0 + at$
$v = \frac{s}{t}$	$s = v_0t + \frac{1}{2}at^2$
	$v^2 = {v_0}^2 + 2as$
where $v_H = v\cos\theta$	*where* $v_0 = v_v = v\sin\theta$ *and* $a = 9.80\ ms^{-2}$ *down*

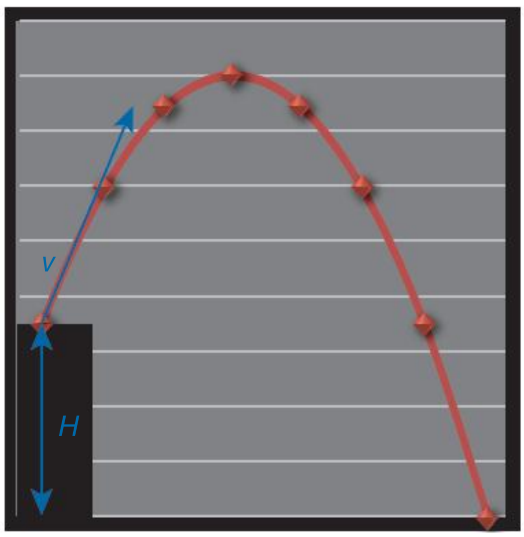


Figure 1.1.10

Case 3: An object being launched at an angle above the horizontal and at a height above the ground

The theory is the same as it is for an object launched at an angle above the horizontal. To find the ***total height*** above the ground, the height reached above the launch position is found and added to the height (*H*) from which the object is launched.

To find the ***total time of flight***, the time taken for the object to rise to its maximum height is found and added to the time it takes to fall the total height.

Changes in the horizontal and vertical components of velocity

The horizontal component of velocity is constant but the vertical component of velocity decreases as the object rises until it is zero at maximum height and then increases as the object falls. The velocity vector is at a tangent to the parabolic path. Figure 1.1.11 shows vector arrows that represent the velocity and the components of velocity at various positions along a parabolic path.

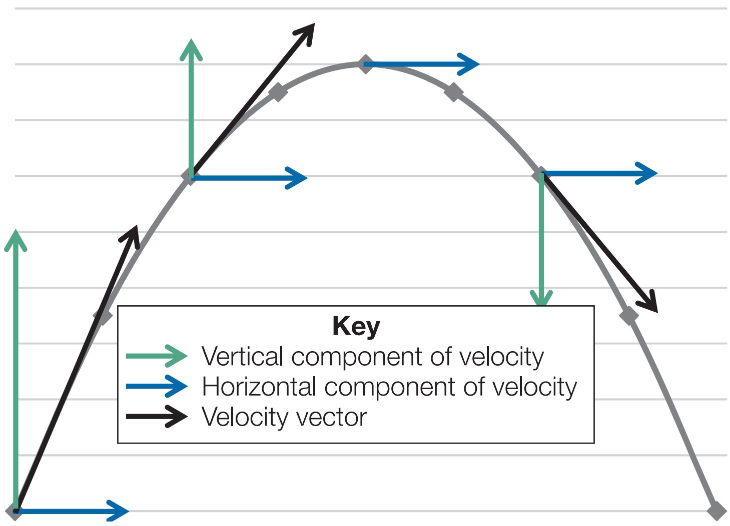


Figure 1.1.11

Acceleration

Recall the gravitational acceleration is constant and only acts in the vertical direction. Figure 1.1.12 shows vector arrows that represent the acceleration of an object at various positions along a parabolic path.

It can be represented by vector arrows of equal length at all points along the parabolic path.

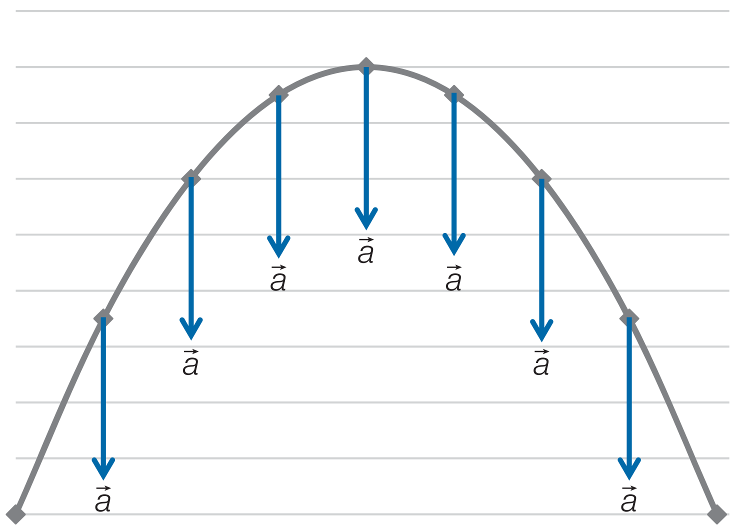


Figure 1.1.12

Worked examples

1. A junior tennis player serves a ball horizontally with a velocity of 72.0 kmh^{-1}. The ball is in the air for 0.55 seconds.

(a) Calculate the range (horizontal displacement) of the ball.

72.0 kmh^{-1} = 20.0 ms^{-1}

$$Range = s = vt = 20 \times 0.55 = 11 \;\; m$$

(b) Calculate the height at which the ball was struck.

$$s = \frac{1}{2}at^2 = \frac{1}{2} \times 9.8 \times (0.55)^2 = 1.5 \;\; m$$

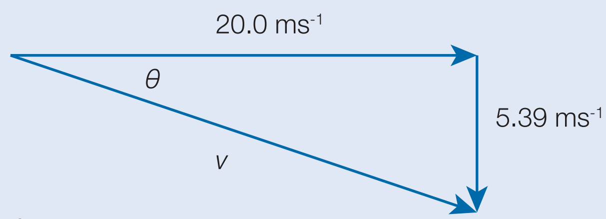
(c) Determine the velocity with which the ball strikes the ground.

$v_H = 20.0 \; ms^{-1} \rightarrow$

$v_v = v_0 + at$

$= 0 + 9.8 \times 0.55$

$= 5.39 \; ms^{-1} \downarrow$

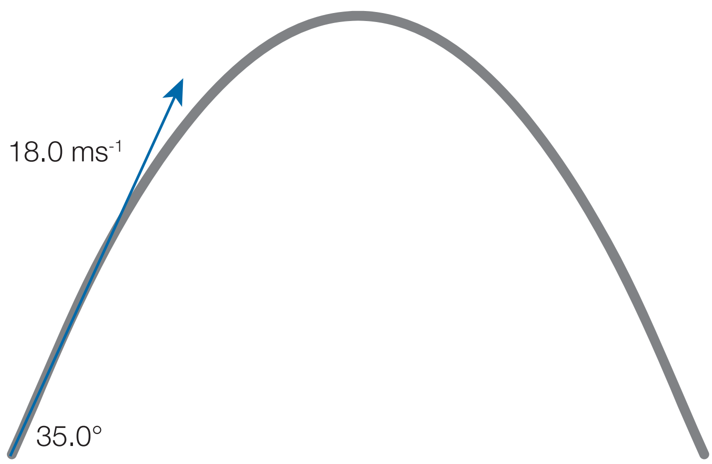


$$v = \sqrt{20^2 + 5.39^2} = 20.7 = 21 \;\; ms^{-1} \quad 2sf$$

$$\tan\theta = \frac{5.39}{20} \Rightarrow \theta = 15^o$$

$\vec{v} = 21 \;\; ms^{-1} \;\; 15^o$ *below the horizontal*

2. A soccer ball is kicked with a velocity of 18.0 ms^{-1} and at an angle of 35.0° above the ground.



(a) Calculate the magnitude of the components of the soccer ball's initial velocity.

$v_H = v\cos\theta = 18\cos35 = 14.7 \;\; ms^{-1}$ $\qquad$ $v_V = v\sin\theta = 18\sin35 = 10.3 \;\; ms^{-1}$

(b) Calculate the maximum height reached by the soccer ball.

$$v^2 = v_o^{\,2} + 2as$$

$$0 = 10.3^2 - 2 \times 9.8s$$

$$s = \frac{10.3^2}{2 \times 9.8} = 5.41 \;\; m$$

(c) Calculate the time of flight of the soccer ball.

$v = v_o + at \quad \therefore \quad t = \frac{v - v_o}{a} \qquad t = \frac{0 - 10.3}{-9.8} = 1.05s$

Total time in the air = 1.05 × 2 = 2.10 s

(d) Calculate the range of the soccer ball.

s = vt = 14.7 × 2.1 = 30.9 m

(e) Determine the velocity of the soccer ball after 1.50 s.

$v_H = 14.7 \ ms^{-1} \rightarrow$

$v_v = v_0 + at$

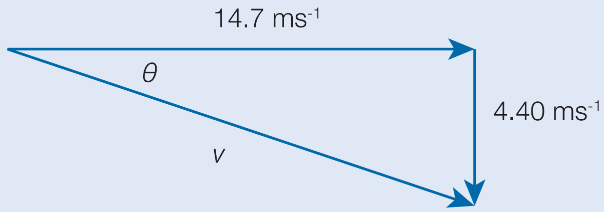
$= 10.3 - 9.8 \times 1.5$

$= -4.40 \quad ms^{-1}$

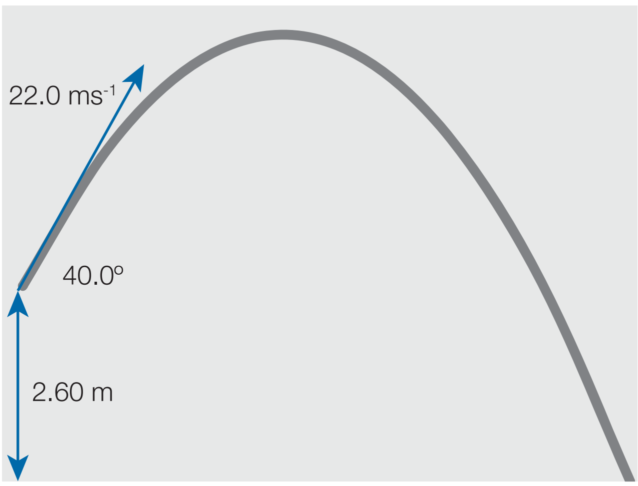
$v = \sqrt{14.7^2 + 4.4^2} = 15.3 \ ms^{-1}$

$\tan\theta = \frac{4.4}{14.7} \Rightarrow \theta = 16.7^o$

$\vec{v} = 15.3 \ ms^{-1}$ 16.7° *below the horizontal*



3. An athlete releases a javelin from a height of 2.60 m, with a velocity of 22.0 ms^{-1} at an angle of 40.0° above the horizontal. The javelin lands on the ground after 1.80 s



(a) Resolve the initial velocity of the javelin into its component vectors.

$v_H = v\cos\theta = 22\cos 40 = 16.9 \ ms^{-1} \rightarrow \quad v_V = v\sin\theta = 22\sin 40 = 14.1 \ ms^{-1} \uparrow$

(b) State the javelin's velocity at its maximum height. Justify your answer.

The velocity at any point is a vector sum of the horizontal and vertical components of velocity. At maximum height the vertical component of velocity is zero so the velocity is 16.9ms^{-1} horizontally and to the right.

(c) Determine the maximum height reached by the javelin above the ground.

$v^2 = v_o^2 + 2as$

$0 = 14.1^2 - 2 \times 9.8s$

$s = \frac{14.1^2}{2 \times 9.8} = 10.1m$

Total height above the ground = 10.1 + 2.6 = 12.7 m

(d) Calculate the distance that the javelin is thrown.

s = vt = 16.9 × 1.8 = 30.4 m

1.2 Forces

Science understanding

1. A force ($\vec{F}$) is any action which causes motion to change ($\vec{a}$).
2. Uniform motion is a state of motion in which the body travels with a constant speed (in a straight line).
3. Rest is a state of uniform motion in which the speed of the body is zero.
4. To change the state of motion of an object, a net force must be applied.
5. Newton's Three Laws of Motion describe the relationship between the force or forces acting on an object, modelled as a point mass, and the motion of the object due to the application of the force or forces.
6. Newton's First Law: An object will remain at rest, or continue in its motion, unless acted upon by an unbalanced force:
   - Explain Newton's First Law using the concept of inertia.
   - Use Newton's First Law to explain the motion of objects in a variety of contexts.
   - Describe and explain the motion of an object falling in a uniform gravitational field with air resistance.
7. Newton's Second Law: If an unbalanced force acts upon an object, the object will accelerate in the direction of the net force.
8. This can be given mathematically as: $\vec{a} = \frac{\vec{F}}{m}$.
   - Solve problems using $\vec{F} = m\vec{a}$.
   - Explain the difference between mass and weight.
9. Newton's Third Law: When two objects interact, they exert forces on each other equal in magnitude and opposite in direction.
10. The forces are identified in pairs, and the accelerations of each object will differ if the objects differ in mass:
    - Use Newton's Third Law to solve problems.
    - Identify pairs of forces in a variety of contexts, including the normal reaction force.
    - Describe and explain motion where Newton's Third Law occurs.
    - Use Newton's Laws to explain the motion of spacecraft.
11. Undertake experiments to investigate the relationship between acceleration and either force or mass.

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A force is a push or a pull.

Force is a vector quantity.

The unit of force is the Newton (N).

Uniform motion involves a body being at rest or travelling with constant speed in a straight line.

When ever a force acts one or more of the following effects are caused:

1. A change in shape (deformation)
2. A change in speed
3. A change in direction

It should be noted that a change in speed or direction constitutes a change in velocity and therefore an acceleration.

Objects as point masses

In physics we often describe objects as point masses, meaning the object's size and shape are irrelevant to the situation.

Newton's Three Laws of motion describe the relationship between force(s) acting on a body modelled as a point mass.

Newton's First Law

Newton's First Law of motion states that an object at rest will remain at rest while an object in motion, continues to move in a ***straight line*** at ***constant speed***, unless acted upon by an unbalanced force.

Examples

A The tablecloth trick

A well-known trick is to pull a table cloth out from under the objects resting on a table. This trick can be explained using Newton's First Law of motion.

When the tablecloth is pulled, an unbalanced force acts on the tablecloth but not the objects resting on the table and tablecloth. According to Newton's First Law, an object at rest will remain at rest unless acted upon by an unbalanced force. As a consequence, the tablecloth is pulled away and the objects remain on the table.

NB A fast action and smooth cloth help minimise friction between the tablecloth and the objects resting on the table. If too much friction acts, the objects will be dragged with the tablecloth.

B A bus suddenly stopping

Many people have experienced a feeling of being 'thrown' forward when a bus suddenly stops. You are not being thrown forward, in fact the experience can be explained in terms of Newton's First Law.

When the bus suddenly brakes, an unbalanced force acts on the bus but not the passenger. According to Newton's First Law, an object in motion will continue to move in a straight line at constant speed unless acted upon by an unbalanced force.

As a consequence, the passenger continues to move forward until they grab a pole or strike another object.

NB The friction between the passenger's feet and the floor of the bus is enough to cause the passenger to stumble rather than slide forward.

Inertia is a property that resists a change in the state of motion of a body unless it is acted upon by an unbalanced force.

Newton's First Law is sometimes referred to as the Law of Inertia. The examples described above can be explained in terms of inertia. In the case of the tablecloth trick, the objects resting on the table are at rest and remain at rest because no unbalanced force is acting on them. We could therefore say 'the objects remain at rest due to their inertia'. In the second example of the bus suddenly stopping we could say 'the passengers continue to move in a straight line with constant speed due to their inertia'.

Helpful online resources

Computer interactive: Forces in 1 dimension

https://phet.colorado.edu/en/simulation/forces-1d

Newton's Second Law

Newton's Second Law states that the acceleration of an object is directly proportional to the force applied providing the mass is constant and inversely proportional to the mass of the object providing the force is constant.

Figure 1.2.1 represents the first part of this law diagrammatically. The same mass is acted upon by an increasing force. The acceleration increases by the same factor as the force. We say the acceleration is proportional to the force providing the mass is constant. This is written as $a \propto F$. Figure 1.2.2 represents the second part of Newton's Second Law. The same force acts on an increasing mass. The acceleration decreases by the same factor that the force increases. We say the acceleration is inversely proportional to the mass providing the force is constant and we write $a \propto \frac{1}{m}$

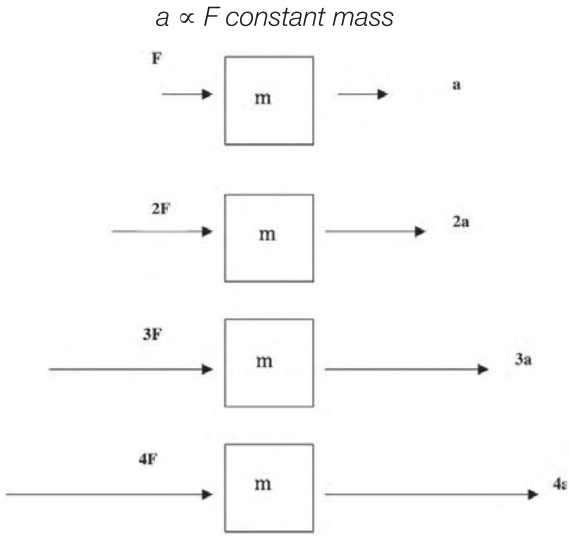


Figure 1.2.1

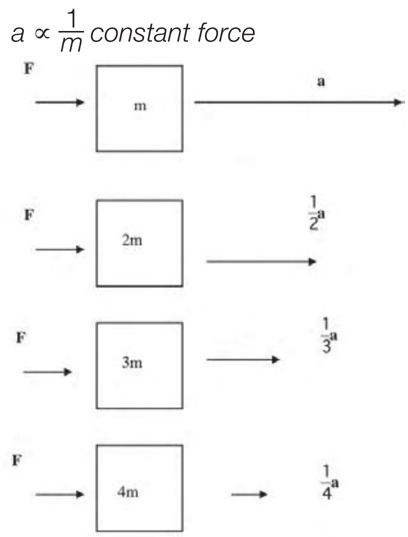


Figure 1.2.2

The object will accelerate in the direction of the net or resultant force. Newton's Second Law can be written mathematically as

$$\vec{a} = \frac{\vec{F}}{m}$$

Extra understanding

Graphing Skills

In general, whenever two variables are plotted and a straight line of best fit passing through the origin results, we say a direct proportionality exists between the two variables. Since Newton's Second Law states that the acceleration of an object is directly proportional to the force exerted on the object, then we would expect a straight line of best fit through the origin if experimental data is collected and acceleration is plotted against force. Figure 1.2.3 illustrates the graph we would expect.

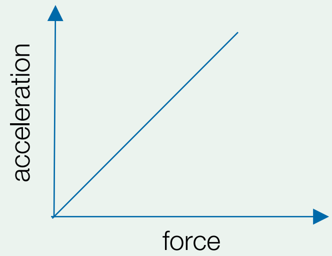


Figure 1.2.3

The general equation for a straight line though the origin is $y = mx$ where m represents the gradient of the line. When this is compared to Newton's Second Law, $a = \frac{F}{m}$, where m represents mass, it can be seen that the gradient is equivalent to $\frac{1}{\text{mass}}$. That is, the mass of the object can be determined experimentally from the gradient of the line of best fit.

Newton's Second Law also states that the acceleration of an object is inversely proportional to the mass of the object providing the force is constant. If experimental data is collected and a graph of acceleration against the inverse of mass is plotted, a straight line of best fit through the origin should result. This is illustrated in Figure 1.2.4.

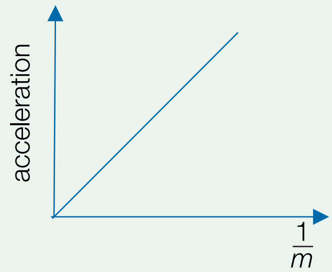


Figure 1.2.4

If the equation $y = mx$ is compared to $a = \frac{F}{m}$, it can be seen that the gradient is equivalent to the force F, acting on the object.

Helpful online resources

Computer interactive: Forces and Motion: Basics

https://phet.colorado.edu/en/simulation/forces-and-motion-basics

Worked examples

1. A 1.5 tonne car accelerates from 60 kmh^{-1} to a constant velocity of 100 kmh^{-1} in 5.0 seconds.

   (a) Calculate the magnitude of the thrust that the car's engine must provide in order to achieve this change in velocity.

   60 kmh^{-1} = 16.7 ms^{-1} 100 kmh^{-1} = 27.8 ms^{-1}

   $$a=\frac{v-v_0}{t}=\frac{27.8-16.7}{5}=2.22ms^{-2}$$

   $$F=ma=1.5\times10^3\times2.22=3300N\ (2sf)$$

   (b) State and explain the magnitude and direction of the collective drag forces acting once the car reaches 100 kmh^{-1}.

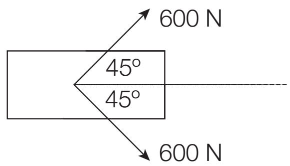
   The car travels with constant velocity. This means that there are no unbalanced forces acting. According to Newton's First Law, the collective drag forces must have a magnitude of 3300 N and act in the opposite direction that the car is travelling.

2. A car can accelerate at 3.00 ms^{-2}. Given the same engine thrust, determine the car's acceleration if it is towing another identical car.

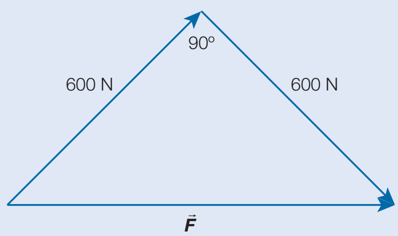
   $$a=\frac{F}{m} \qquad a\propto\frac{1}{m}$$

   If the same engine thrust acts on twice the mass, then the acceleration is halved i.e.1.50 ms^{-2}

3. A barge is being towed along a canal. The forces acting on the barge are shown in the diagram below.



   (a) Determine the magnitude of the resultant force $\vec{F}$ on the barge.



   $$\vec{F}=\vec{F}_1+\vec{F}_2$$

   $$F=\sqrt{600^2+600^2}=850N\ (2sf)$$

   (b) Calculate the acceleration $\vec{a}$ of the barge if it has a mass of 350 kg.

   $$\vec{a}=\frac{\vec{F}}{m}=\frac{850\rightarrow}{350}=2.4\ ms^{-2}\rightarrow$$

? Science inquiry practicals

Some ideas for student inquiry practicals.

1. Investigate Newton's First Law moving objects of different mass over surfaces of very low friction. This may include: air tracks, ice, or layers of ball bearings.
2. Investigate the relationships between terminal speeds and forces in a variety of contexts. Design and carry out individual or group investigations involving dropping objects in different fluids to observe and quantify non-uniform acceleration.
3. Investigate spring constants using Hooke's Law. Design experiments to investigate the effect of multiple springs. Students could test elastic bands, spaghetti, noodles, or confectionery to compare differences in results.
4. Use an air track, light gate, and slotted masses to investigate relationship between forces and acceleration.
5. Investigate different types of air or water rockets. The design may be manipulated and the effect on the rockets' motion determined.
6. Determine the coefficient of kinetic friction by measuring the acceleration of a moving object as it comes to rest. Design, build, and evaluate structures individually or in groups.

Weight and mass

The ***mass*** of an object is the amount of matter making up the object. Mass determines a bodies inertia.

Mass is measured in kilograms (kg) and doesn't change no matter what your position in the universe.

Weight is the gravitational force acting on an object due to its mass.

Weight is measured in Newtons (N) and will change depending on your position in the universe. For example, your weight on the Moon is approximately six times smaller than your weight on Earth. This means that you are pulled down towards the surface of the Moon with six times less force than on the surface of the Earth. Although your weight is less, your mass does not change.

$$W = mg$$

Where

W = weight (N)

m = mass (kg)

g = gravitational acceleration (ms^{-2})

Useful data:

$g_{earth} = 9.80\ ms^{-2}$

$g_{moon} = 1.67\ ms^{-2}$

Worked examples

1. (a) Calculate the weight of a 60.0 kg student on Earth.

   $W = mg = 60 \times 9.8 = 588\ N$

   (b) State the student's mass on the Moon.

   60.0 kg

   (c) Determine the student's weight on the Moon.

   $W = mg = 60 \times 1.67 = 100\ N$

2. Two 50.0 g masses hang from a spring. Calculate the force acting on the spring.

   The weight of the masses provides the force $W = mg = 0.1 \times 9.8 = 0.980\ N$

Newton's Third Law

Every action force has an equal and opposite reaction force.

Alternatively

When object A exerts a force on object B, then object B exerts an equal and opposite force on object A.

Example

An egg thrown at a wall will break.

When the egg strikes the wall, it exerts an ***action force*** on the wall. According to Newton's Third Law, the wall applies an equal and opposite ***reaction force*** on the egg. It is this reaction force that causes the egg to break.

Normal reaction force

For a body resting on a table, the gravitational force acts vertically down but there must be an equal and opposite upward force acting on the body due to the table (Newton's Third Law). This upward force is called the normal force. Figure 1.2.5 shows the forces acting on an object resting on a flat surface.

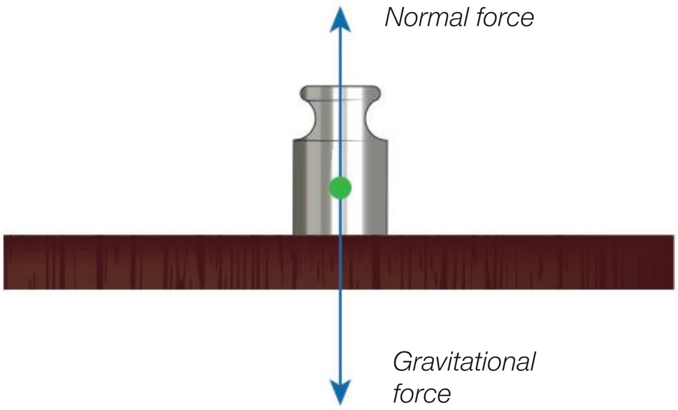


Figure 1.2.5

Science as a human endeavour

Modern car manufactures incorporate many safety features into cars.

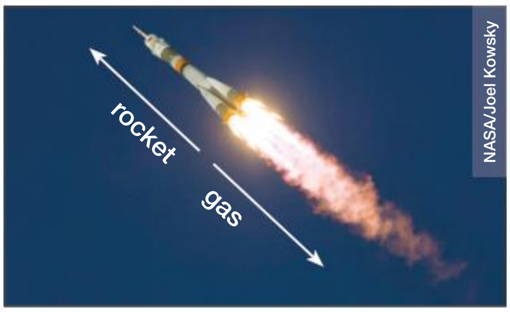
Investigate the development of car safety features. How do Newton's Three Laws of Motion apply?

The motion of a spacecraft

A spacecraft burns and ejects some fuel or ions from the rear of the spacecraft. A force is therefore exerted on the burnt fuel or ions by the spacecraft. The burnt fuel or ions exert an equal and opposite force on the spacecraft (Newton's Third Law). The spacecraft therefore accelerates forwards with an acceleration given by (Newton's Second Law).

$$a_{spacecraft} = \frac{F_{spacecraft}}{m_{spacecraft}}$$

Since there are very few unbalanced forces in space the spacecraft with continue with constant velocity indefinitely (Newton's First Law).



Science as a human endeavour

Newton wasn't the only scientist interested in explaining the motion of objects.

In the early 1600s Johannes Kepler explained the motion of planets around the Sun. His three laws were

1. The planets trace an elliptical path around the Sun, with the centre of the Sun being located at one focus.
2. An imaginary line drawn from the centre of the Sun to the centre of the planet will sweep out equal areas in equal intervals of time.
3. The ratio of the squares of the periods of any two planets is equal to the ratio of the cubes of their average distances from the Sun.

Kepler's laws were derived from data that his mentor Tycho Brahe had collected.

Investigate the work of Aristotle, Galileo, Einstein and Heisenberg. How did their work influence the theories explaining motion?

Exercises

1.1 Motion under Constant Acceleration

Speed

1. (a) A cyclist travels 5.0 km in 15 minutes. Calculate the average speed of the cyclist in ms^{-1} and kmh^{-1}.

(b) Explain why the cyclist's speed is referred to as an average speed.

2. A car is moving with a constant speed of 60.0 kmh^{-1}.

(a) Calculate the distance travelled by the car in 8.0 minutes.

(b) Calculate the time it would take the car to travel 1250 km at this speed.

3. A satellite is in orbit around the centre of the Earth at a height of 16 000 km above its surface. The satellite completes one rotation of the Earth in 7.4 hours and the radius of the Earth is 6.4×10^6 m. Calculate the average speed of the satellite.

4. Light travels with a speed of 3.00×10^8 ms^{-1}. Light from Alpha Centauri takes 4.20 years to reach the Earth. Calculate the distance between Earth and Alpha Centauri in km.

5. The distance travelled by a car along a straight road during 3.0 hours is shown in the table below.

Distance (km)	0	40	90	130	170	210	210
Time (h)	0	0.50	1.0	1.5	2.0	2.5	3.0

(a) Plot a graph of distance versus time.

(b) Draw a line of best fit for the plotted points.

(c) Explain whether the motion of the car is constant over the 3.0 hours.

(d) Use your graph to determine the average speed of the car during the first 2.5 hours of its motion (in kmh^{-1})

(e) Convert your answer to part (d) to ms^{-1}

6. The multi-image diagram below represents the motion of a ball rolling across a smooth surface. The distance between the first and last image is 36.0 cm. The time between images is 0.180 s.

(a) Explain why the images indicate that the ball is travelling with constant speed.

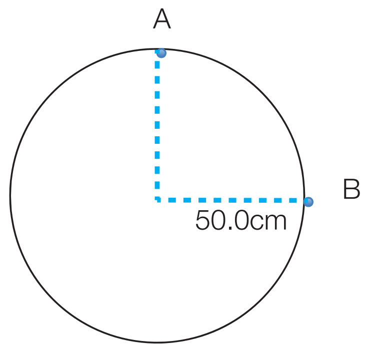
(b) Calculate the speed of the ball.

Displacement and Velocity

1. (a) Describe one situation in which the distance you travel is the same as your displacement.

(b) Describe one situation in which your speed is not zero but your velocity is zero.

2. A mouse circles round a circular cage of radius 50.0 cm as shown in the diagram. The mouse starts at point A and travels to point B along the circular arc.



(a) Calculate the distance travelled by the mouse.

(b) Calculate the displacement of the mouse.

(c) Calculate the average velocity of the mouse if it reaches point B in 3.00 s.

3. An ant travels 20.0 cm east, then 30.0 cm north and then 50.0 cm west. The journey takes 45.0 s.

(a) State the distance travelled by the ant.

(b) Calculate the ant's final displacement.

(c) Calculate the ant's average speed.

(d) Calculate the ant's average velocity.

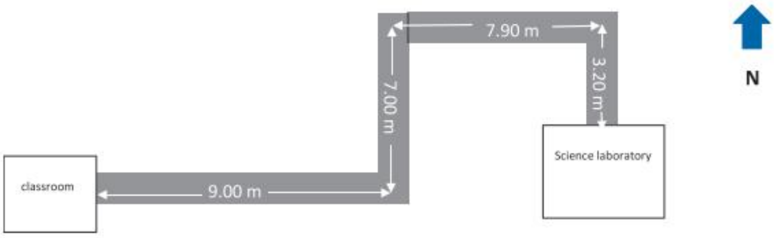
4. A remote controlled plane is flying with a velocity of 15 ms^{-1} east. It encounters a wind blowing with a speed of 5.5 ms^{-1} in a northerly direction.

(a) Determine the resultant velocity of the plane.

(b) Calculate the displacement of the plane after 2.0 minutes.

(c) How far off its straight-line course is the plane after 2.0 minutes?

5. A student walks through a series of corridors to get from their classroom to the science laboratory. The diagram shown below represents the path taken by the student and the distance walked along each corridor. The diagram is not to scale. The direction of north is also indicated on the diagram. The student takes 72.0 s to walk from the classroom to the science laboratory.



(a) Explain why the magnitude of the student's velocity is smaller than their average speed.

(b) Determine the student's average velocity.

6. An air-balloon is drifting with a speed of 6.00 ms^{-1} in a southerly direction. A wind blowing from the east results in the air balloon drifting with a resultant velocity of magnitude 9.00 ms^{-1}. Determine the speed of the wind.

Acceleration

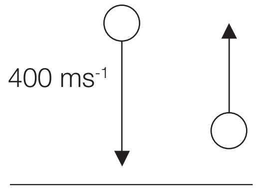
1. A plane can accelerate from rest to reach a speed of 460 kmh^{-1} in 12.0 seconds.

   Calculate the acceleration of the plane.

2. A dart strikes a wooden board with a speed of 10.0 ms^{-1}. It comes to rest in 220 ms. Calculate the acceleration experience by the dart.

3. An object decelerates at 3.0 ms^{-2}, reaching a speed of 20 ms^{-1} in 8.0 s. Calculate the initial speed of the object.

4. A gas particle rebounds from the wall of its container in 0.01 s and without a loss in speed.



Calculate the acceleration of the gas particle.

5. An arrow is fired vertically into the air with an initial speed of 25.0 ms^{-1}.

(a) State the speed of the arrow at it's maximum height.

(b) State the magnitude of the acceleration of the arrow at it's maximum height.

(c) Calculate the time taken for the arrow to reach it's maximum height.

Graphing Motion

1. State the quantity given by the:

(a) gradient of a distance-time graph

(b) gradient of a speed–time graph

(c) area under a speed–time graph

(d) gradient of a displacement-time graph

(e) gradient of a velocity-time graph

(f) area under a velocity–time graph

2. The distance vs time graph shown below represents the motion of a remote controlled car.

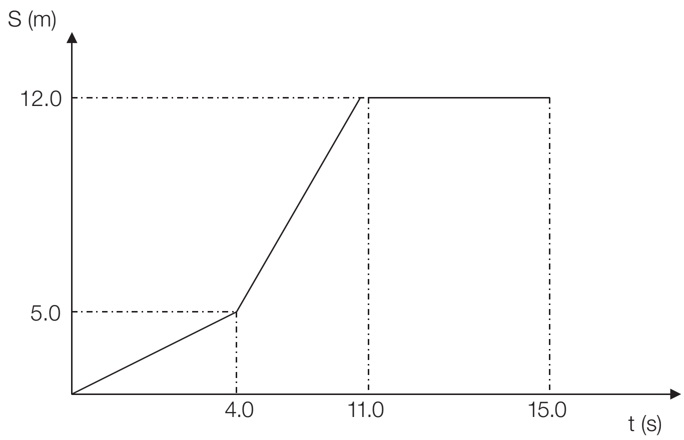


Diagram not to scale

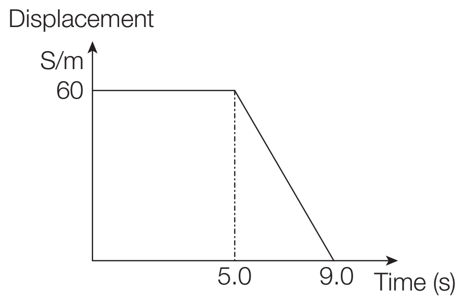
(a) Describe the motion of the remote controlled car.

(b) State the total distance travelled by the remote controlled car.

(c) Calculate the average speed of the remote controlled car during its 15.0 s journey.

(d) Calculate the speed of the remote controlled car at a time of 7.0 s.

3. The displacement vs time graph shown below represents the motion of an object. The graph is not to scale.

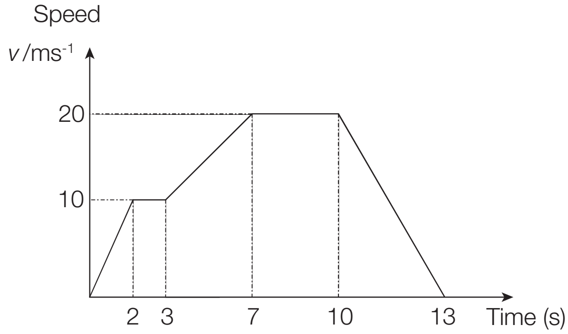


(a) State the length of time for which the object was stationary.

(b) Calculate the average velocity of the object over the last 4.0 s.

(c) Describe the motion of the object over the 9.0 s.

4. The speed vs time graph shown below represents the motion of an object. The graph is not to scale.



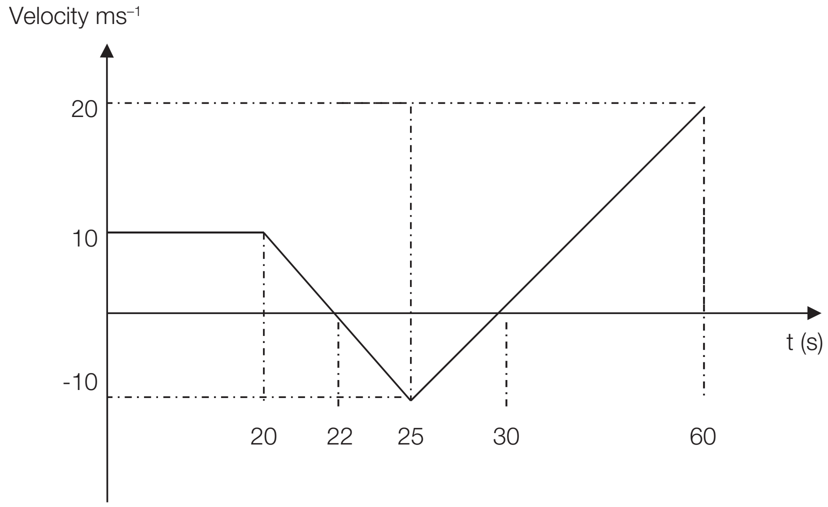
(a) Describe the motion of the object throughout the 13 s.

(b) Determine the greatest acceleration experienced by the object. Justify your answer.

(c) Determine the distance travelled by the object in the 13 s.

5. The velocity vs time graph shown below illustrates the motion of an object over a time of 60 s.

The graph is not drawn to scale. The times are written below the time axis so that they can be seen clearly.



(a) Describe the motion of the object depicted by the graph.

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(b) State or determine the acceleration of the object:

(i) between t = 0 and 20 s

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(ii) t = 20 and 25 s

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....

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(iii) t = 25 and 60 s

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(c) Determine the distance travelled by the object in the first 25 s of its motion.

....

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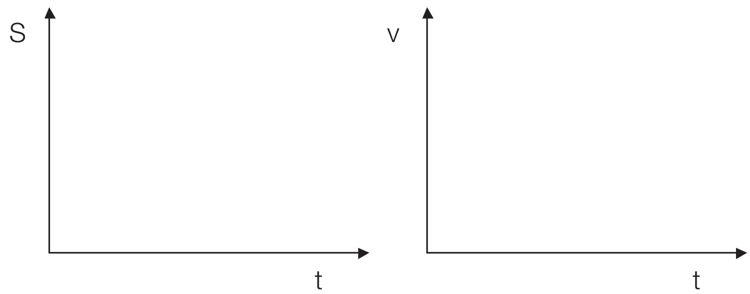
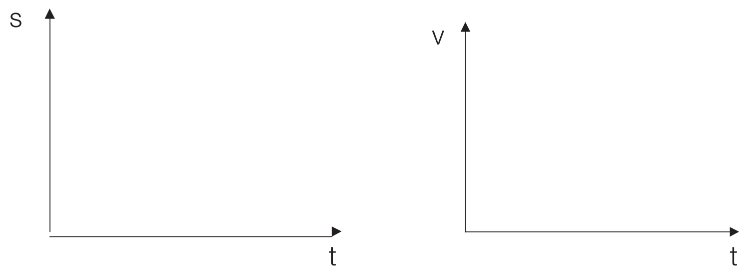
(d) Comment on the magnitude of the object's displacement compared to the distance it has travelled after 25 s of motion. Calculate the object's displacement after 25 s of motion.

6. A parachutist jumping out of a plane will accelerate freely under the action of gravity and then reach a constant 'terminal' velocity.

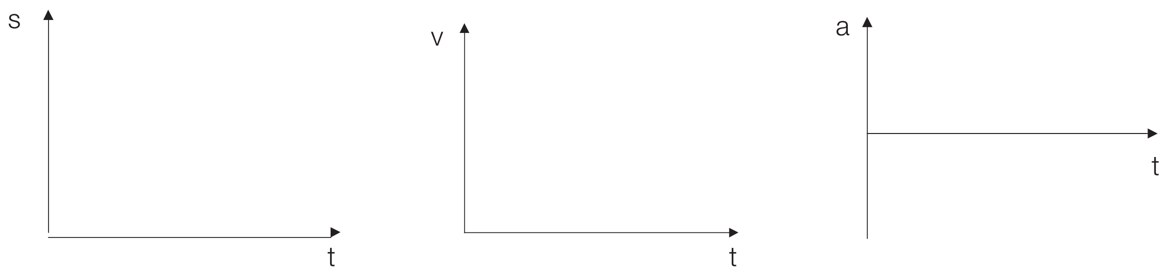
Sketch a distance vs time and a speed vs time graph for this situation.



7. A ball is thrown vertically into the air and returns to its original position. Ignore the effects of air resistance and sketch distance vs time and speed vs time graphs for this situation.



For the same situation, sketch displacement vs time, velocity vs time and acceleration vs time graphs.



Equations of motion for constant acceleration

1. A car accelerates from rest to a speed of 1.00×10^2 kmh^{-1} in 7.20 s.

   (a) Calculate the acceleration of the car.

   (b) Calculate the distance travelled by the car during the 7.20 s.

   (c) Calculate the time taken for the car to move 2.00×10^2 m.

   (d) Calculate the average speed of the car during the first 7.20 s of its motion.

2. A box is dropped from rest. The box takes 0.75 s to hit the ground.

   (a) Calculate the height from which the box was dropped.

   (b) Calculate the speed of the box just before it hits the ground.

   (c) Calculate the speed of the box half-way down to the ground.

3. A ball is thrown vertically into the air with a speed of 25.0 ms^{-1}.

   (a) Calculate the time taken for the ball to reach maximum height.

   (b) Calculate the time taken for the ball to return to the person's hand. Justify your answer.

(c) Calculate the vertical height reached by the ball.

(d) Determine the ball's velocity after 3.55 s.

4. A woman travelling in a car with a velocity of 72.0 kmh^{-1} notices an injured cat 35.0 m away on the road directly ahead of her car.

She takes 0.130 s to react and the car can decelerate at a constant rate of 6.00 ms^{-2}.

(a) Calculate the distance travelled by the car before the woman reacts.

(b) Calculate the distance travelled by the car while it is decelerating.

(c) Determine whether the car stops before hitting the cat.

(d) Calculate the total time taken for the car to stop.

5. A sharp knife is dropped onto a wooden block by its point. The knife strikes the wooden block with a speed of 5.00 ms^{-1} and penetrates the wooden block a distance of 1.20 cm.

(a) Calculate the height from which the knife was dropped.

(b) Calculate the acceleration of the knife in the wooden block.

6. Workmen and women often wear work boots with a reinforced steel toe in order to protect their toes from falling objects. A bricklayer drops a brick from a height of 1.56 m directly onto their foot.

   (a) Calculate the speed with which the brick strikes the bricklayer's foot.

   (b) Calculate the time taken for the brick to fall 1.56 m.

7. A vehicle manufacturer tests their vehicle to determine the maximum deceleration of different models. For one particular model, the average stopping distance is 12.9 m when its initial speed is 60.0 kmh^{-1}.

   (a) Calculate the average deceleration of this model.

   (b) Calculate the average time it would take this model to stop.

Projectile Motion

1. A girl throws a tennis ball as hard as she can off the top of a building.

   Ignore the effects of air resistance in answering the following questions.

   The ball is thrown horizontally with a speed of 70.0 kmh^{-1} and takes 4.00 s to land on the ground.

   (a) Calculate the height of the building.

   (b) How far from the base of the building does the ball land?

(c) Determine the velocity of the ball as it hits the ground.

space for vector diagram

(d) The girl enters a competition which requires the ball to land at least 100 m from the base of the cliff. Determine the initial velocity of the ball required to do this (still thrown horizontally). Is it worth her while entering the competition?

(e) The girl's friend tells her that she could win the competition if she throws the ball at an angle slightly above the horizontal. Explain why her friend is right.

2. A golf ball is struck with a velocity of 30.0 ms^{-1}, 30.0° above the ground and lands at the same height that it is struck. In answering the following questions, ignore the effects of air resistance.

(a) Draw a vector triangle that represents the initial velocity of the golf ball and hence calculate the initial horizontal and vertical components of the ball's velocity.

(b) Calculate the golf ball's time of flight.

(c) Calculate the height reached by the golf ball.

(d) Calculate the range of the golf ball.

(e) State the acceleration of the golf ball at it's maximum height.

(f) State the velocity of the golf ball on impact with the ground.

3. A shot put is thrown from a height of 2.00 m with a velocity of 10.0 ms^{-1}, 45.0° above the horizontal. Consider the effects of air resistance to be negligible.

(a) Calculate the magnitude of the initial components of the shot put's velocity.

(b) Calculate the height reached by the shot put.

(c) Determine the time taken for the shot put to land on the ground.

(d) Calculate the range achieved by the shotput.

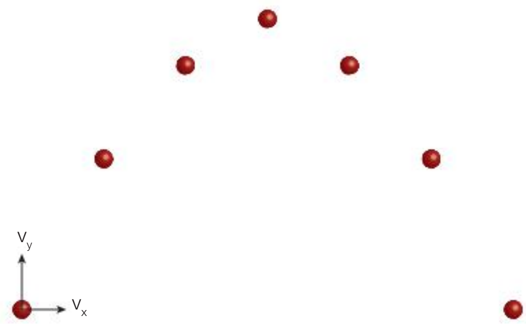
(e) State the shot put's velocity at maximum height.

(f) Determine the shot put's velocity after 1.0 s.

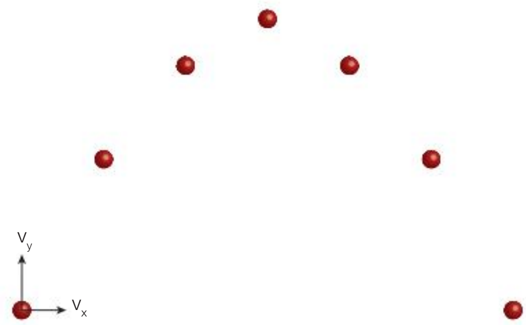
space for vector diagram

(g) Sketch a diagram that compares the path of the shot put with and without a significant amount of air resistance acting.

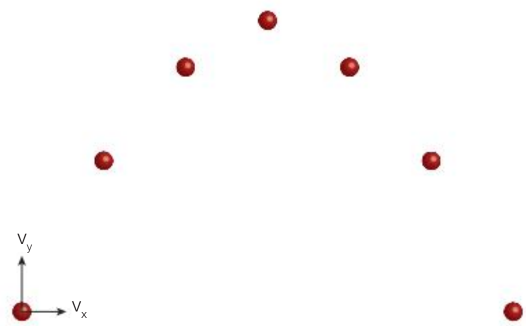
4. Complete the diagram below by drawing vector arrows at the various points along the path which represent the way in which the **components of velocity** vary at each point.



5. Complete the diagram below by drawing vector arrows at the various points along the path which represent the way in which the **velocity** varies at each point.



6. Complete the diagram below by drawing vector arrows at the various points along the path which represent the **acceleration** at each point.



1.2 Forces

1. A student exerts a force of 140 N on a bicycle in order to accelerate forwards. The student is riding on a road that provides a frictional force of 5.0 N on the tyres of the bicycle. Consider any force due to air resistance to be negligible.

   (a) Sketch a diagram of the situation and draw clearly labelled vector arrows that represent the forces acting.

   (b) State the resultant force on the bicycle.

2. Sketch a diagram and draw clearly labelled arrows that represent the forces acting on a *heavy block being pulled across a floor with constant speed.*

3. A truck of mass 12.0 tonnes is travelling at 25.0 ms^{-1} when it brakes heavily and comes to rest. The braking force is 20.0 kN. Calculate the

   (a) magnitude of the deceleration of the truck.

   (b) time taken for the truck to stop.

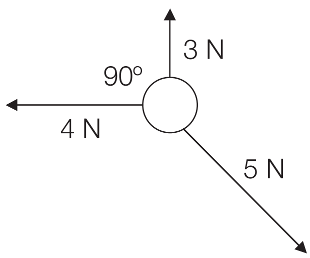
   (c) distance required to stop the truck.

4. A 0.200 kg ball falling through the air is acted upon by drag forces of magnitude 0.150 N.
   (a) Sketch diagram and draw clearly labelled vector arrows that represent the forces acting on the ball.

   (b) Determine the resultant force acting on the ball.

   (c) Calculate the resultant acceleration of the ball.

5. A 62 kg ice skater resting on ice is pulled in three directions as shown in the diagram below.

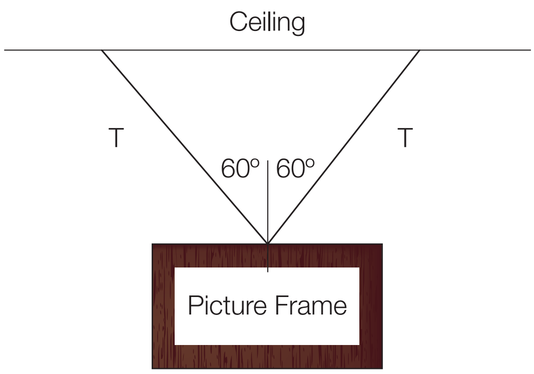


Determine the resultant acceleration of the ice skater.

6. Explain how Newton's Third Law applies to swimming.

7. A parachutist of mass 110 kg (including the parachute) falls to the ground with a terminal speed of 3.00 ms^{-1}. Giving reasons, calculate the drag forces acting on the parachutist.

8. The diagram below shows a 2.5 kg picture frame, hanging freely from a ceiling by two strings.



(a) Calculate the weight of the picture frame.

(b) Determine the magnitude of the force T, in each of the strings.

space for vector diagram

9. An earlier question described how a vehicle manufacturer tested their vehicle to determine the maximum deceleration of different models.

For one particular model of mass 1120 kg, the average deceleration was 10.8 ms^{-2}.

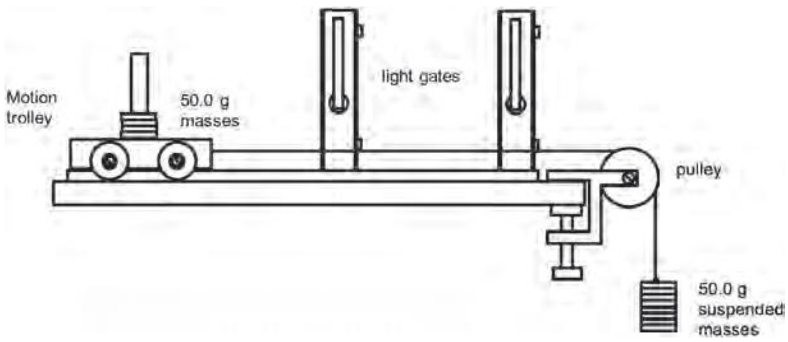
(a) Calculate the magnitude of the braking force required to bring this car to rest.

(b) A cheaper model of the same car has the same mass but can only provide half the braking force calculated in part (a). Use Newton's Second Law to explain why you'd expect half the acceleration.

10. A group of students performed an experiment designed to verify Newton's Second Law.

The students were particularly interested in showing that the acceleration of a motion trolley is directly proportional to the force exerted on the motion trolley.

The diagram below shows the experimental arrangement used by the students.



Four 50.0 g masses were added to a motion trolley of mass 2.30 kg and one 50.0 g mass was attached to the trolley using a piece of string. The single 50.0 g mass was suspended over the side of the bench. When released, the suspended mass fell towards the ground and caused the motion trolley to accelerate across the bench. The 50.0 g mass provided a force of 0.500 N as it fell. The light gates were used to record the time taken for the motion trolley to accelerate from rest across a distance of 0.500 m. The equation $a = \frac{2s}{t^2}$ was used to calculate the acceleration of the motion trolley.

The students then moved one 50.0 g mass from the motion trolley to the hanging mass to form a hanging stack. This kept the overall mass of the system constant but changed the force acting on the trolley. The students determined the new acceleration of the trolley. The process of moving masses from the trolley to the hanging stack and calculating the acceleration was repeated until there were no 50.0 g masses left on the trolley. The whole procedure was repeated a further two times.

The table shown below represents the data collected by the students.

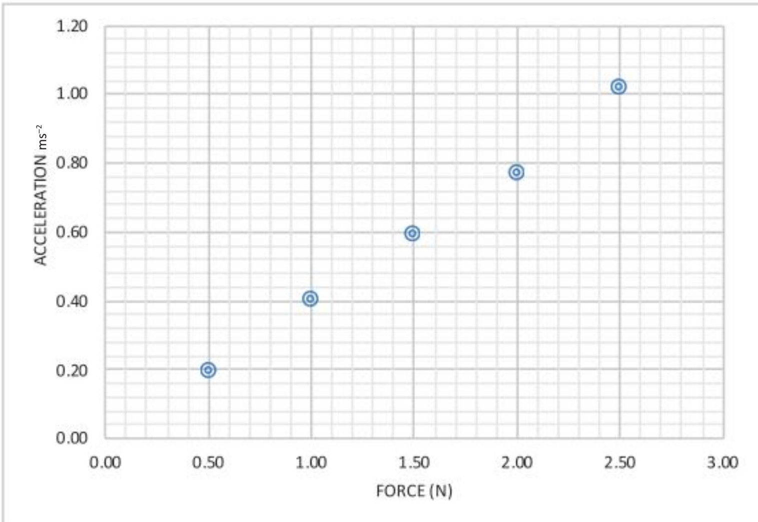
Force (N)	Time				Acceleration (ms^{-2})
	Trial 1	Trial 2	Trial 3	Average	
0.500	2.25	2.20	2.30	2.25	0.198
1.00	1.58	1.59	1.54	1.57	
1.50	1.29	1.30	1.30	1.30	0.592
2.00	1.11	1.16	1.14		0.769
2.50	0.97	0.99	1.00	0.99	1.02

(a) State the independent variable for this experiment. ....

(b) One value of average time is missing from the table. Calculate this value to an appropriate number of significant figures. Add the missing value to the table.

(c) One value of acceleration is missing from the table. Calculate this value and add it to the table.

(d) The student's data has been plotted. The graph is shown as follows.



(i) Draw a line of best fit for the data.

(ii) Explain whether Newton's Second Law has been verified by the results of this experiment.

....

....

....

....

(iii) Calculate the gradient of the line of best fit (include units).

....

....

....

(iv) Use the gradient of the line of best fit to calculate the mass of the trolley. Comment on the accuracy of the value.

....

....

....

....

....

(v) The students accelerated the motion trolley across a laboratory bench. The effect of friction was not taken into account. Explain the effect that friction would have on the data collected by the students.

....

....

....

....

(vi) Suggest one modification to the experimental procedure that would allow the effect of friction to be reduced.

(e) The students decide to perform another experiment to investigate the relationship between the distance travelled by the motion trolley and the time taken. Describe a method that the students could use given the same or other equipment.

Weight and Mass

1. (a) Calculate the weight of a 54.0 kg student on Earth.

(b) State the student's mass on the Moon.

(c) Determine the student's weight on the Moon.

2. Three 820g pendant lamps hang from a wire. Calculate the tension in the wire.

3. A 80 kg astronaut has a weight of 296 N on a planet (without his space suit).

   Calculate the gravitational acceleration on this planet.

   Can you identify the planet?

4. Explain why a person can jump approximately six times higher on the Moon compared to the height they can jump on Earth.

Topic 2: Electric circuits

2.1 Potential difference and Electric current

Science understanding

1. Atoms contain positively-charged protons and negatively-charged electrons.
2. Objects become charged when electrons are transferred from one object to another or redistributed on an object.
3. Two like charges exert repulsive forces on each other, whereas two opposite charges exert attractive forces on each other.
   - Describe electric forces between like and opposite charges.
   - Explain various phenomena involving interactions of charge.
   - Explain how electrical conductors allow charges to move freely through them, whereas insulators do not.
4. Energy is required to separate positive and negative charges and this charge separation produces an electrical potential difference that can be used to drive current in circuits.
5. The energy available to charges moving in an electrical circuit is measured using electric potential difference (voltage). This is defined as the change in potential energy per unit charge between two defined points in the circuit and is measured using a voltmeter.
   - Describe how a voltmeter is used in an electric circuit.
   - Explain the purpose of measuring potential difference in electric circuit.
6. Describe how electrical safety is increased through the use of
   - fuses or circuit breakers
   - residual current devices
7. Electric current is carried by discrete charge carriers. Charge is conserved at all points in an electrical circuit.
   - Distinguish between electron current and conventional current.
8. Electric current is the rate of flow of charge.
   - Solve problems involving $I = \frac{q}{t}$.
9. An ammeter is used to measure the electrical current at a point in a circuit. It is placed in series with the electrical component through which the current is to be measured.

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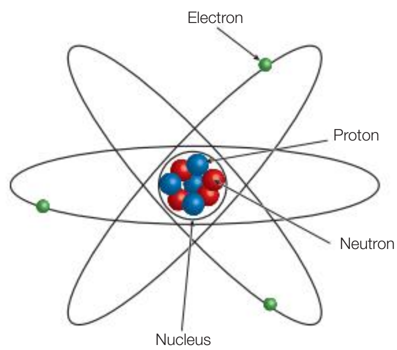
Electric charge

There are two types of charge: positive and negative.



Atoms contain positively-charged protons and negatively-charged electrons.

The nucleus is tiny and dense and located in the centre of the atom. It contains protons and neutral neutrons. The nucleus is therefore positively charged. Electrons circle the nucleus.

A neutral atom contains equal numbers of protons and electrons.

Charging objects

Electrons are less tightly bound to the atom than protons. It is therefore possible to remove electrons from one object and transfer them to another. In doing so, both objects become charged.

Positively charged materials lack electrons.

Negatively charged materials contain excess electrons.

Note: If the object is not charged, it is said to be neutral. This means that it has an equal amount of positive and negative charge.

It is also possible to charge an object when the charge becomes redistributed on that object.

Possible activities

1. Charging by rubbing or friction

An ebonite rod is made of hardened rubber. Figure 2.1.1 shows an ebonite rod being charged negatively by rubbing it with fur. Friction enables electrons to be rubbed off the fur. The ebonite rod readily accepts the electrons.

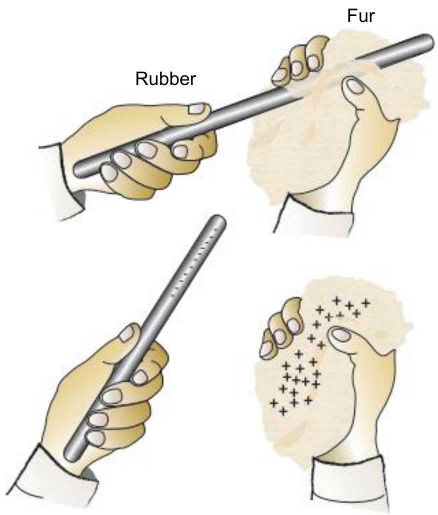


Figure 2.1.1

This occurs because different materials hold on to their electrons more tightly than others. In this case, the ebonite rod holds onto its electrons more tightly than the fur. The characteristic of holding on to its electrons is sometimes referred to as a material's **electronegativity**.

Once rubbed, the ebonite rod has excess negative charge and is therefore negatively charged. The fur will have excess positive charge. The amount of positive charge on the fur is equal to the amount of negative charge on the rod. This is an example of the **law of conservation of charge**.

In a similar way, a glass rod can be charged positively by rubbing it with silk. The same explanation applies except that the electrons are transferred from the glass rod to the silk. The glass rod lacks negative charge and is therefore positively charged.

Consider charging an ebonite rod negatively by rubbing it with fur and hanging it by a string from a retort stand as shown in the figure 2.1.2. If another negatively charged ebonite rod is brought near the hanging rod without touching it, the two rods repel one another. We say **like charges repel**. If a glass rod is charged positively by rubbing it with silk and brought near the hanging rod, the two rods attract. We say **unlike or opposite charges attract**. This is illustrated in figure 2.1.3.

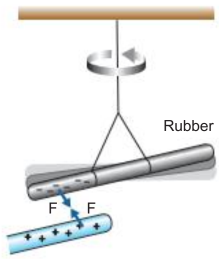


Figure 2.1.2

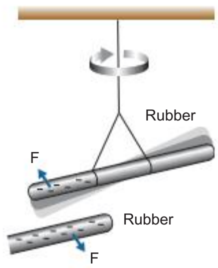


Figure 2.1.3

An everyday example of charging by friction is dragging your feet across carpet. When you touch another person, or a metallic object, a spark is produced. Charging by friction also occurs when liquids or gases pass through tubes (e.g. a gas is sprayed from a pressurised can).

Helpful online resources

If you are not prepared to get zapped by dragging your feet across the carpet, then try the PHET interactive tool:

phet.colorado.edu/sims/html/john-travoltage/latest/john-travoltage_en.html

2. The electroscope

The electroscope is a device that detects the presence of charge. There is more than one style of electroscope, as shown in Figure 2.1.4 but they all work in the same way.

Figure 2.1.4

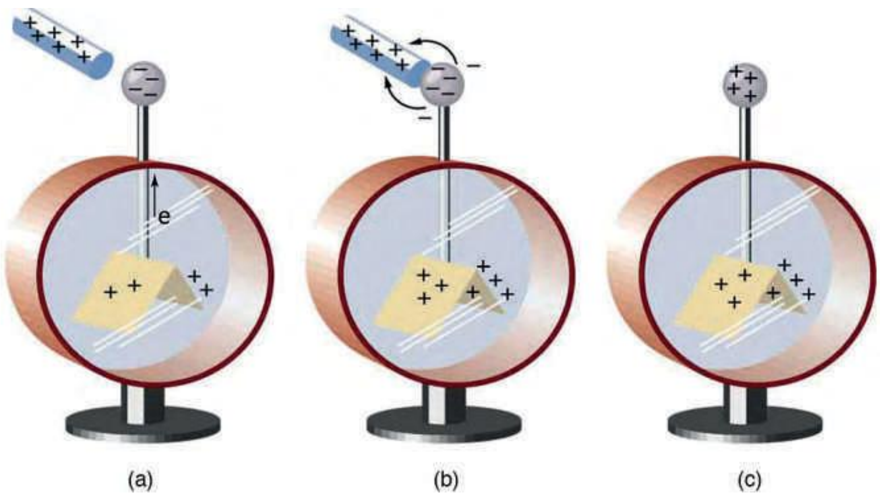


Figure 2.1.5

Figure 2.1.5 illustrates the method for charging an electroscope positively.

1. Start by touching the ball (sometimes called the cap) of the electroscope with your finger. This will earth the electroscope. This is because charge can flow through you to or from the Earth to neutralise any charge on the ball. The needle (or gold leaf, depending on the model) will lie un-deflected.
2. Charge a glass rod positively by rubbing it with silk. As the glass rod approaches the ball, electrons in the stem and needle (or the two gold leaves) are attracted towards the cap. The stem and the needle both become positively charged as they lack negative charge. Since there has been a separation of charge, we also say that a charge is **induced** (this explored further in the next activity).
3. The stem and needle will repel one another.

   The greater the charge on the rod, the more electrons are attracted to the ball. This means that the stem and needle will have a greater positive charge and repel each other more strongly. The needle experiences a greater deflection.
4. Now touch the ball with the rod. The electroscope becomes positively charged by contact because electrons are transferred from the ball to the rod.
5. Touch the cap with your finger. This will earth it again. In this case, electrons flow from the cap and through you to Earth.
6. Repeat this activity with a negatively charged ebonite rod.

3. Charging by contact or conduction

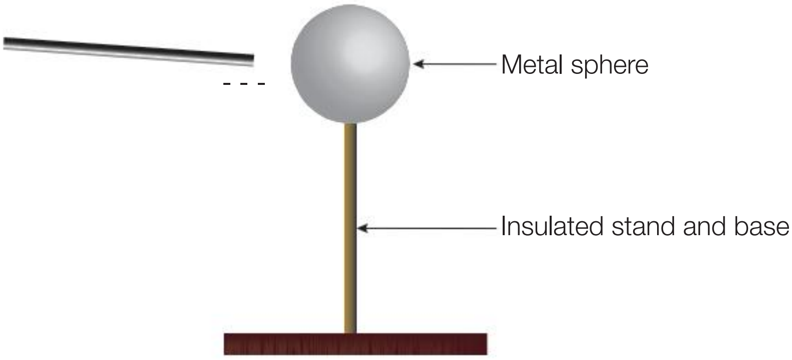


Figure 2.1.6

If a negatively charged ebonite rod touches a neutral metal sphere (usually mounted on an insulated stand), as shown in figure 2.1.6 the sphere becomes negatively charged by contact, as electrons from the ebonite rod move onto the sphere.

If a positively charged glass rod touches the neutral metal sphere, it becomes positively charged by contact, as electrons from the sphere move onto the rod.

You can check this using an electroscope. For example if you want to check that the metal sphere is positively charged, charge an electroscope positively by further touching it with a positively charged glass rod. When the positive sphere approaches the ball the needle will deflect.

Charging the electroscope negatively is not a good idea. You cannot confirm positive charge. If the deflection of the needle is reduced it could indicate that the sphere is positively charged or that it is neutral.

4. The Van de Graaff generator

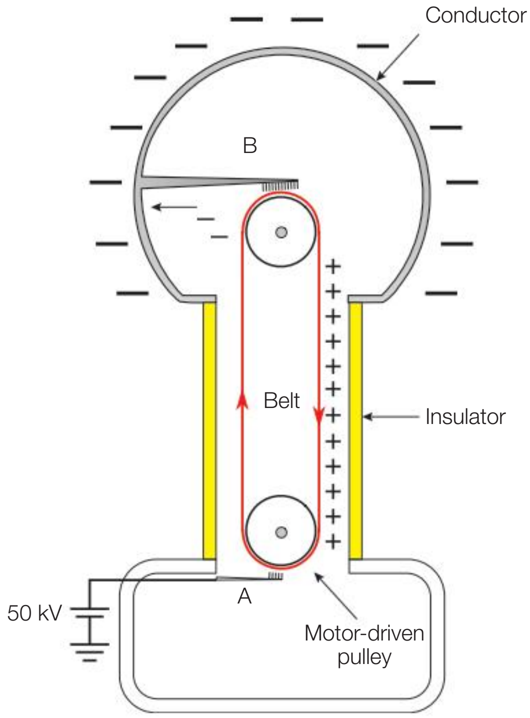


Figure 2.1.7

The Van de Graaff generator shown in figure 2.1.7 is electrostatic generator that is capable of producing a large voltage by accumulating a large amount of electrical charge on a hollow metal dome. It was invented by American physicist Robert J. Van de Graaff in 1929 and most schools have a small version in their physics laboratories.

A motor drives a neutral rubber belt around the inside of the generator.

The belt scrapes past a knife edge or a sharply pointed metal comb at the top wheel (B). Electrons are removed from the belt (due to friction) and transferred to the dome. The belt is now positively charged and returns to the bottom wheel where another knife edge earths the belt so that it is neutral. This process repeats many times and the dome accumulates a large amount of negative charge.

Make your hair stand on end!

If you place your hand on the dome before starting the Van de Graaff and stand in a plastic tray, negative charges are transferred to your body once the generator is switched on. Each strand of your hair and your scalp become negatively charged by contact. They are repelled from one another and your scalp, causing your hair to stand on end.

5. Charging by induction

If a charged rod is placed near a neutral conductor, the charges in the conductor separate and redistribute themselves. A charge is said to be **induced**.

Figure 2.1.8 shows that negative charges are attracted towards the positively charged rod. This induces a negative charge on the side of the conductor closest to the rod and a positive charge on the other side.

The conductor is attracted towards the rod because the force of attraction is greater than the force of repulsion (electric forces decrease with distance – this is covered later in the topic).

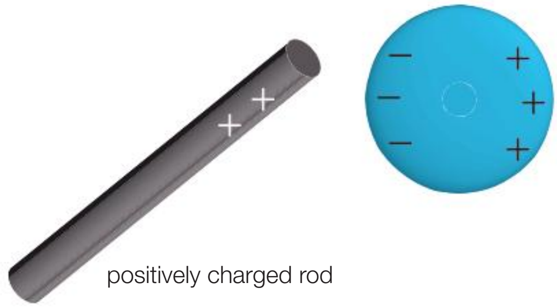


Figure 2.1.8

Note: The object is still neutral. If the rod is removed, the charges on the conductor will return to their original positions.

If two neutral conducting spheres are placed in contact, they behave as one conductor. If you touch them with your hand, they will be earthed. Two such conductors are shown in figure 2.1.9.

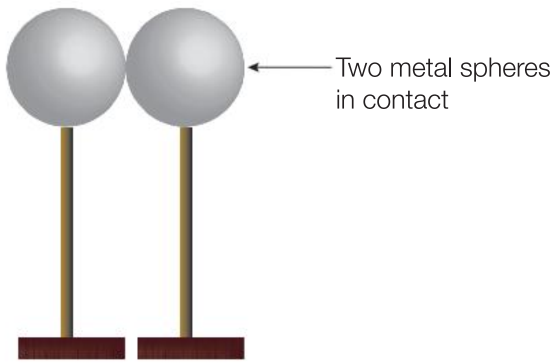


Figure 2.1.9

If a negatively charged rod is introduced without touching the spheres, a charge will be induced on the spheres. The sphere closest to the rod is charged positively by induction because electrons are repelled to the other sphere. The other sphere acquires an induced negative charge. If the spheres are separated without removing the rod they will have an equal and opposite charge. This is illustrated in figure 2.1.10.

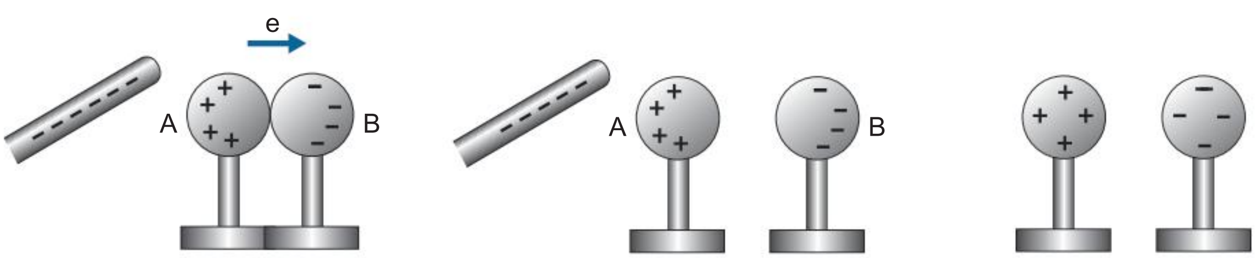


Figure 2.1.10

The charge on each sphere can be checked with an electroscope.

6. Charging by induction for non-conductors

Charging by induction also applies to materials that are not metals. Instead of the charges moving, rearrangement of the charges within the molecules occurs. One side of the object becomes slightly more negatively charged than the other. The molecules are said to be **electrically polarised** to form a **dipole**.

Figure 2.1.11 shows a positively charged rod near a non conducting material. Negative charges within the molecules of the material are attracted to the side closest to the rod. The material is attracted towards the rod because the force of attraction is greater than the force of repulsion (electric forces decrease with distance).

This is why paper is attracted towards charged rods, combs or balloons as shown in figure 2.1.12. Once the paper comes into contact with the rod it acquires the same charge as the rod and is repelled from the rod.

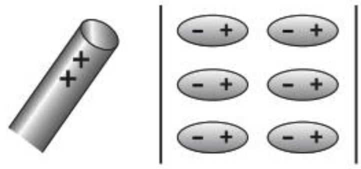


Figure 2.1.11

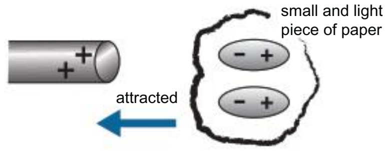


Figure 2.1.12

The law of conservation of charge

The law of conservation of charge states that the total charge in a closed system remains constant. That is, charge cannot be created or destroyed; it can only be transferred from one material to another.

Conductors and insulators

A material is a **conductor** if it allows charge to flow freely or redistribute itself evenly over the whole surface.

Metals are good conductors because their structure consists of positive ions surrounded by a ‘sea’ of free or **delocalised electrons**.

Solutions that conduct charge (called electrolytes) contain positive and negative ions that are free to move.

A material is an **insulator** if it does not allow charge to flow freely. Any charge that is introduced to the surface of a solid insulator is confined to a localised area. This is because electrons are held tightly and are not free to move throughout the material. Electrons can accumulate on the surface but cannot redistribute themselves.

Earthing a charged object

When a charged metal object is touched by your finger, the charges easily flow through your body to or from the Earth. The Earth can store a large amount of charge. If the conductor is negatively charged, excess electrons flow to Earth. If the conductor is positively charged, electrons flow from the Earth toward the conductor and neutralise it. The concept of earthing a conductor was referred to in some of the activities described earlier in this chapter.

Science as a human endeavour

At the end of 1749, Benjamin Franklin had noted many similarities between lightning and electricity. He decided to study charges using lightning. In 1752 Franklin flew a kite in a thunderstorm with the help of his son William.

The kite was attached to a wet silk string. An iron house-key was attached to the other end of the string. A thin metal wire was attached to the key and inserted into a Leyden jar (an early form of a capacitor designed to store charge).

Franklin attached a dry silk string to the key and flew the kite in an approaching thunderstorm. Franklin observed that some loose threads of the silk string were repelling one another. After the storm, he touched the key and received an electric shock. The negative charges stored in the cloud moved onto the kite, down the wet silk string to the key, and then into the Leyden jar where the charge was stored. Franklin's experiment therefore showed that lightning was **static electricity**.

Franklin knew that if lightning actually struck his kite he was likely to be electrocuted and die. Several other people repeated Franklin’s experiment and were killed.

Questions

1. Why did Franklin receive a shock when he touched the iron key?
2. Why was the silk string that Franklin held dry and the string that connected the kite to the key wet?
3. It is reported that Franklin sheltered himself from the thunderstorm in a barn. Why would this help keep him safe?

Answers

1. The iron key was a good conductor and became charged. The negative charge was attracted to the positive charge in his body and 'jumped' across to give him an electric shock.
2. Water conducts charge well. The dry string acted as a good insulator and prevented the negative charge reaching Franklin. The wet part of the silk string conducted charge well so that it flowed from the kite, down the string, onto the key and into the Leyden jar.
3. The barn helped keep Franklin and the silk string he was holding dry. Getting wet would increase his chances of being electrocuted because water conducts charge well.

Electric force

Earlier we saw that like charges repel and that unlike or opposite charges attract.

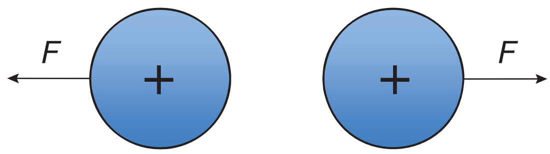


Figure 2.1.13

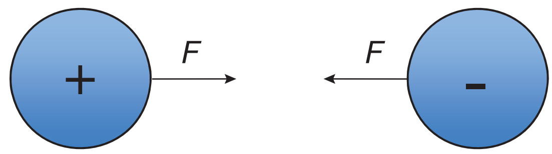


Figure 2.1.14

Electric forces are **non-contact forces**. A positively charged object will exert a repulsive force upon a second positively charged object; this force will push the two objects apart. The force acting on two positive charges shown in Figure 2.1.13. The same concept apples for two negatively charged objects.

However, a positively charged object will exert an attractive force upon a negatively charged object; this force will draw the two objects together. The force acting on two opposite charges is shown in figure 2.1.14.

Coulomb's Law

The electrostatic force of **attraction or repulsion** between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between their centres.

The magnitude of the force between two charges is given by:

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$$

where q_1 *and* q_2 *are the charges in Coulombs*

r is the distance between the charges in metres

$\frac{1}{4\pi\varepsilon_0} = 9.00 \times 10^9\ Nm^2C^{-2}$

F is the force in Newtons

The force acts along the line joining the centre of the charges.

Proportionality

- $F \propto q_1$ *for* q_2, r *constant*
- $F \propto q_1 q_2$ *for* r *constant*
- $F \propto \frac{1}{r^2}$ *for* $q_1 q_2$ *constant*

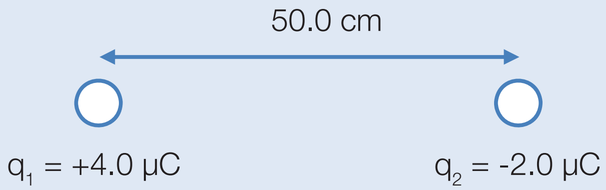
Note: An attractive force becomes a repulsive force and vice versa if the sign of one of the charges is reversed.

Principle of superposition

The force acting on a point charge when more than two point charges are present is a **vector sum** of the forces due to each of the other point charges present.

Worked examples

1. (a) Calculate the magnitude and direction of the force acting between a +4.0 μC charge and a –2.0 μC charge placed 50.0 cm apart in a vacuum.



$$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = \frac{9 \times 10^9 \times 4 \times 10^{-6} \times 2 \times 10^{-6}}{0.5^2} = 0.29 \text{ N } \textit{attraction}$$

(b) Use proportionality to determine the new force if the charges are placed 1.00 m apart.

$F \propto \frac{1}{r^2}$ *for* q_1, q_2 *constant*

The distance between the charges has been doubled. This means that the force will be 4 times smaller.

i.e. $\frac{0.29}{4} = 0.073$ N *attraction*

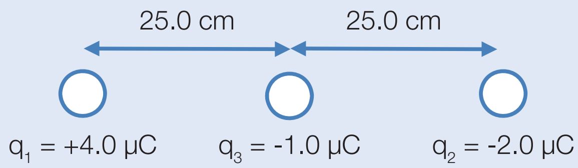
(c) Use proportionality to determine the new force if one charge is tripled.

$F \propto q_1$ *for* q_2, r *constant*

If one of the charges is tripled, the force will be 3 times larger.

i.e. 0.29 × 3 = 0.87 N *attraction*

(d) Calculate the force $\vec{F}$ acting on a –1.0 μC charge placed midway between the original two charges.



Force due to q_1: $\vec{F}_1 = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_3}{r_1^2} = \frac{9\times10^9 \times 4\times10^{-6} \times 1\times10^{-6}}{0.25^2} = 0.576\,N \quad \leftarrow$

Force due to q_2: $\vec{F}_2 = \frac{1}{4\pi\varepsilon_0}\frac{q_2 q_3}{r_1^2} = \frac{9\times10^9 \times 1\times10^{-6} \times 2\times10^{-6}}{0.25^2} = 0.288\,N \quad \leftarrow$

$\vec{F} = \vec{F}_1 + \vec{F}_2 = 0.576 \leftarrow +0.288 \leftarrow = 0.864\,N \leftarrow$

2. Two identical charges experience a repulsive force of 5.75 × 10^{-27} N when placed 20.0 cm apart in air. Calculate the magnitude of the charges. Identify the charges.

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2} = \frac{9\times10^9 \times q^2}{r^2}$$

$$q = \sqrt{\frac{Fr^2}{9\times10^9}} = \sqrt{\frac{5.75\times10^{-27} \times 0.2^2}{9\times10^9}} = 1.60\times10^{-19}C$$

The two charges are either two electrons or two protons.

Electrical discharges

An electric discharge is a flow of electric charge through a solid, liquid or gas.

Electric discharges have many applications, including vapour lamps, spark plugs, Geiger-Muller tubes, corona discharges in photocopiers, electric arc furnaces and piezo igniters.

Vapour lamps

Vapour lamps (or electric discharge lamps) work by passing an electrical discharge through the atoms of an ionised gas. An ionised gas is one in which electrons have been removed from the atom. Free electrons are then accelerated through the lamp (usually consisting of a tube). The electrons collide with the ionised gas particles and cause electrons held in energy levels (this will be discussed later) to become excited (i.e. jump up to higher energy levels). When the excited electrons return to a lower energy level they emit energy. The energy emitted is in the form of light. The colour of the light emitted depends on the gas inside the tube. Vapour lamps often contain a mixture of gases.

Fluorescent lamps are a common example of a vapour lamp. They emit ultraviolet light. This is then converted to visible light when it strikes the fluorescent coating on the inside of the lamp's tube.

Extra understanding

A spark plug is essential to a petrol engine. The spark produced causes a fuel and air mixture to ignite. This in turn causes pistons to move.

Piezo igniters produce a spark and are used to ignite a gas. They are commonly found in barbecue lighters. They work on the principle that some materials, such as quartz create an electrical discharge or spark when struck. Such materials are referred to as **piezoelectric**. When the button mechanism is pressed on a barbecue lighter, a spring-loaded hammer hits a quartz crystal to produce a spark.

Further investigate the application of electrical discharges in spark plugs and/or piezo igniters.

Helpful online resources

View this video to see how a spark plug works:

blog.micksgarage.com/how-spark-plugs-work/

View this video to see how a piezo barbecue igniter works:

www.youtube.com/watch?v=oegbv-1cKCA

Science as a human endeavour

Research innovative applications and limitations of semi-conductors (e.g. photovoltaic cells in solar panels, LEDs) or superconductors (e.g. maglev trains, MRIs).

Potential difference

Energy is needed to separate positive and negative charges. This separation of charge produces an electrical potential difference that can be used to drive current in circuits.

Consider electric charges in a circuit. The charges are static (still). The charges only move if a battery is present or a power source is turned on. We say that the battery has a voltage (potential difference) and supplies the charges with energy so that the charges can move.

The energy available to charges moving in an electrical circuit is measured using electric potential difference or voltage.

The electric potential difference (ΔV) is defined as the change in electrical potential energy or work done per unit charge (*q*) between two defined points in a circuit.

$$\Delta V = \frac{E_p}{q} \quad or \quad \Delta V = \frac{W}{q}$$

where ΔV is the potential difference in volts (V)

q is the charge in Coulombs (C)

Ep is the electrical potential energy in Joules (J)

units JC^{-1} or Volts (V)

2

Worked examples

1. A proton of charge $+1.60 \times 10^{-19}$ C gains 8.5×10^{-18} J of electrical potential energy.

   Calculate the potential difference through which the proton is moved.

   $$\Delta V = \frac{E_p}{q} = \frac{8.5 \times 10^{-18}}{1.6 \times 10^{-19}} = 53 \text{ V}$$

2. The potential at a point A is 2.00 V and the potential at a point B is 10.0 V.

   (a) State the potential difference between the points.

   8.00 V

   (b) State the change in potential energy experienced by an electron moving from A to B. The charge of an electron is -1.60×10^{-19} C . Will the electron lose or gain electrical potential energy? Justify your answer.

   Change in potential energy = $E_p = q\Delta V = 1.60 \times 10^{-19} \times 8 = 1.28 \times 10^{-18}$ J

   The electron loses electrical potential energy (and gains kinetic energy) because it is moving towards a point of higher potential.

Application of potential difference

X-rays

X-ray tubes like the one shown in figure 2.1.15 are used to produce medical images. Electrons released from a heated filament are passed through a large potential difference of 100 000 V or more.

The electrons accelerate across the X-ray tube towards a positive anode and strike a target metal. At this point, the electrons lose kinetic energy and this energy is released as X-rays.

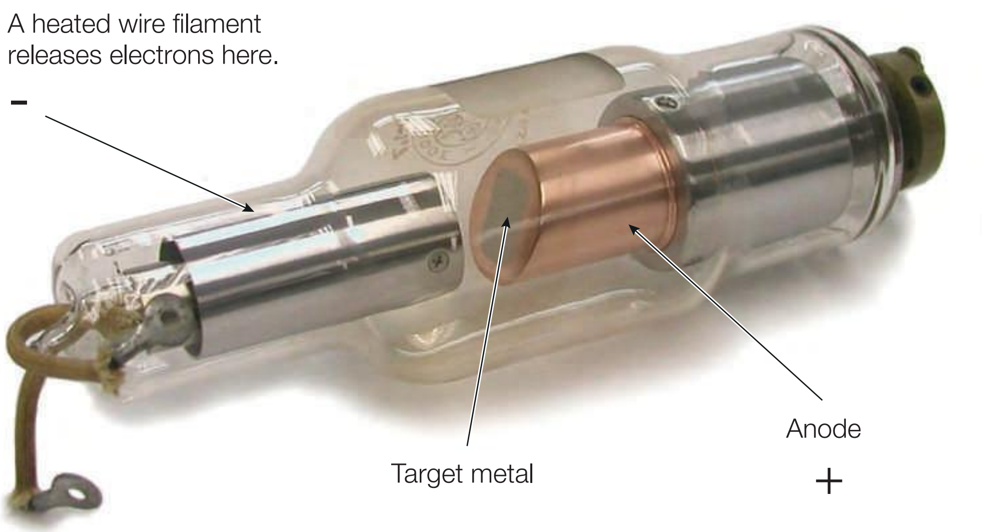


Figure 2.1.15

Science as a human endeavour

Explore the application of potential difference in particle accelerators. How are they useful for producing radioisotopes that can be used in medical imaging?

What are the social and economical impacts (for example, access and affordability) of such treatment in different parts of the world?

Current

Electric current is defined as the charge flowing past a point in a conductor per second or the rate of flow of charge.

$$I = \frac{q}{t}$$

where I is the current in Amperes

q is charge in Coulombs (C)

t is the time over which the charge is flowing

SI units: Ampere (A)

1 A = 1 Cs^{-1}

Charge-carriers in a metal

Electric current is carried by discrete charge-carriers. Electrons are the charge-carriers in metals.

The sign of an electron is negative and the charge is $e = 1.60 \times 10^{-19}$ C.

Electron current and conventional current

Conventional current refers to the direction that positive charges flow through a circuit. When analysing electric circuits (and in other topics such as magnetism) we use conventional current. While we now know that current involves the movement of electrons through a conductor, conventional current is a convention that has remained. Electron current refers to the direction that electrons flow through a circuit.

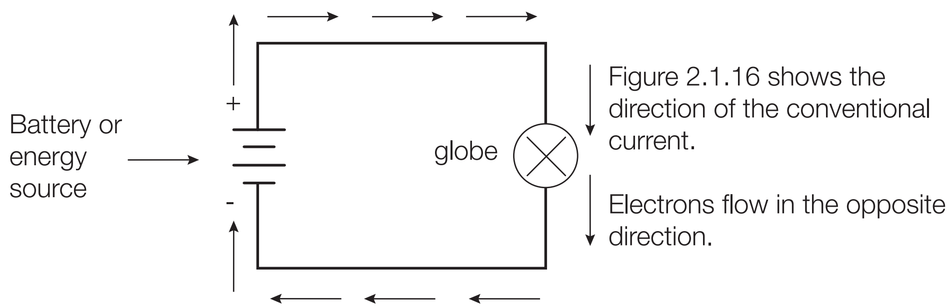


Figure 2.1.16

Worked examples

(a) 3.50×10^2 C of charge passes through the element of a kettle in 1.5 minutes. Calculate the current flowing.

$$I = \frac{q}{t} = \frac{3.5 \times 10^2}{1.5 \times 60} = 3.9 \text{ A}$$

(b) Calculate the number of electrons that flow through the element in this time.

$$\text{Number of electrons} = \frac{\textit{total charge}}{e} = \frac{3.5 \times 10^2}{1.6 \times 10^{-19}} = 2.2 \times 10^{21}$$

Extra understanding

Observe how the conductivity of metals, molten and aqueous ionic compounds, and ionised gases provide evidence for a variety of charge carriers.

Measuring potential difference

Voltmeters are used to measure the potential difference between two points in a circuit.

A voltmeter is connected in **parallel** with the component across which the potential difference is to be measured.

Measuring current

An ammeter is used to measure the electrical current at a point in a circuit. Ammeters are connected in **series** with the electrical component through which the current is to be measured.

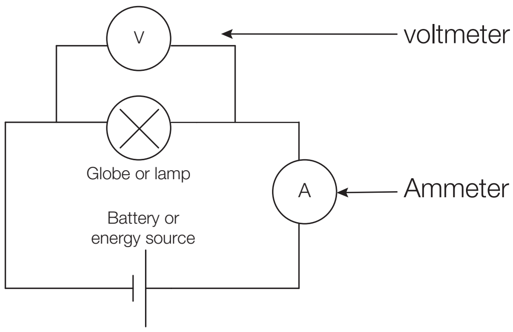


Figure 2.1.17

Figure 2.1.17 illustrates how to correctly connect an ammeter and voltmeter in a circuit.

2.2 Resistance

Science understanding

1. Resistance for ohmic and non-ohmic components is defined as the ratio of potential difference across the component to the current in the component.
2. The resistance of a conductor depends on its length, area of cross-section, temperature, and the type of material of which it is composed.
3. Resistance is constant for ohmic resistors, which conform to Ohm's Law.
4. Ohm's Law states that current is directly proportional to the potential difference, providing the temperature of the conductor remains constant.
   - Solve problems involving $R = \frac{V}{I}$.

Charge-carriers (electrons) flowing through a conductor collide with each other and the positive ions in the metal. The electrons transfer kinetic energy to the vibrating positive ions. The positive ions vibrate faster and the conductor heats up. This gives rise to the concept of resistance.

Resistance is an indication of how hard it is for charge to flow through a conductor. The higher the resistance, the harder it is for the charge to flow.

Conductors of charge have a low resistance. Insulators have a large resistance.

The electrical resistance of a component is defined as the ratio of the potential difference applied across the component to the current flowing in the component.

$$R = \frac{V}{I}$$

where R is the resistance of the component in Ohms (Ω)

V is the potential difference across the component in volts (V)

I is the current flowing in the component in Amperes *(A)*

SI units: Ohm (Ω)

$1\ \Omega = 1\ \mathrm{V\ A^{-1}}$

Wires with high resistances are used to make the heating elements of toasters, incandescent globes and heaters. Electrons struggle to pass through the material, undergo many collisions and lose their kinetic energy as heat.

Resistance increases as the temperature of the material increases. The charges in the material start to vibrate and move faster, causing more collisions and further retarding the movement of charge.

Ohm's Law

Ohm's Law states that the current is directly proportional to potential difference providing the temperature of the conductor remains constant.

$$I \alpha V$$

As an equation Ohm's Law can be expressed as $R = \frac{V}{I}$

Worked examples

1. A current of 0.235 A flows through a circuit when a potential difference of 12.0 V is applied. Calculate the resistance of the circuit.

$$R = \frac{V}{I} = \frac{12}{0.235} = 51.1\ \Omega$$

2. (a) A coil of wire has a resistance of 22 Ω. Calculate the current that flows when a potential difference of 6.0 V is applied.

$$R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{6}{22} = 0.27\ \text{A}$$

(b) Determine the number of electrons passing a point in the conductor in half a minute.

$$q = It = 0.27 \times 30 = 8.1\ C$$

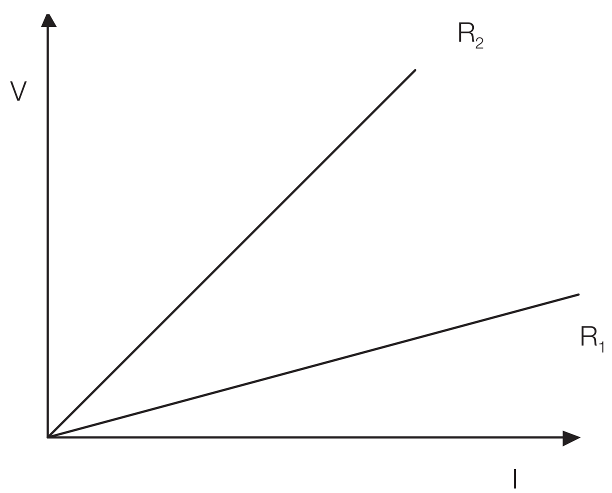
$$\text{Number of electrons} = \frac{\text{total charge}}{e} = \frac{8.1}{1.6 \times 10^{-19}} = 5.1 \times 10^{19}$$

Representing Ohm's law graphically

Since $R = \frac{V}{I}$ then $V = IR$ or $I = \frac{V}{R}$.

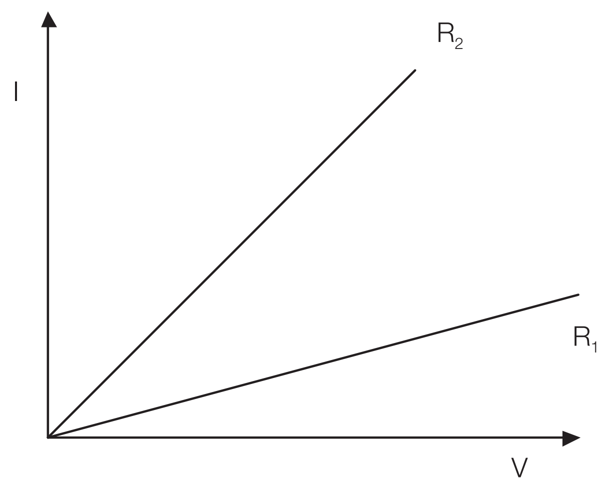
When these equations are compared to $y = mx$, it can be seen that the gradient of a *V vs I* graph gives the value for resistance (*R*), and the gradient of an *I vs V* graph gives $\frac{1}{R}$.

Figure 2.2.1 shows that the gradient is greater for a greater resistance. Figure 2.2.2 shows that the gradient is smaller for a greater resistance.



R_2 is greater than R_1

Figure 2.2.1



R_2 is less than R_1

Figure 2.2.2

? Science inquiry activity

Verifying Ohm's law

Set up the circuit shown in figure 2.2.3. The arrow through the energy supply means that the potential difference can be varied. The rectangular box represents a resistor.

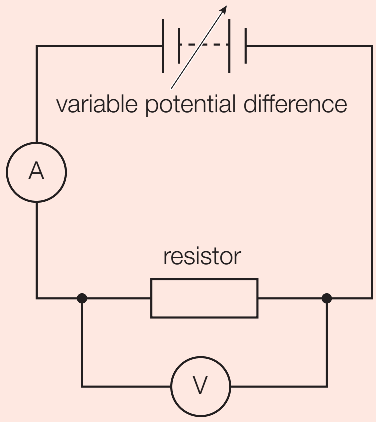


Figure 2.2.3

Vary the potential difference using a power pack and record the potential difference and corresponding current. You can use the table shown in figure 2.2.4 to record your data. Think about the amount of data that should be collected so that a suitable graph of current against potential difference can be plotted i.e. independent variable on the horizontal axis and the dependent variable on the vertical axis.

Potential difference (V)	Current (A)

Figure 2.2.4

Results

A straight line of best fit through the origin should result. This would verify Ohm's Law i.e. current is directly proportional to the potential difference.

$R = \frac{V}{I}$ so $I = \frac{V}{R}$. Comparing this to $y = mx$ indicates that the gradient represents $\frac{1}{R}$.

The resistance of the resistor connected in the circuit is given by $\frac{1}{gradient}$.

Key ideas

Accuracy is a measure of how close an experimental value is to a known value.

Precision is indicated by the amount of scatter in a set of results.

Questions

Use the gradient of the graph to determine the resistance of the resistor in the circuit.

How accurate is your experimental value of the resistance?

What changes could you make to the procedure to improve the precision of the results?

Ohmic and non-ohmic conductors

Conductors that obey Ohm's Law ($I \alpha V$) are said to be ohmic conductors.

Many conductors are ohmic over a reasonable range of current and potential difference but, due to the heat created with larger currents, Ohm's Law is not followed for all values of current and potential difference. This means that a conductor is an ohmic conductor if the temperature remains constant.

Resistance is constant for ohmic resistors which conform to Ohm's Law.

When a conductor or device does not obey Ohm's Law it is said to be non-ohmic. A filament globe or lamp heats up when it is turned on and the temperature increases with time. A typical graph of current against potential difference is shown in figure 2.2.5.

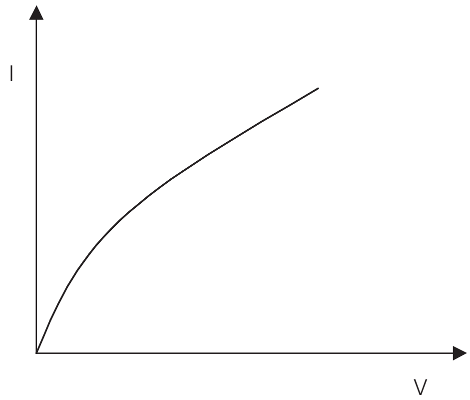


Figure 2.2.5

As the conductor (e.g. light bulb) gets hotter, the metal atoms vibrate more vigorously and the electrons in the delocalised electron cloud move faster. This creates more collisions between the electrons and the metal atoms. This has the effect of increasing resistance and decreasing the gradient (gradient = $\frac{1}{R}$).

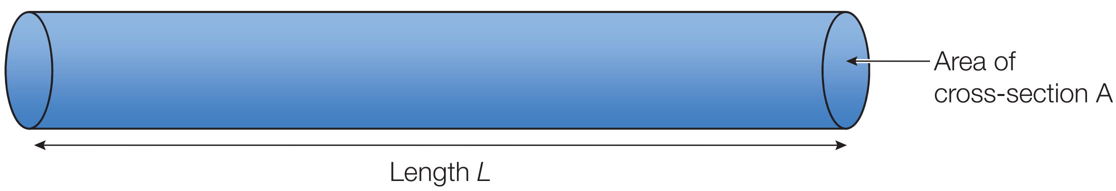
Helpful online resources

Resistance in a wire:

phet.colorado.edu/en/simulation/resistance-in-a-wire

Resistivity and resistance

Charges flow through a conductor when a potential difference is applied. The resistance of a conductor depends on several factors.



1. *Length (L)*

   Resistance is directly proportional to the length of a conductor ($R \alpha L$). This means that the resistance increases by the same factor as the length increases.

   If the length doubles so does the resistance. This is because the electrons suffer twice as many collisions.

2. *Area of cross-section (A)*

   Resistance is inversely proportional to the area of cross-section of a conductor ($R \alpha \frac{1}{A}$). This means that the resistance decreases by the same factor as the area of cross-section increases.

   If the area of cross-section of a conductor doubles then the resistance will halve. This is because the electrons suffer half as many collisions with in the conductor.

3. *Type of material*

Resistivity (ρ) of a material is the resistance of a 1 m length of the wire with an area of cross-section of 1 m^2.

Resistance is directly proportional to the resistivity of a conductor ($R \alpha \rho$). This means that the resistance increases by the same factor as any increase in resistivity.

If the resistivity doubles so does the resistance.

4. *Temperature*

As discussed earlier in the chapter, the resistance increases with temperature. Electrons gain kinetic energy and move faster. As a result they suffer more collisions in the conductor.

$$R = \frac{\rho L}{A}$$

where *R* is the resistance of the conductor in Ohms (Ω)

L is the length of the conductor in metres (m).

ρ is the resistivity of the material in Ω m

A is the area of cross-section of the wire in m^2

2

Worked examples

1. Copper has a resistivity of 1.7×10^{-8} Ω m. Calculate the resistance of a 2.00 m length of copper wire that has a diameter of 2.00 mm.

$R = \frac{\rho L}{A}$ where $A = \pi r^2$

$$R = \frac{\rho L}{A} = \frac{1.7 \times 10^{-8} \times 2}{\pi (1 \times 10^{-3})^2} = 1.1 \times 10^{-2}\ \Omega$$

2. Given that a 50.0 cm length of wire with a radius of 3.0 mm has a resistance of 4.0 Ω, calculate the resistivity of the material making up the wire.

$$R = \frac{\rho L}{A} \quad \therefore \quad \rho = \frac{RA}{L} = \frac{R\pi r^2}{L} = \frac{4 \times \pi \times (3 \times 10^{-3})^2}{0.5} = 2.3 \times 10^{-4}\ \Omega\ m$$

3. If the resistance of a wire is R. State the new resistance, in terms of R, if the area of cross-section decreases by a factor or 4.

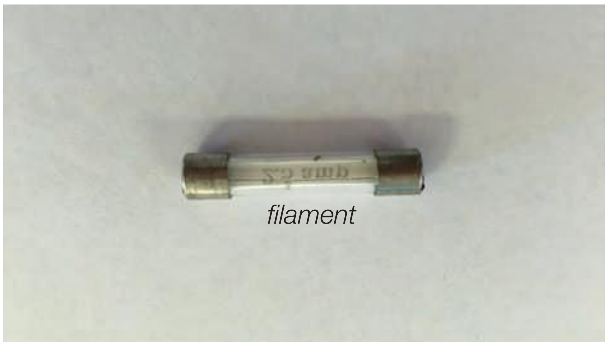
$R \alpha \frac{1}{A}$ The resistance will be 4 times larger if the area of cross-section decreases by a factor or 4.

New resistance is 4R.

? Science inquiry activity

Design a practical to investigate one factor that affects the resistance of a conductor.

Electrical safety devices – circuit breakers and fuses



A typical fuse

Figure 2.2.6

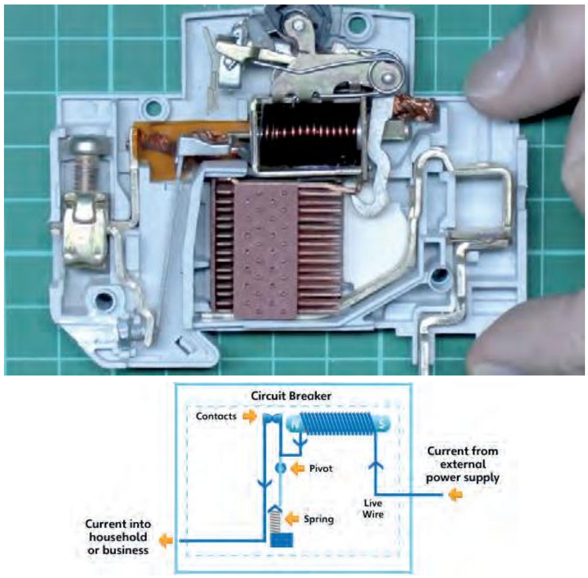
This fuse is part of a circuit board

Figure 2.2.7

Fuses consist of a metal wire or filament enclosed in a glass or ceramic and metal casing. A fuse can protect the appliances in your home. All the wiring of the home passes through a central fuse box. If there is a power surge or an overload, too much current flows and the filament in the fuse quickly melts. This will stop the flow of electricity to the appliances in a section of the home and save the appliances from damage. The fuse will need to be replaced. Figure 2.2.6 shows a fuse. The filament is clearly visible. Figure 2.27 shows a fuse in a circuit board.

A typical circuit breaker

Figure 2.2.8



Inside a circuit breaker

Figure 2.2.9

Circuit breakers consist of a bimetallic strip or a solenoid. A bimetallic strip consists of two different metal strips bonded together. The strips expand at different rates when heated. A solenoid consists of a coil of wire which becomes magnetic when a current flows. Figure 2.2.8 shows a typical circuit breaker.

If there is a power surge and too much current flows, the bi-metallic strip heats up and bends or, in the case of an electromagnet, becomes strong enough to attract the metal lever at the contact. In either case the circuit is broken and the current stops flowing. The inside of a circuit breaker is shown in figure 2.2.8.

Once the problem is addressed, the switch is turned back on and the current can flow to the appliance as normal. Both fuses and circuit breakers prevent the circuit from overheating. This will prevent the dangers associated with fire.

Science as a human endeavour

Assess the economic, social, and environmental impacts of electrical safety devices, such as circuit beakers and fuses.

2.3 Circuit analysis

Science understanding

1. Circuit analysis and design involve calculation of the potential difference across, the current in, and the power supplied to, components in series, parallel and composite circuits.
2. The current is equal in each series component.
   - Solve problems involving $V_t = V_1 + V_2 + ..V_n$ *and* $R_t = R_1 + R_2 + ..R_n$ for components in series.
3. The potential difference is equal across each parallel component.
   - Solve problems involving $I_t = I_1 + I_2 + ...I_n$ *and* $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + ..\frac{1}{R_n}$
4. Undertake experiments to investigate current, resistance or potential difference in series and parallel circuits using various circuit elements.

2

Electrical circuit symbols

To make drawing circuit diagrams easier and consistent, symbols are allocated to represent different components in a circuit. Figure 2.3.1 is a summary of the common symbols that may be useful to this course.

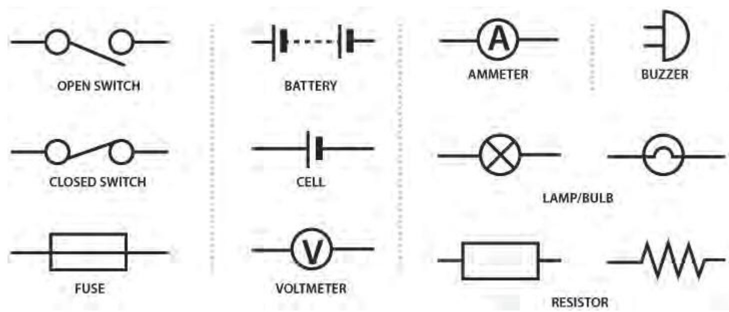


Figure 2.3.1

Resistors in series and parallel

Series circuit

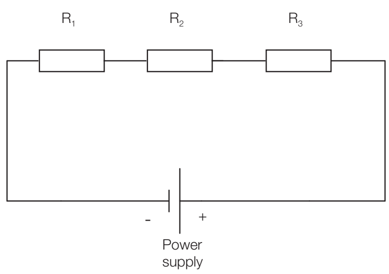


Figure 2.3.2

Resistors are connected end to end as shown in figure 2.3.2.

The current is equal in each series component

$I_1 = I_2 = I_3$

$V_t = V_1 + V_2 + V_3$

$R_t = R_1 + R_2 + R_3$

Parallel circuit

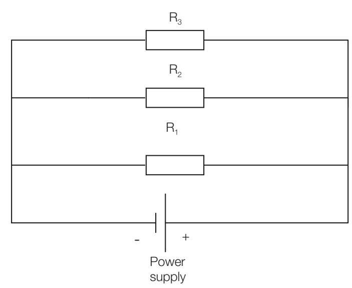


Figure 2.3.3

Resistors are connected across one another as shown in figure 2.3.3.

The potential difference is equal across each parallel component

$V = V_1 = V_2 = V_3$

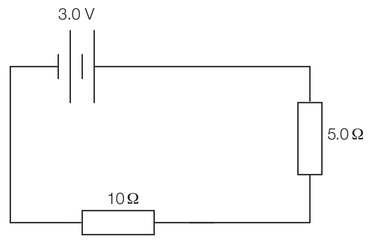
$I_t = I_1 + I_2 + I_3$

$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

The ideas presented above can be extended to *any number of components*.

Worked examples

1. **Series circuit**



(a) State the effective resistance in the circuit.

15 Ω

(b) Calculate the current flowing through the circuit.

$$I = \frac{V}{R} = \frac{3}{15} = 0.20\ A$$

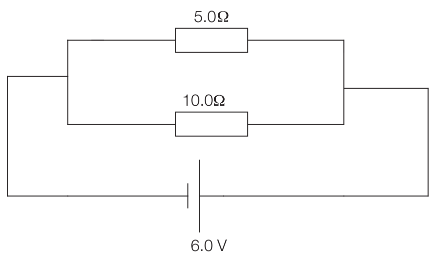
(c) Calculate the potential difference across each resistor.

10 Ω $V = IR = 0.2 \times 10 = 2.0\ V$

5.0 Ω $V = IR = 0.2 \times 5 = 1.0\ V$

(NB: 2.0 V + 1.0 V = 3.0 V)

2. **Parallel circuit**



(a) Calculate the resistance of the circuit.

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R} = \frac{1}{5} + \frac{1}{10}$$

$R = 3.3\ \Omega$

(b) Calculate the current flowing through the circuit.

$$I = \frac{V}{R} = \frac{6}{3.3} = 1.8\ A$$

(c) State the potential difference across the 10 Ω resistor.

6.0 V

(d) Calculate the current flowing through the 10 Ω resistor.

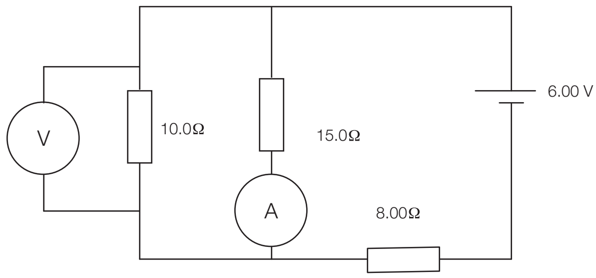
$$I = \frac{V}{R} = \frac{6}{10} = 0.60\ A$$

(e) Calculate the current flowing through the 5.0 Ω resistor.

$$I = \frac{V}{R} = \frac{6}{5} = 1.2\ A \text{ or } 1.8 - 0.6 = 1.2\ \text{A}$$

3. **A composite circuit**

A composite circuit is a combination of series and parallel circuits.



(a) Calculate the resistance of the circuit.

Parallel branch

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R} = \frac{1}{15} + \frac{1}{10}$$

$R = 6.00\ \Omega$

Total resistance

6 + 8 = 14.0 Ω

(b) Calculate the current flowing through the circuit.

$$I = \frac{V}{R} = \frac{6}{14} = 0.429\ A$$

(c) Determine the reading on the voltmeter.

The potential difference across the 8.00 Ω resistor is given by

$V = IR = 0.429 \times 8 = 3.43\ V$

since $V_{total} = V_{parallel} + V_{8\Omega}$

then the voltmeter reads

6 − 3.43 = 2.57 V

(d) Determine the reading on the ammeter.

The potential difference is equal across parallel components

The potential difference across the

15.0 Ω resistor is 2.57 V.

$$I = \frac{V}{R} = \frac{2.57}{15} = 0.171\ A$$

Helpful online resources

Computer interactive: Build some circuits using the following interactive link.

www.physicsclassroom.com/Physics-Interactives/Electric-Circuits

? Science inquiry activity

Building and analysing electric circuits is a valuable skill. Set up a variety of series, parallel and composite circuits. The resistors available will vary from school to school.

Determine the current at various points in the circuit and the potential difference across various components.

Do your experimental values for current and potential difference confirm the theoretical values?

2.4 Electrical Power

Science understanding

1. Power is the rate at which energy is transformed by a circuit component.
   - Solve problems involving $P = \frac{\Delta E}{t}$ and $P = IV$ and the use of Ohm's Law formula.
   - Solve problems involving the cost of electrical energy, using kilowatt-hours.
2. Electrical circuits enable electrical energy to be transferred efficiently over large distances and transformed into a range of other useful forms of energy including thermal and kinetic energy, and light.
   - Solve problems involving $efficiency = \frac{useful\ energy\ /\ power\ output}{total\ energy\ /\ power\ input} \times 100$

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Power

All electrical devices have a power rating, e.g. a kettle with a power rating of 1200 W uses 1200 J of electrical energy every second.

Power is the rate at which energy is transformed by a circuit component.

$$P = \frac{\Delta E}{t}$$

SI unit: Watt (W)

1 W = 1 Js^{-1}

Other expressions for power

$$P = \frac{W}{t} = \frac{qV}{t} = \frac{(It)V}{t} = IV$$

since $V = IR$ *then* $P = IV = I(IR) = I^2R$

also $I = \frac{V}{R}$ *then* $P = IV = \frac{V \times V}{R}$ $P = \frac{V^2}{R}$

The cost of running electrical appliances

If electrical energy is charged by the kilowatt-hour then the cost of running an appliance is the product of energy used in kilowatts and the price of the electrical energy per kilowatt-hour.

Energy in kilowatts = Power in kilowatts × t

Cost = Energy in kilowatts × cost per kilowatt hour

Or

Cost = Power in kilowatts × number hours × cost per kilowatt

Efficiency

Electric circuits enable electrical energy to be transferred efficiently over large distances and transformed into a range of other useful forms of energy including thermal, kinetic and light.

Efficiency is expressed as a percentage and can be calculated using the equation:

$$efficiency = \frac{useful\ energy\ /\ power\ output}{total\ energy\ /\ power\ input} \times 100$$

Worked examples

1. An electric motor operates on 240 V and draws a current of 2.0 A.

(a) Calculate the power input to the motor.

$P = VI = 240 \times 2 = 480\ W$

(b) If the motor delivers a maximum power of 300 W. Calculate the efficiency of the motor.

$$efficiency = \frac{power\ output}{power\ input} = \frac{300}{480} = 0.625$$

i.e. an efficiency of 63%

2. An electric fan is rated 2400 W, 240V.

(a) Calculate the current drawn by the fan while it is switched on.

$$P = VI \quad \therefore \quad I = \frac{P}{V} = \frac{2400}{240} = 10\ A$$

(b) Calculate the electrical energy used by the fan in 3.0 hours.

$$P = \frac{\Delta E}{t} \quad \therefore \quad \Delta E = Pt = 2400 \times (3 \times 60 \times 60) = 2.6 \times 10^7\ J$$

(c) Electricity costs 15c per kilowatt hour (kWh). Determine the cost of running the fan for 3.0 hours.

Cost = P(kilowatts) × number hours × cost per kilowatt = 2.4 × 3 × 15 =108 cents = $1.10

(d) Calculate the efficiency of the fan if 3.8×10^6 J of energy are lost to heat and sound while the fan is operating over the 3.0 h period.

Useful energy = $2.6 \times 10^7 - 3.8 \times 10^6 = 2.22 \times 10^7$ J

$$efficiency = \frac{useful\ energy}{total\ energy} = \frac{2.22 \times 10^7}{2.6 \times 10^7} = 0.85$$

i.e. an efficiency of 85%

? Science inquiry activity

Select an electrical appliance in your home, e.g. a heater.

Find out the power rating of the appliance and the average cost of electricity from your last household bill.

Can you work out the average operating cost of the appliance for one day? One week? One year?

Science as a human endeavour – example

High voltage transmission lines

Power loss in transmission lines occurs due to the resistance of the conductors. It is lost or dissipated as heat.

Let *P* represent the power to be transmitted, *V* the voltage with which the power is transmitted and *R* the resistance of the transmission line, then the current *I* flowing through the transmission line is $I = \frac{P}{V}$.

The power loss $P_{loss} = I^2R = (\frac{P}{V})^2 R$. Since P and R are constant, then less power will be lost if high-voltage lines are used. In other words, a small current is used to deliver the electrical energy over large distances.

Extra understanding

Research local and large-scale electricity generation and compare them in terms of their efficiency, convenience and effect on the local and global environment.

Exercises

Electric charge

2.1 Potential Difference and Electric Current

1. Complete the following table

Sign of one charge	Sign of second charge	Description of force between the charges
positive	positive	
positive		attraction
	negative	repulsion

2. The electronegativity of wool is less than the electronegativity of brass but greater than that of glass. State, with reasons, the sign of the charge acquired by brass and glass if they are individually rubbed with wool.

3. Explain why a car will immediately attract dust after it has been polished.

4. A student wishes to use a Van de Graff generator to make her hair stand on end. Explain why the student needs to stand in a plastic tray in order to be successful.

5. Rubbing a balloon on your hair charges it negatively.

   Describe how an electroscope can be used to confirm the balloon is negatively charged.

6. A positively charged glass rod is brought close to a thin stream of water. Describe and explain what you would observe.

7. (a) Describe the difference between a conductor of charge and an insulator of charge.

   (b) Explain why a copper rod can never be charged by friction while being held in the palm of your hand.

8. This question requires a longer response.

   In answering the question that follows you should:

   - *communicate your knowledge clearly and concisely*
   - *use physics terms correctly*
   - *present information in an organised and logical sequence*
   - *include information that is relevant to the question.*

   Figure 1 shows a Van de Graaff generator with several neutral metal pie plates resting on the dome. Figure 2 shows the metal pie plates lifting off the dome a short time after the Van de Graaff generator is switched on. The top plate lifts off first, followed by the others beneath it.

Figure 1

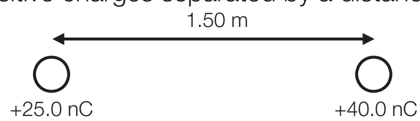
Figure 2

   Explain why the neutral metal plates lift off the dome in the manner described.

Electric force

1. Calculate the force $\vec{F}$ acting between a –6.5 × 10^{-3} C charged sphere and a +7.5 × 10^{-3} C charged sphere placed 35 cm apart in a vacuum.

2. The diagram below represents two positive charges separated by a distance of 1.50 m in a vacuum



   (a) Calculate the magnitude and direction of the electric force acting between the two charges.

   (b) Draw vector arrows to represent the force acting on each of the charges.

   (c) Use proportionality to determine the effect on the magnitude of the force acting between the two charges when

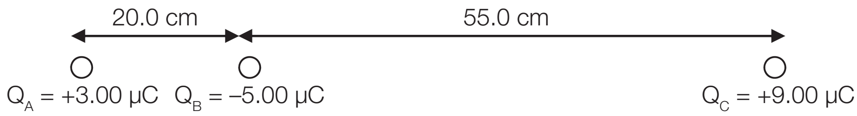
      (i) the +25.0 nC charge is replaced with a –75.0 nC charge.

      (ii) the distance between the charges is halved.

      (iii) the +25.0 nC charge is replaced with a –75.0 nC charge and the distance between the charges is halved.

3. The magnitude of the electric force between a +5.0 μC charge and a +3.0 μC charge is 0.50 N. Show that the distance between the two charges is 0.52m.

4. Calculate the magnitude and direction of the electric force acting on charge Q_C in the situation below. Assume the charges are in a vacuum.



5. (a) The magnitude of the electric force between two charges placed 2.0 m apart in a vacuum is 4.0×10^4 N. One of the charges is known to be 5.0 mC. Calculate the magnitude of the other charge present.

(b) The distance between the charges is changed such that the magnitude of the force increases to 6.4×10^5 N. Determine the new distance between the charges.

6. Calculate the electric force $\vec{F}$ acting on the –0.60 C charge in the situation illustrated below. Assume the charges are in a vacuum.

Potential difference

1. Calculate the potential difference through which an alpha particle with a charge of 3.2×10^{-19} C needs to be accelerated in order to gain 5.0×10^{-17} J of electrical potential energy.

2. An electron is accelerated through a potential difference of 6000 V.

   (a) Calculate the gain in electrical potential energy experienced by the electron.

   (b) State the amount of kinetic energy gained by the electron.

3. An x-ray tube operates at 30.0 kV. Calculate the gain in electrical potential energy of electrons which are accelerated across this potential difference.

Current

1. Define the term ‘current’.

2. (a) 8.00 C of charge passes through a point in a circuit every 30.0 s. Calculate the current flowing.

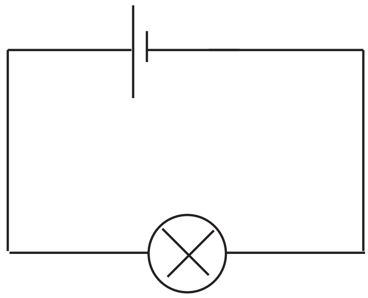
   (b) Calculate the number of charge carriers that have passed this point of the circuit in 30.0 s.

3. 0.500 A of current is measured flowing through a component of a circuit. Calculate the charge and the number of electrons passing through the component every minute.

4. 3.00×10^{19} electrons pass through the filament of a light globe every 10.0s. Calculate the current flowing through the filament.

5. (a) Distinguish between electron current and conventional current.

(b) On the diagram of the circuit shown below, clearly mark in the direction of electron and conventional current.



2.2 Resistance

1. A potential difference of 8.0 V is applied across the component of a circuit. The potential difference causes a current of 0.15 A to flow through the component. Calculate the resistance of the component.

2. (a) Define the term 'electrical resistance'.

(b) Explain why the resistance of a circuit results in the production of heat.

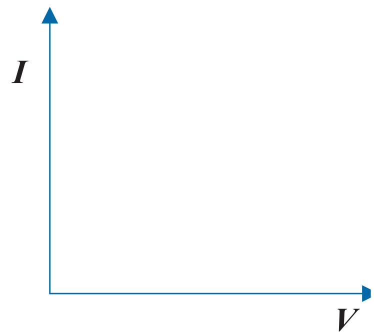
3. The component of a circuit has a resistance of 10.0 Ω. Calculate the potential difference required for a current of 1.5 A to flow through the component.

4. (a) Explain what is meant by the term ‘ohmic conductor’.

(b) Explain why a conductor can’t be ohmic if its temperature increases.

5. The filament of a heater has a resistance of 50 Ω. Calculate the current flowing when 240 V is applied to the filament.

6. A student collects data for Ohm’s law and plots a graph of current against potential difference.



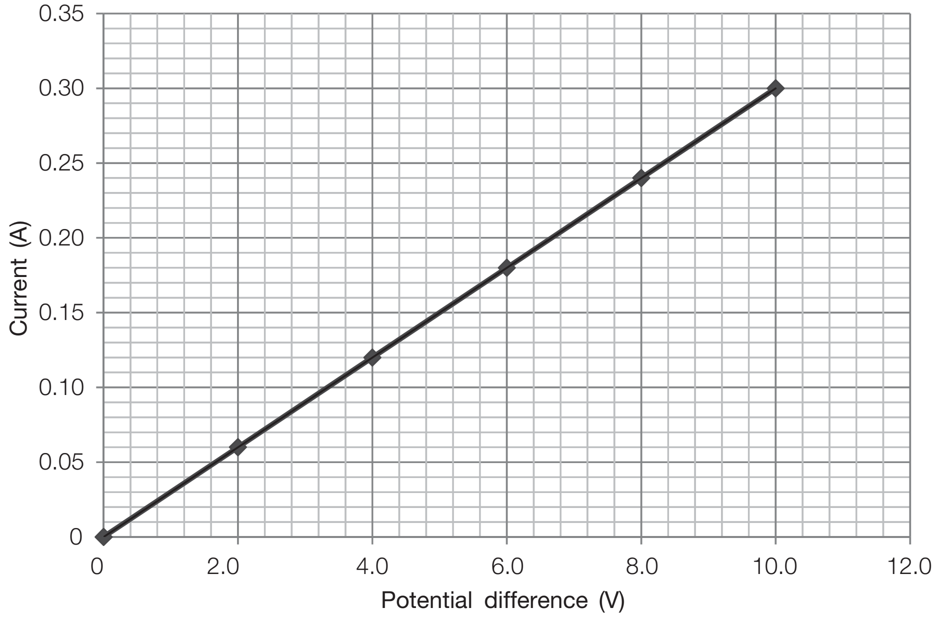
(a) Describe the graph that the student would expect if Ohm’s law is confirmed.

(b) State the quantity represented by the gradient.

(c) State the units of the gradient.

(d) Describe how the resistance of the resistor used in the circuit can be calculated.

7. The graph shown below represents the data collected by student investigating the relationship between the current through a component in a circuit and the potential difference applied across the component.



(a) State the relationship between current and potential difference.

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(b) Calculate the gradient of the line.

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(c) Calculate the resistance of the circuit used to collect the data.

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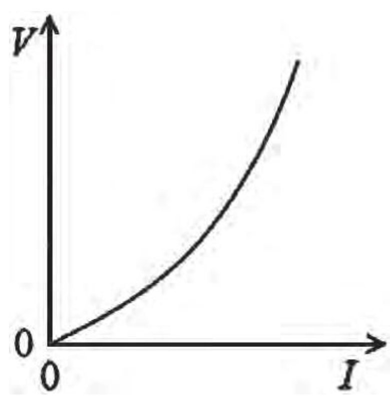
8. The graph shown below is a sketch that represents how the potential difference varies with current across a typical filament globe.



(a) Describe how the resistance of the filament is determined from such a graph for a particular value of current.

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(b) Explain whether the graph indicates ohmic or non-ohmic behaviour by the filament.

Resistance and resistivity

1. A particular wire has a resistivity of 1.8×10^{-8} Ωm, an area of cross-section of 4.5×10^{-6} m^2 and a length of 25 cm. Calculate the resistance of this wire.

2. (a) Define the term 'resistivity of a conductor'.

   (b) A conductor of length 1.5 m and area of cross-section of 2.0×10^{-6} m^2 has a resistance of 1.3×10^{-3} Ω. Calculate the resistivity of the conductor.

3. (a) Given the resistivity of copper is 1.70×10^{-8} Ωm, calculate the resistance of a 1.00 m length of copper wire that has a radius of 1.50×10^{-3} m.

   (b) Calculate the length of copper wire required to make a resistance of 1.00 Ω.

4. A student wishes to confirm the relationship between the resistance of a wire and its area of cross-section.

   Describe the graph that would need to be plotted and the graph that should result.

5. A 3.00 m length of wire has a resistance of 7.25 Ω.

   (a) State with reason the new resistance of a 9.00 m length of the same wire.

   (b) State with reason the new resistance of the wire if its radius is doubled.

6. Two students conduct an experiment to investigate the relationship between the resistance (R) and length (l) of a conductor. They measure the resistance of various lengths of nichrome wire. The area of cross-section of the wire is 1.0×10^{-5} m^2.

   The table below summarises the results of the experiment.

Length (m) × 10^{-2}	Resistance (Ω)
10.0	0.010
15.0	0.014
20.0	0.020
25.0	0.026
30.0	0.030

   (a) State the dependent variable in this experiment.

   (b) On the next page, plot a graph of resistance against length and draw a line of best fit for the plotted data.

   (c) Using the graph to

   (i) Calculate the gradient of the line.

   (ii) Write an equation for the line of best fit.

(iii) Calculate the resistivity of nichrome.

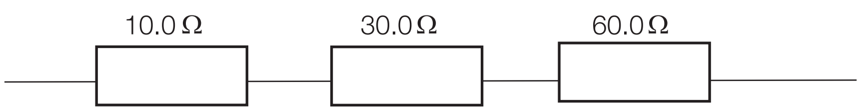
(d) Suggest one improvement that the students could make to the experimental procedure.

7. Describe how electrical safety is increased through the use of fuses and circuit breakers in a circuit.

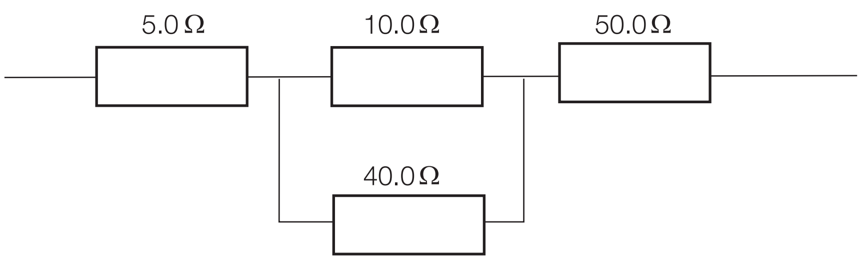
Circuit analysis

1. The diagrams below show resistors in various arrangements. Calculate the total resistance of each arrangement.

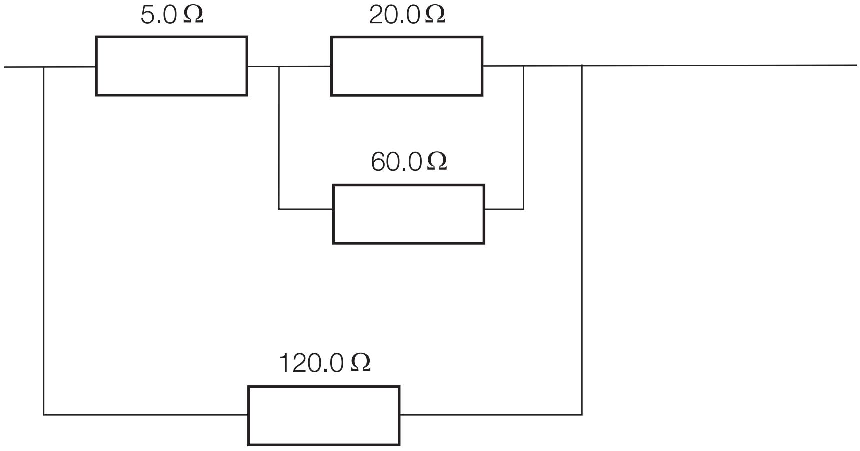
(a)



(b)



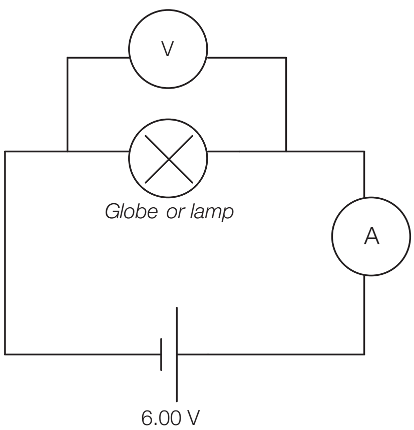
(c)



2. An 8.00 Ω, 9.00 Ω and a 10.0 Ω resistor are connected so that their total resistance is 13.4 Ω.

   Use the space below to determine and draw the arrangement of the resistors that results in a total resistance of 13.4 Ω. Justify your answer with a calculation.

3. Consider the simple circuit below.



(a) Name the device used to measure current.

....

(b) Name the device used to measure potential difference.

....

(c) If the lamp has a resistance of 10.0 Ω, calculate the current flowing through the circuit.

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(d) Calculate the number of charge-carriers passing through the ammeter every minute.

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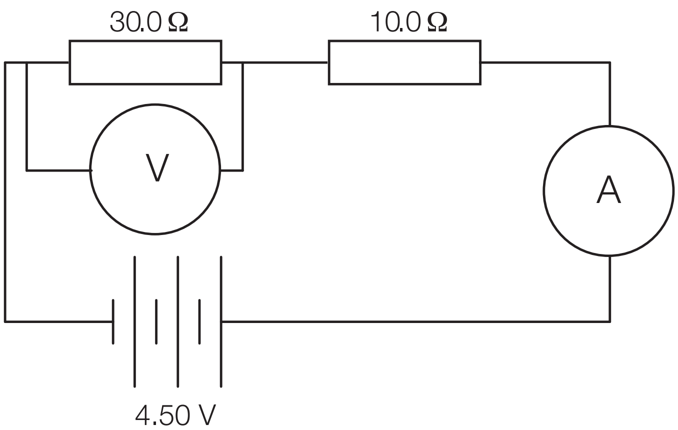
4. Consider the circuit below.



(a) Describe how the circuit was constructed.

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(b) State the total resistance of the circuit.

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(c) Show that the reading on the ammeter is 0.113 A.

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(d) Determine the reading on the voltmeter.

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5. (a) Use the space below to sketch a 40 Ω resistor connected in parallel with a 10 Ω resistor.

(b) This combination of resistors is now connected to a potential difference of 8.0 V. State the potential difference across the 10 Ω resistor.

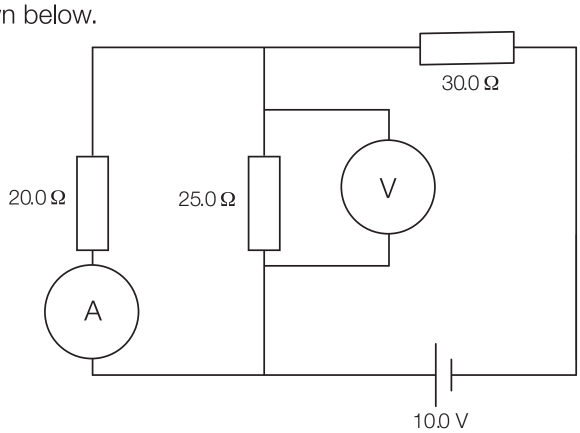
(c) Show that the resistance for this combination of resistors is 8.0 Ω.

(d) Calculate the current flowing through the circuit and each of the resistors.

(e) State the potential difference across the 40 Ω resistor.

(f) The 40 Ω resistor is removed from the circuit. Calculate the current flowing through the 10 Ω resistor.

6. Consider the circuit shown below.



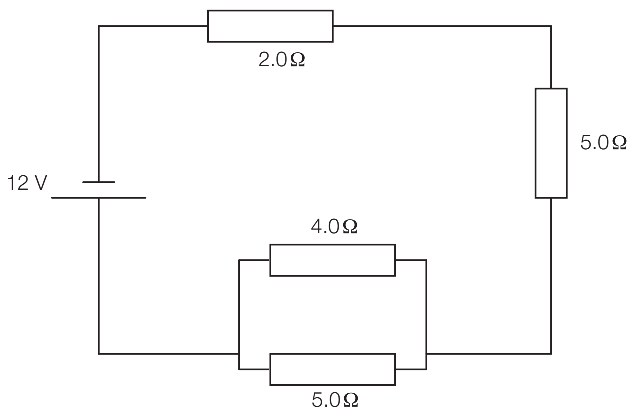
(a) Calculate the total resistance of the circuit.

(b) Calculate the current flowing through the circuit.

(c) Determine the reading on the voltmeter.

(d) Determine the reading on the ammeter.

7. Consider the circuit shown below.



(a) Show that the effective resistance of the circuit is 9.2 Ω.

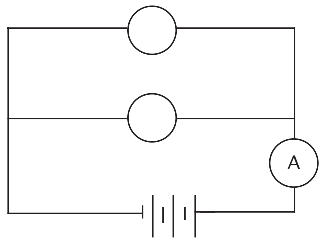
(b) Calculate the current flowing through the circuit.

(c) Calculate the potential difference across the 5.0 Ω resistor that is connected in series with the 2.0 Ω resistor.

(d) Determine the potential difference across the 4.0 Ω resistor.

(e) Calculate the current flowing through the 4.0 Ω resistor.

8. The diagram below shows two identical light globes in a circuit. The ammeter shows a reading of 0.50 A.



Determine the resistance of each light bulb.

2.4 Electrical Power

1. Calculate the power rating of a light globe that operates at 50.0 V and draws 1.2 A of current.

2. Calculate the power rating of an electrical component in kilowatts if it has a resistance of 150 Ω and operates at a potential difference of 550 V.

3. An electric toaster has a power rating of 2.40×10^3 W.

   (a) Calculate the electrical energy transformed in 95.0 s when toasting a piece of bread.

(b) The efficiency of the toaster is 30%. Calculate the useful heat energy supplied in the 95.0 s.

4. A 2.2 kW fan heater is used for 5.0 hours. Calculate the cost of running the heater if electricity is charged at 18 cents per kilowatt hour.

5. The heating element of a kettle has a resistance of 450 Ω and draws a current of 2.0 A

(a) Show that the power rating of the kettle is 1800 W.

(b) The kettle takes 3.0 minutes to boil 2.0 litres of water. Calculate the energy delivered in 3.0 minutes.

(c) Electricity is charged at 20 cents per kilowatt hour. Calculate the cost of boiling 2.0 litres of water using this kettle.

(d) Calculate the efficiency of the heating element given that 1.0×10^5 J of the energy delivered by the heating element is absorbed by the outer plastic casing of the kettle.

6. A current of 35 mA flows through a coil of wire.

(a) Calculate the charge passing a point in the coil every 20 μs.

(b) Calculate the resistance of the coil if a potential difference of 6.0 V is applied across the coil.

(c) Calculate the power dissipated by the coil every 20 μs.

(d) Calculate the number of electrons passing a point in the coil every 20 μs.

7. A circuit regulates the voltage from 10.0 V to 6.0 V. The current flowing through a component is 0.50 A.

(a) Calculate the input power.

(b) Calculate the output power.

(c) Calculate the efficiency of the circuit.

Topic 3: Heat

3.1 Heat and temperature

Science understanding

1. Thermal energy is made up of the combined potential energy and kinetic energy due to the vibration of the particles within the object.
2. The particles within objects with higher temperatures have a higher average kinetic energy.
3. An increase in the temperature of an object is due to an increase in its thermal energy.
   - Describe the links between temperature, vibrating particles, and thermal energy.
4. Temperature can be measured with different scales (common ones being Celsius, Fahrenheit and Kelvin).
5. As the temperature decreases the average kinetic energy of the particles drops until the lower limit (known as ‘absolute zero’) is reached.
6. When a hot object is put into contact with a cooler object, some of the thermal energy transfers from the hotter object to the cooler one. This flow of energy is referred to as heat.
7. If the objects remain in contact then eventually the objects will reach the same temperature, putting the objects into ‘thermal equilibrium’.
   - Describe heat as the flow of energy from hotter to cooler objects.
   - Describe thermal equilibrium.
8. Heat transfer can occur through conduction, convection, and radiation.
   - Explain how heat transfer can occur through conduction, convection, and radiation.
   - Describe examples of each heat-transfer process.
9. Most solids, liquids, and gases expand when heated.
   - Describe applications of the expansion of matter due to heat transfer.

Most matter on Earth is of the form of a solid, liquid or gas.

Most matter in the universe is in plasma state. High temperatures cause atoms and molecules to become ionised. This means that electrons are excited and leave the atom. A positive ion results. Plasma contains positive ions, electrons and some neutral particles.

Key idea

The **kinetic theory** or **particle model** is based on the following basic assumptions

- All matter is made up of **tiny particles**.
- The particles are in **constant random motion** referred to as Brownian motion.
- The collisions between the particles are elastic. This means that the particles do not lose **kinetic energy** as they collide. Kinetic energy is the energy possessed by moving objects, where kinetic energy $K = \frac{1}{2}mv^2$. This was covered in year 10 and will be revisited in Topic 4.
- There are forces of **mutual attraction** between particles (mutual means that the force experienced by each particle has the same magnitude).

NB: The chemical bonds and electrostatic forces between particles give rise to the attraction between particles and means that the particles possess **potential energy** as well as kinetic energy.

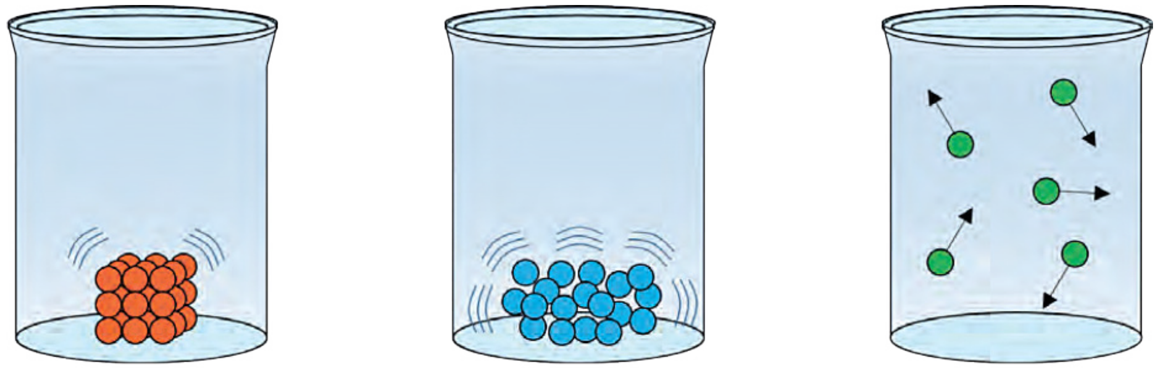


Figure 3.1.1

Extra understanding

Macroscopic properties

Property	Solid	Liquid	Gas
Shape	Fixed Does not change shape easily	Variable Changes shape easily and takes the shape of its container	Variable Changes shape easily to completely fill its container
Volume	Fixed Volume remains the same no matter what shape the solid is	Fixed Volume remains the same no matter what shape the container is	Variable Gases fill their containers – the larger the container, the larger the volume
Compressibility	Almost incompressible	Very difficult to compress	Easy to compress
Diffusion	Generally do not diffuse – some are able to diffuse slightly	Diffuse (but slowly)	Diffuse easily and quickly
Density	Very high	High	Low

Microscopic properties

Property	Solid	Liquid	Gas
Kinetic energy	Vibrational	Vibrational Rotational Some translational (straight line)	High vibrational High rotational Mostly translational
Potential energy	High	Very high	Extremely high
Molecular separation *(Where $r_0 = 2.5 \times 10^{-10}$ m)*	r_0	r_0	$10\ r_0$
Number of molecules per cubic metre (m^3)	10^{28}	10^{28}	10^{25}

Thermal energy

Thermal energy is defined as the combined potential energy and kinetic energy that comes from the vibration of the particles within the object.

The particles that make up any object at a particular temperature have a range of kinetic energies. Figure 3.1.2 illustrates the range of kinetic energies at various temperatures.

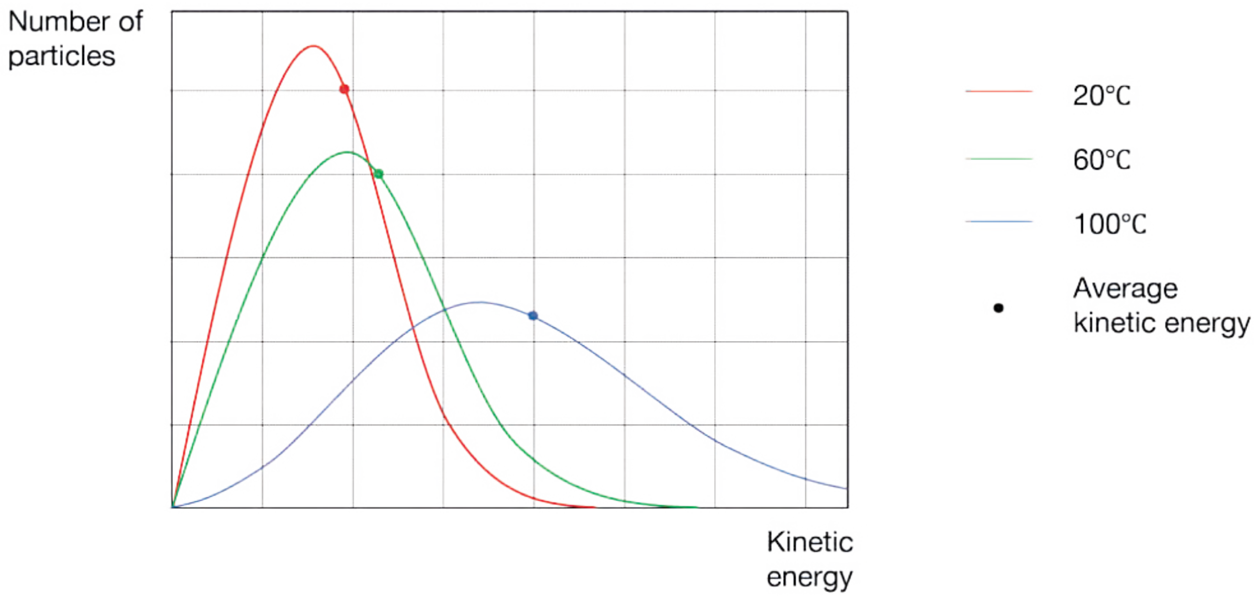


Figure 3.1.2

The particles within materials at higher temperatures have a higher average kinetic energy.

An increase in the temperature of a material is due to an increase in its thermal energy.

As the temperature of a material increases, each of the particles within the object vibrates faster and gains kinetic energy. As a consequence, the average kinetic energy of the particles increases. It follows that the thermal energy increases as it is the combined potential and kinetic energy of all the particles within the object.

Temperature is defined as a measure of the average kinetic energy of the particles in a substance.

Different temperature scales

Temperature can be measured with different scales (common ones being Celsius, Fahrenheit and Kelvin).

In Australia we mainly use the Celsius scale. In America the Fahrenheit scale is commonly used.

Zero degrees Celsius is equivalent to 32 degrees Fahrenheit.

The conversions between degrees Celsius and Fahrenheit are shown below.

$$T(°C) = \frac{T(°F) - 32}{1.8} \text{ or } T(°F) = 1.8T(°C) + 32$$

The SI unit for temperature is neither degrees Celsius nor degrees Fahrenheit.

The SI unit for temperature is the Kelvin.

The conversion between degrees Celsius and Kelvin is

$$T(K) = T(°C) + 273 \text{ or } T(°C) = T(K) - 273$$

NB: A change in temperature of one degree Celsius is equivalent to a change in temperature of one Kelvin.

Worked examples

Convert the following temperatures

1. 100°F to °C

$$T(°C) = \frac{T(°F) - 32}{1.8} = \frac{100 - 32}{1.8} = 37.8°C$$

2. 100°C to °F

$$T(°F) = 1.8 \times 100 + 32 = 212°F$$

3. 35°C to K

$$T(K) = T(°C) + 273 = 35 + 273 = 308\ K$$

4. 0 K (zero K) to °C

$$T(°C) = T(K) - 273 = 0 - 273 = -273°C$$

Extra understanding

- Your teacher may demonstrate thermometers with different temperature scales: Celsius, Fahrenheit and Kelvin. These may include those used to measure air temperature and the temperature of stars like the Sun.
- Your teacher may ask you to use a thermometer to compare the temperature of a range of different objects, e.g. body temperature, boiling water, ice, a light bulb, liquid nitrogen, a warm room.
- Your teacher may demonstrate Brownian motion i.e. you may observe random motion of particles by viewing a smoke cell with an attached light source through a microscope.

Helpful online resources

Energy changes and energy forms:

https://phet.colorado.edu/en/simulation/legacy/energy-forms-and-changes

Absolute zero

As the temperature of an object decreases, the average kinetic energy of the particles decreases until the lower limit (known as 'absolute zero') is reached. If an object gets to absolute zero, the movement of its particles is minimal. This corresponds to a temperature of –273°C.

Absolute zero (0K) is the lower fixed reference point for temperature and is defined as the temperature at which particle motion almost stops.

Science inquiry practical

- Conduct an investigation to determine the value of absolute zero.
- Compare the change in temperature of a volume of water when you add:
  (a) a small, hot object
  (b) a large, warm object.

Helpful online resources

This link will assist with the the above Science inquiry practical:

http://youtu.be/wTi3Hn09OBs

Helpful online resources

Construct thermometers. These can be made with coloured liquids (alcohol) in thin tubes or straws that expand as temperature increases.

http://youtu.be/wTi3Hn09OBs

How to build a thermometer:

http://www.energyquest.ca.gov/projects/thermometer.html

Investigate daily temperature changes using the Bureau of Meteorology's temperature maps:

http://www.bom.gov.au/climate/outlooks/#/temperature/maximum/median/seasonal/0

Science as a human endeavour

Possible ideas for an investigation:

- Explore the international conventions involving different temperature scales and analyse the significance of using a consistent system. Examples include Imperial, Fahrenheit, Celsius, and Kelvin.
- Research the influence of engineering and technology on the development of the world's most sensitive thermometers, e.g. https://www.adelaide.edu.au/news/news70922.html

Heat

When two objects at different temperatures are placed into contact with each other, the cooler object heats up and the hotter object cools down. This is because thermal energy is transferred between the objects. This flow of energy is referred to as heat. Figure 3.1.3 shows the direction of heat flow between two objects that are at different temperatures.

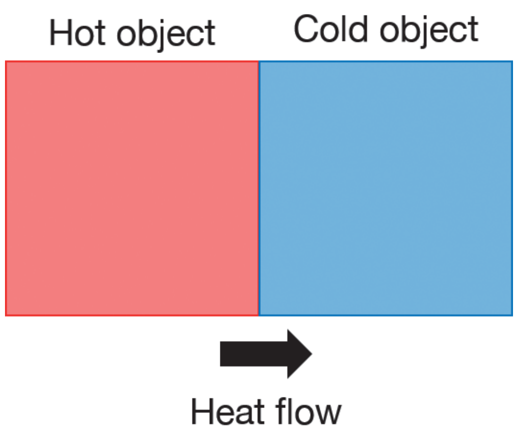


Figure 3.1.3

Heat is the thermal energy that is absorbed, released or transferred between objects.

Heat flows from a region of high temperature to a region of low temperature.

Temperature determines the **direction of thermal energy transfer** between two objects in thermal contact.

If the objects remain in contact they will eventually reach the same temperature and the transfer of thermal energy will stop. We say that the objects have reached thermal equilibrium.

Two objects in contact are said to be in **thermal equilibrium** when they are at the same temperature.

Heat transfer

There are three methods by which heat transfer can occur. These are conduction, convection and radiation. The main method of heat transfer will depend on the materials involved.

1. Conduction

Conduction is the transfer of thermal energy from a region of high temperature to a region of low temperature by particle collision and without a transfer of matter.

Conduction occurs in solids, liquids and gases.

Figure 3.1.4 shows a metal being heated at one end by a Bunsen burner flame.

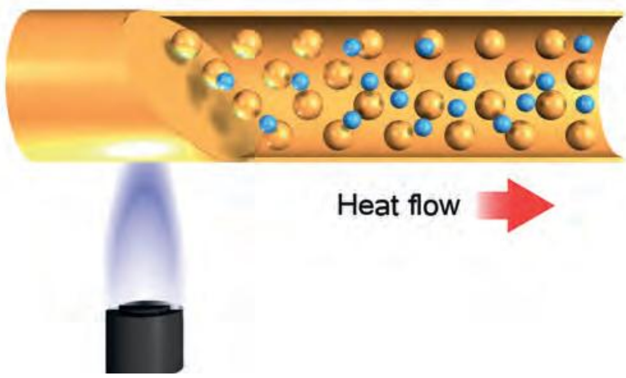


Figure 3.1.4

The thermal energy supplied by the flame increases the kinetic energy of the particles making up the metal near the flame. These particles vibrate faster and, in turn, vibrate their slower neighbouring particles. These neighbouring particles vibrate faster and, in turn, vibrate their neighbours. The process continues and thermal energy is transferred along the metal.

By definition, an increase in the kinetic energy of an object's particles increases the temperature of the object.

Metals have a delocalised electron cloud. These electrons gain kinetic energy and move faster. This means that the transfer of heat occurs faster. This is why metals are good conductors of heat.

A good conductor of heat allows the transfer of thermal energy to occur readily.

A good insulator of heat does not allow the transfer of thermal energy to occur readily.

Metals are generally good conductors, while liquids and gases are poor conductors (good insulators). Good insulators include air, polystyrene and plastic.

Examples

1. A bathmat

When you step out of a hot shower straight onto the bathroom tiles, you immediately feel cold. This is because thermal energy flows from a region of high temperature (your body) to a region of low temperature (the floor). The bathroom tiles easily conduct thermal energy away from your body and you feel cold. Figure 3.1.5 shows the direction of heat flow in this situation.

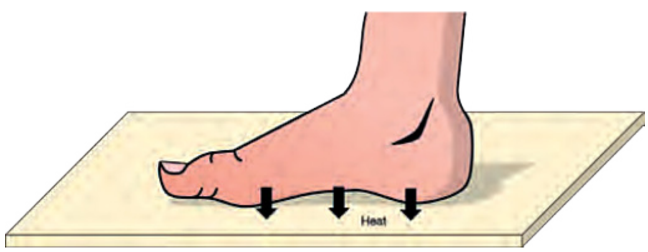


Figure 3.1.5

A bathmat is a good insulator of heat and slows the transfer of heat energy away from your body. This is why you do not feel as cold when you step out onto a bathmat.

2. Esky – used to keep food and drinks cool.

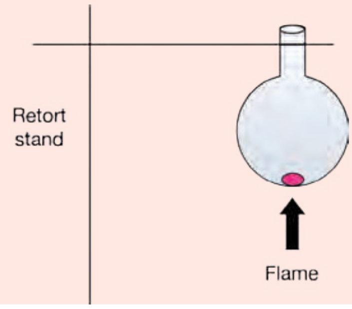
An Esky is made of material that acts as a good insulator (e.g. polystyrene). This slows down the heat transfer from a region of high temperature (outside the Esky) to a region of low temperature (inside the Esky). This is why the food stays cool.

2. Convection

Convection is the transfer of thermal energy in a fluid (liquid or gas) from a region of high temperature to a region of low temperature by the mass movement of the fluid particles themselves.

Activity

1. Fill a round-bottomed flask with water and suspend it over a Bunsen burner using a retort stand.
2. Gently lower a small amount of potassium permanganate crystals to the bottom of the flask using a straw.
3. Heat the flask.
4. Watch the crystals carefully.
5. Repeat with a flat-bottomed flask. Is there a difference in the flow of the crystals? Does the position of the crystals matter?



When the liquid in the flask is heated, the water near the bottom of the flask becomes less dense and starts to rise. As it rises, it displaces the cooler more dense water near the top of the flask. This water sinks to the bottom, is heated, and the process repeats.

A **convection current** forms and the liquid continues to heat up. The potassium permanganate makes the convection current visible by tracing out its path with a purple trail. As the liquid heats, the water becomes progressively darker.

Examples

Convection is the means by which:

- a traditional radiator (without a fan) heats a room
- a flame or heating element heats an oven
- sea breezes, ocean currents and winds are created.

3. Radiation

Radiation is the transfer of thermal energy from a region of high temperature to a region of low temperature by means of electromagnetic waves or light. It is the only means of heat transfer that can occur in a vacuum (i.e. does not require matter).

Radiation or thermal radiation is emitted by any object that has temperature. Dull black objects absorb and emit radiation better than shiny and/or white objects, which tend to reflect radiation. This is why a black car gets very hot, very quickly. It is also the reason why cricket players traditionally wear white. It takes longer for white clothes to heat up because they reflect radiation more readily than dark clothes.

For objects with temperatures less than 100°C, thermal radiation is in the form of electromagnetic waves mainly in the infra-red region. For temperatures greater than 100°C, visible and ultraviolet light are also present.

Example

Radiation is the main process by which heat reaches the Earth from the Sun.

Thermal energy from the Sun cannot heat the Earth through conduction because the Sun and the Earth are not in contact. Thermal energy cannot reach the Earth via convection because it needs to travel through empty space (approximately 1.5×10^8 km) before reaching the Earth's atmosphere.

Thermal energy reaches the Earth through the process of radiation. Some of this heat penetrates the Earth's atmosphere and is absorbed by the land, water and air. Some of the thermal energy absorbed is reflected back into space. Convection then heats our atmosphere and conduction heats objects in contact with one another.

Figure 3.1.6 illustrates the proportion of solar radiation that is absorbed once it reaches the Earth.

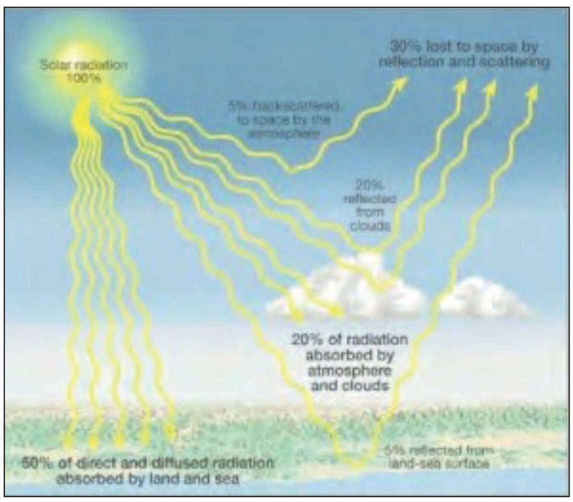


Figure 3.1.6

? Science inquiry practical

Stubby holder

NB: This activity can be completed using thermometers or a data logger and temperature probes.

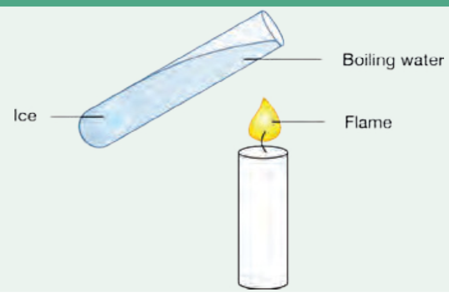
1. Take two identical bottles or cans that have been refrigerated for a significant amount of time and are at the same temperature. Check the initial temperature of the water using a thermometer.
2. Place one water bottle in a stubby holder.
3. Record the temperature of the water in each bottle every minute until the water reaches room temperature.
4. Plot a graph of temperature against time.
5. Describe the trend in the data.
6. Name the main type of heat flow that is reduced by the stubby holder.
7. Can you determine the factor by which the stubby holder reduces the heat flow?
8. Does the gradient of the graph have a significance?

Stubby holders and wetsuits are made out of a similar material and work in a similar way. The stubby holder slows the transfer of thermal energy by conduction. In addition, a wetsuit traps a layer of water between the suit and the person's body. Water is a good insulator and slows down the transfer of heat energy away from your body to the cooler surrounding water.

Extra understanding

Your teacher can provide you with the equipment needed to perform the following activities.

- Use a conductivity star made of four different metals to demonstrate the different thermal conductivities of different metals.
- Show that water is a poor conductor by boiling water at the top of a test tube while water frozen at the bottom of the tube does not melt.



? Science inquiry practical

- Explore the conduction of heat in a metal bar with small pieces of wax holding pins, and with one end of the bar being heated. (Graph distance and time.)

Science as a human endeavour

Possible ideas for an investigation:

- Analyse ways in which the use of poor conductors can have social and economic advantages, e.g. air in feather and down quilts, building insulation.
- Explore how an understanding of heat transfer during climate cycles (such as ocean currents or air currents) and their effects on weather can enable scientists to make predictions and design action for sustainability.
- Explore the social, economic, and environmental impacts of applications of thermal expansion, for example:
  - thermostat control of heaters, irons, kettles
  - engineering of bridge building
  - turbines (particularly in power stations) driven by steam.
- Investigate changing technologies involving heat engines, including steam engines (external combustion), diesel and petrol engines (internal combustion), and Stirling engines Explore innovations to reduce the environmental impact of these engine types.

The effect of heating on solids, liquids and gases

Most solids, liquids and gases expand when heated and contract when cooled.

When heated, the particles of a solid vibrate faster over a greater distance. The particles take up more space and the object expands. Similarly, the particles of a heated liquid move around each other faster and take up more space; the particles of a heated gas move faster in all directions and take up more space.

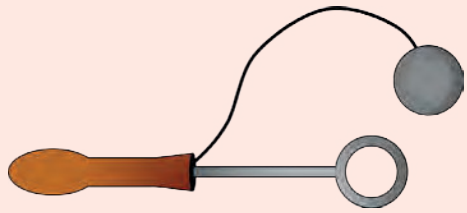
In general, liquids expand more than solids, and gases expand the most. This is because the forces between the particles become weaker as the state of an object changes from solid to liquid to gas. When heated, the particles move further apart. In addition, the pressure of gas will increase if it is heated at a constant volume. Pressure is due to the gas particles colliding with the walls of their container. If the gas is heated, the particles gain kinetic energy and experience a greater change in momentum when they bounce from the container wall. As a consequence the force per unit area increases, increasing the pressure.

The reverse reasoning applies when materials cool and they contract. Water however, behaves differently. When water is cooled, it contracts like other liquids until it reaches a temperature of about four degrees Celsius. At this temperature, water starts to expand as it continues to cool and reaches zero degrees Celsius. Once frozen, and in solid state, it has expanded and its volume has increased by around nine percent. This makes it less dense than liquid water.

Activity

1. Expansion in solids

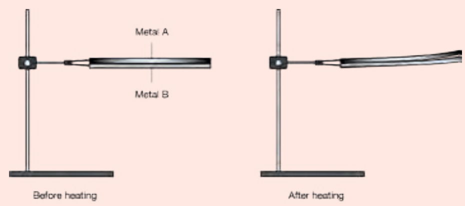
A Ball and ring apparatus



1. Check that the ball can pass through the ring.
2. Heat the ball for a short time while it is attached to the ring using a Bunsen burner.
3. Try to pass the ball through the ring.

Can you explain your observation?

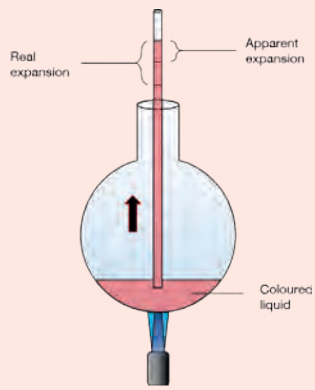
B Bimetallic strip



1. Find out which metals were used to make the bimetallic strip you have been given.
2. Use a retort stand to secure the bimetallic strip.
3. Heat the strip for a short time using a Bunsen burner.
4. Remove the bimetallic strip from the flame and allow it to cool.

Can you explain your observations?

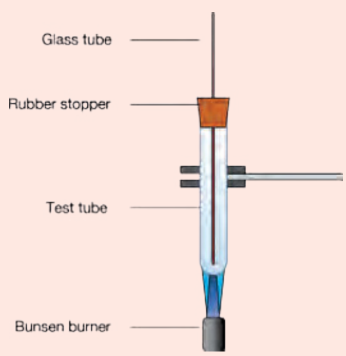
2. Expansion in liquids



1. Take a round-bottomed flask and add some coloured water.
2. Seal the flask with a single-holed rubber stopper that has a glass tube fitted firmly through the hole. Some coloured water should rise into the glass tube.
3. Heat the coloured water using a Bunsen burner or hot plate for a short time.
4. Remove the flask from the heat source and allow it to cool.

Can you explain your observations?

3. Expansion in gases



1. Trap some water in a glass tube that fits firmly into a single-holed rubber stopper.
2. Slide the tube through the hole in the rubber stopper.
3. Seal an empty test tube with the rubber stopper.
4. Heat the test tube using a Bunsen burner for a short time.
5. Remove the test tube from the heat source and allow it to cool.

Can you explain your observations?

Applications of the expansion of matter due to heat transfer

1. **Bimetallic strip**

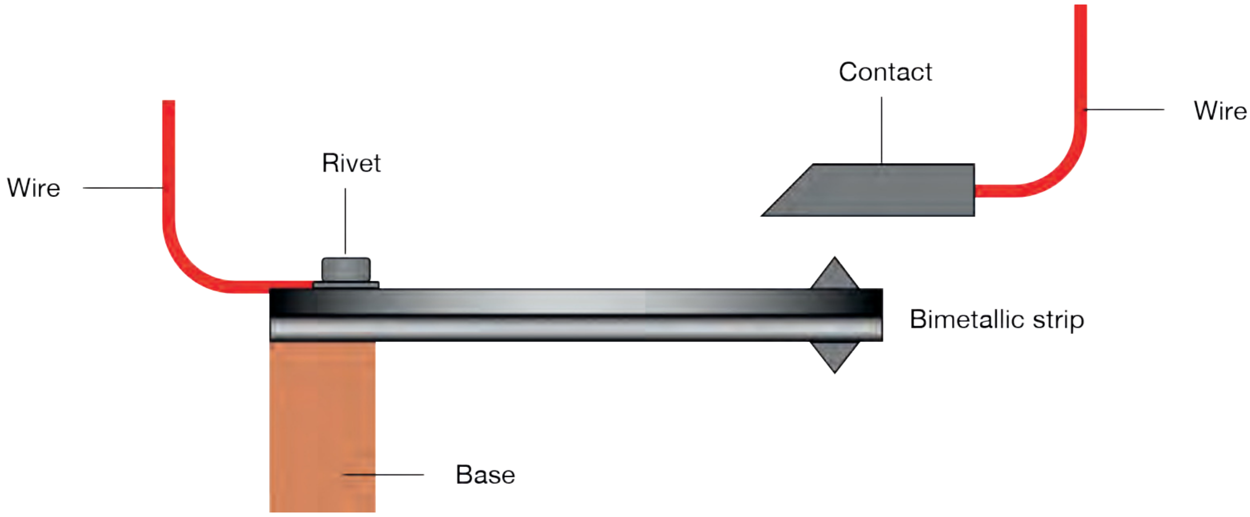


Figure 3.1.7

The use of bimetallic strips in circuit breakers was discussed in Chapter 2.

A bimetallic strip consists of two metal strips bonded together. The different metals expand at different rates when heated. Two common metals used are brass and steel, with brass expanding faster than steel.

If there is a power surge and too much current flows through a circuit, the bimetallic strip heats up and bends. This breaks the circuit and the current stops flowing.

The bimetallic strip shown in figure 3.1.7 will bend upwards and complete the circuit if the bottom strip of metal expands faster that the top strip. It will bend downwards if the top strip of metal expands faster than the bottom strip.

Since a bimetallic strip bends when it is heated, it can be used as a sensor in a thermostat. The bimetallic strip starts off straight but bends away or towards the contact when it gets hot. It will open or close a circuit and can therefore be used as a switch. When the bimetallic strip cools it straightens and its original position is restored.

For this reason bimetallic strips are used in ovens, irons, refrigerators and thermometers. For instance, when an oven gets too hot, the bimetallic strip bends away from the contact preventing the flow of current. In an iron, a bimetallic strip bends as the iron heats up until it makes contact with another piece of metal. This results in a switch being opened so that the iron does not overheat. The position of the bimetallic strip can be adjusted to vary the temperature of the iron so that it suits the material being ironed.

2. **Expansion joints in bridges**

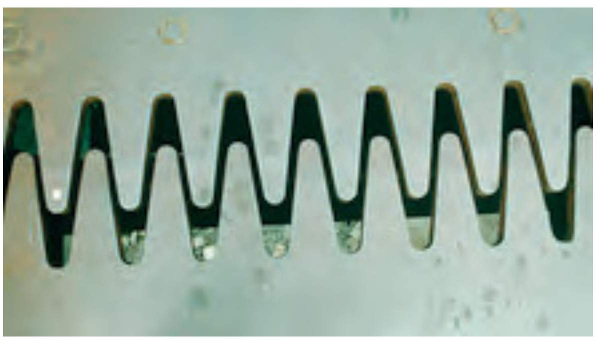


Figure 3.1.8

Engineers build bridges with expansion joints. These enable the metal to expand when it heats up in summer. This will prevent the bridge warping out of shape. A typical bridge expansion joint is shown in figure 3.1.8.

3. **Gaps between railway tracks**

Figure 3.1.9

Figure 3.1.9 shows the gap between two rails. The gap enables the metal to expand when it gets hot in summer. Railway tracks are laid with gaps between the rails.

4. **Opening the lid of a jar**

If the metal lid on a jar is closed tightly it can be very hard to open. It will help to place the jar in hot water. The metal lid will expand as the hot water heats it. This can help loosen the lid so that it can be opened.

5. **Liquid bulb thermometers**

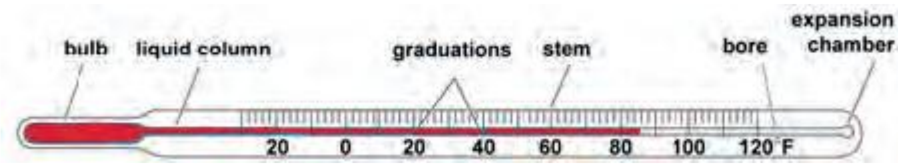


Figure 3.1.10

The common liquid bulb thermometer has a reservoir of liquid that expands when it is heated and rises up a thin tube.

6. **Radiator coolant**

A coolant is used to fill a car's radiator and is designed to draw heat away from the engine. If the radiator is filled with coolant on a cool day, the coolant will expand and potentially overflow when it heats up. Modern cars are fitted with an overflow container that collects the coolant that overflows and returns it to the radiator once the engine cools down.

7. **Soft drink cans in summer**

A can of soft drink contains gas. If left in the sun or a hot room, the can may burst as the gas expands and tries to escape the can.

8. **Deodorant cans**

A deodorant can carries a warning not to expose the can to high temperatures. The can may explode if it is heated. Figure 3.1.11 shows a typical warning found on pressurised containers.

Figure 3.1.11

3.2 Specific heat capacity

Science understanding

1. Energy can be added to or removed from a system without causing a change of state. The energy that is added or removed causes a change in temperature ΔT.
2. The change in temperature depends on the mass of the object (m), the amount of heat transferred to or from the object *(Q),* and the nature of the material (its **specific heat capacity**, c). These variables are linked through the formula: $Q = mc\Delta T$.
   - Describe and explain specific heat capacity
   - Solve problems using the formula $Q = mc\Delta T$.

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Energy can be added to or removed from a system without causing a change of state. The energy that is added or removed causes a change in temperature ΔT. If heat energy is added to a system i.e. it is heated up, the final temperature of the system will be greater than the initial temperature and $\Delta T = T_f - T_i$ will have a positive value. If heat energy is removed from a system i.e. it is cooled down, the final temperature of the system will be smaller than the initial temperature and $\Delta T = T_f - T_i$ will have a negative value. We will use this concept later in the chapter when we solve numerical problems.

The change in temperature that occurs will depend on the mass (m) of the object, the amount of heat (Q) transferred to or from the object and the nature of the material (its 'specific heat capacity' c).

These variables are linked through the formula:

$$Q = mc\Delta T$$

Q = the amount of thermal energy transferred to or from the object in Joules J

m = the mass of the object in kilograms (kg)

ΔT = the change in temperature in Kelvin (K)

c = specific heat capacity of the material in J kg^{-1} K^{-1}

It can be seen that $\Delta T = \frac{Q}{mc}$. This means that the change in temperature experienced by an object is directly proportional to the amount of thermal energy transferred to or from the object ($\Delta T \propto Q$) and inversely proportional to the mass ($\Delta T \propto \frac{1}{m}$) and specific heat capacity of the object ($\Delta T \propto \frac{1}{c}$).

The specific heat capacity is defined as the heat energy required to raise the temperature of one kilogram of a substance by one Kelvin.

$$c = \frac{Q}{m\Delta T} \quad \text{units: J kg}^{-1}\text{ K}^{-1}$$

Water

1. *Water has a specific heat capacity of 4180 J kg^{-1} K^{-1}.* This means that 4180 J of thermal energy are required to increase the temperature of 1 kg of water by one Kelvin (or degree Celsius).

   This is why water is used as a coolant in car radiators. A car radiator is shown in figure 3.2.1. Water absorbs a lot of heat energy away from the motor for only a small rise in temperature. This keeps the engine cool, so that it does not overheat.

Figure 3.2.1

2. Water is also used in hot water bottles as shown in figure 3.2.2. Water absorbs a lot of heat energy when it is heated. It will therefore release a lot of heat energy for every degree Celsius or Kelvin that it cools. This is why a hot water bottle is useful when trying to keep warm.

Figure 3.2.2

Metals

The specific heat capacity of lead is 130 J kg^{-1} K^{-1} and that of copper is 385 J kg^{-1} K^{-1}.

This means that 130 J and 385 J of heat or thermal energy are required to increase the temperature of one kilogram of lead or copper respectively by one Kelvin.

Metals are good conductors of thermal energy. Copper makes a good base for cooking pans. A pan with a copper base is shown in figure 3.2.3.

Figure 3.2.3

Problem solving

Since heat flows, it is never lost or created. Heat energy is transferred from one object to another. The law of conservation of energy applies. This law was covered in year 10 and will be revisited in Topic 4.

We use $Q = mc\Delta T$ if heat energy is absorbed by an object and the temperature increases without a change of state.

We use $Q = -mc\Delta T$ if heat energy is released by an object and the temperature decreases without a change of state.

The change in temperature $\Delta T = T_f - T_i$ is positive if heat is absorbed and negative of heat energy is released.

Electric filaments such as those found in kettles are often used to heat liquids. Electrical devices have a **power rating** in Watts. As discussed in Topic 2, power is the rate at which energy is converted. The equation for power can therefore be used in this topic.

$$P = \frac{\Delta E}{t} = \frac{Q}{\Delta t} \qquad \therefore Q = Pt$$

where P = power rating in Watts (W)

t = heating time in seconds (s)

Key ideas

1. It is useful to know that 1 mL of water has a mass of 1 g. It follows that 1 L of water has a mass of 1 kg.
2. A change in temperature of one degree Celsius is equivalent to a change in temperature of one Kelvin. Calculations can therefore be performed using either unit of temperature.

Worked examples

1. A mass of substance absorbs 2.0×10^5 J of thermal energy and experiences an increase in temperature of 15 K. Determine the increase in temperature if the same mass of substance absorbs 6.0×10^5 J of heat energy.

   Since $\Delta T \propto Q$, it follows that if three times as much thermal energy is absorbed then the increase in temperature will be three times greater, i.e. 45 K

2. Calculate the thermal energy absorbed in raising the temperature of 200 mL of water from 20.0°C to boiling point. (c_{water} = 4180 J kg^{-1} K^{-1})

   $Q = mc\Delta T = 0.2 \times 4180 \times 80 = 6.69 \times 10^4\ J$

3. A hot water bottle contains 500 g of water at 75.0°C. It cools down over a period of time to 30.0°C.

   (c) Calculate the amount of thermal energy released by the hot water bottle.

   $Q = -mc\Delta T = -0.5 \times 4180 \times (30-75) = 9.41 \times 10^4\ J$

   (d) State (with reason) the amount of thermal energy absorbed by a person using the hot water bottle as a warming device.

   Using the law of conservation of energy, the energy released by the water bottle will be the heat absorbed by the person i.e. 9.41×10^4 J.

4. A kettle rated at 1200 W heats 1.0 L of water at 290 K for 2.0 minutes.

   (a) Calculate the thermal energy released by the kettle.

   $Q = Pt = 1200 \times (2 \times 60) = 1.4 \times 10^5\ J$

   (b) State the amount of thermal energy that is absorbed by the water. State any assumptions that you have made.

   Using the law of conservation of energy, the water absorbs 1.4×10^5 J of energy. This assumes that there are no losses in thermal energy to the surroundings, e.g. the air and the kettle.

   (c) Calculate the equilibrium temperature of the water after 2.0 minutes. (i.e. the final temperature of the water)

   $$Q = mc\Delta T = mc(T_f - T_i)$$

   $$T_f = \frac{Q}{mc} + T_i = \frac{1.4 \times 10^5}{1 \times 4180} + 290 = 323 = 320\ K$$

5. A 200 g lump of iron (*Fe*) is heated in a flame before being plunged into a container filled with 1.0 L of water at 15.0°C. The temperature of the water rises to 24.0°C.

   Show that temperature of the flame is 442°C to three significant figures. (c_{iron} = 450 J kg^{-1} K^{-1})

   $$Q_{released\ by\ iron} = Q_{absorbed\ by\ water}$$

   $$-m_{Fe}c_{Fe}\Delta T_{Fe} = m_w c_w \Delta T_w \qquad \Delta T = T_{final} - T_{initial}$$

   $$-m_{Fe}c_{Fe}(T_{final\ Fe} - T_{initial\ Fe}) = m_w c_w (T_{final\ w} - T_{initial\ w})$$

   $$-0.2 \times 450\,(24 - T_{initial\ Fe}) = 1 \times 4180\,(24-15)$$

   $$-90\,(24 - T_{initial\ Fe}) = 37620$$

   $$T_{initial\ Fe} = -(\frac{37620}{-90} - 24) = 442^\circ C$$

   Assuming the iron was in thermal equilibrium with the flame, the initial temperature of the iron when it was placed in the water must be the temperature of the flame.

6. 300 g of water at 343 K is mixed with 200 g of water at 293 K. Determine the equilibrium temperature of the water in Kelvin and degrees Celsius. Express your answer to three significant figures.

   $$Q_{released\ by\ hot\ water} = Q_{absorbed\ by\ cooler\ water}$$

   $$-m_H c_H \Delta T_H = m_c c_c \Delta T_c \qquad \Delta T = T_{final} - T_{initial}$$

   $$-m_H c_H (T_{final} - T_{H\ initial}) = m_c c_c (T_{final} - T_{c\ initial})$$

   $$-0.3 \times 4180\ (T_{final} - 343) = 0.2 \times 4180 \times (T_{final} - 293)$$

   $$-0.3 \times (T_{final} - 343) = 0.2 \times (T_{final} - 293)$$

   $$-0.3T_{final} + 102.9 = 0.2T_{final} - 58.6$$

   $$-0.5T_{final} = -161.5$$

   $$T_{final} = 323K = 50.0^\circ C$$

Extra understanding

Experimental determination of specific heat capacity – brass

1. Place 100 mL of water in a polystyrene cup.
2. Measure the initial temperature of the water.
3. Place enough water in a beaker so that a 50 g brass slotted mass can be completely submerged in the water.
4. Tie a piece of cotton to the slotted mass.
5. Boil the water in the beaker and then suspend the 50 g slotted mass in the water for several minutes. The idea is that the slotted mass will reach thermal equilibrium with the boiling water and will therefore have an initial temperature of 100°C.
6. Quickly transfer the slotted mass to the water in the polystyrene cup and suspend it in the water. (You may wish to gently and quickly dry the slotted mass).
7. Record the maximum and hence equilibrium temperature reached. This is the final temperature of both the slotted mass and the water.
8. Repeat the process two more times.

Record your results in the table below.

$T_{iBrass} = 100°C$

$M_{water} = 0.100$ kg

$c_{water} = 4180 \text{ J kg}^{-1}\,°C$

Trial	***T_i* Water (°C)**	***T_f* Water (°C)**	**ΔT_{water} °C**	**ΔT_{brass} °C**
1				
2				
3				
		Average ΔT		

Calculation

$$Q_{\text{released by brass}} = Q_{\text{gained by water}}$$

$$-m_B c_B \Delta T_B = m_w c_w \Delta T_w \qquad \Delta T = T_{final} - T_{initial}$$

$$\therefore \quad c_B = \frac{m_w c_w \Delta T_{Ave\,w}}{-m_B \Delta T_{Ave\,B}}$$

Perform your calculation here:

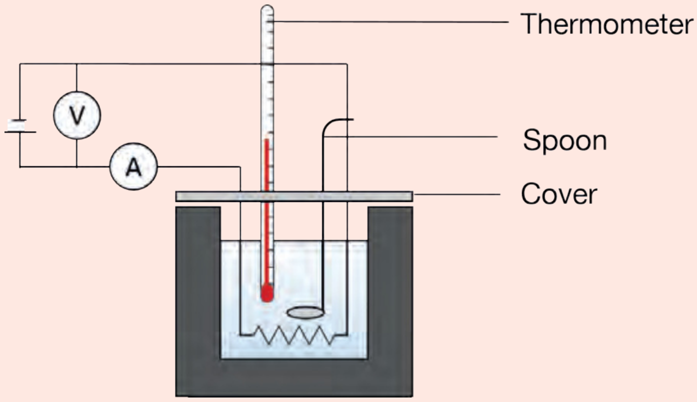
Questions

1. Find an accepted value for the specific heat capacity of brass. Calculate a percentage error in your experimental value and comment on its accuracy.
2. Describe the sources of experimental error for this procedure.
3. Suggest some possible improvements to the method.
4. The polystyrene cup can be replaced with a copper calorimeter and the thermal energy absorbed by the calorimeter can be taken into account. Show how the calculation for the specific heat capacity of brass would change.

3

? Science inquiry practical

The diagram below illustrates a possible experimental arrangement for determining the specific heat capacity of a liquid.



Using your knowledge of thermal energy, and the equipment shown, write a method for determining the specific heat capacity of a liquid graphically.

Design a method to investigate whether salt concentration affects the specific heat capacity of salt water.

Science as a human endeavour

We have already discussed that metals expand when heated. An engine gets hot while it is operating. A radiator draws thermal energy away from the engine but a better understanding of specific heat capacity can help in the engineering of engines.

Explore the significance to engineering of an understanding of specific heat capacity, for example, in metal parts in an engine.

3.3 Change of state

Science understanding

1. Matter commonly exists in three states: solid, liquid, and gas.
2. To change a solid to a liquid (melting or fusion) and to change a liquid to a gas (boiling or vaporisation) requires the input of energy.
3. This energy breaks the bonds between atoms or molecules but does not change the temperature and is thus known as 'latent heat'.
   - Describe and explain latent heat.
   - Explain the difference between evaporation and boiling, using the particle model.
4. The amount of latent heat required (Q) depends upon the nature of the substance (specifically, its latent heat capacity (L)) and the mass of the substance m, and is calculated using $Q = mL$.
5. During the change of state from a gas to a liquid (condensation) or from a liquid to a solid (freezing/solidification), heat is released due to the formation of bonds between atoms or molecules.
   - Solve problems using the formula $Q = mL$.
6. Some substances change from solid to gas (sublimation) or from gas to solid (deposition) without going through a liquid phase.
7. Undertake experiments to determine the specific heat capacity or latent heat of different materials.

3

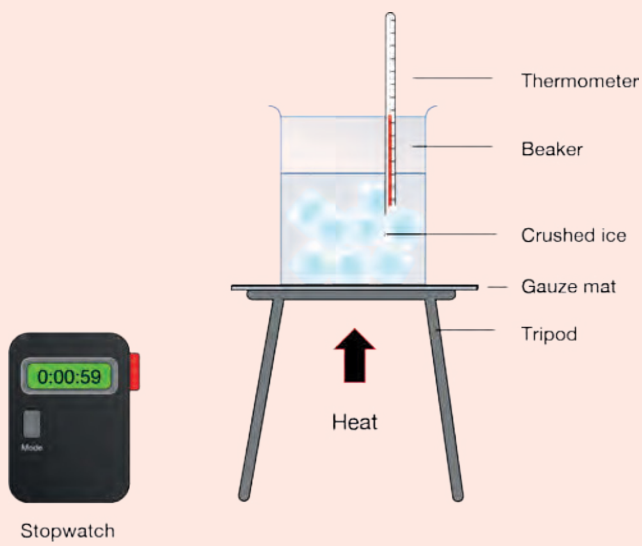
Changes of state

As discussed earlier in the chapter, matter commonly exists in three states: solid, liquid, and gas.

To change a solid to a liquid (**melting**) and to change a liquid to a gas (**boiling**) requires the input of energy.

Activity

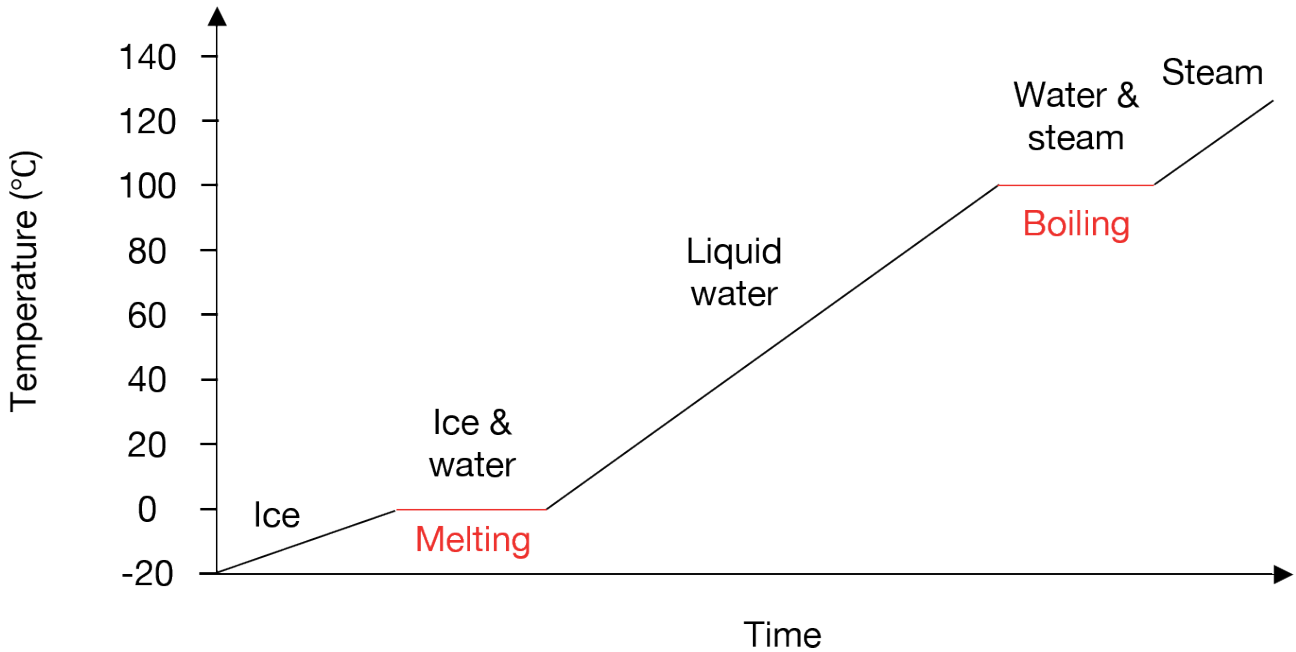
1. Place ice in a beaker.
2. Use a thermometer to measure the initial temperature.
3. Predict the trend in the change in temperature as the ice is heated.
4. Heat the ice with a Bunsen burner or with a hot plate.
5. Measure the temperature of the ice every minute.
6. Continue to measure the temperature until the ice has completely melted and the water produced from the melted ice has boiled for several minutes.
7. Graph the results.
8. Describe the trend in the data.
9. Can you explain the trend that results?
10. Can you predict the shape of the graph for benzene which has a melting point of 5.5°C and a boiling point of 80°C?



NB: This experiment can be performed with a data logger and temperature probe instead of a thermometer.

Heating curves

A heating curve illustrates the change in temperature of a substance as it is heated and undergoes change(s) of state. The ***heating curve*** for ice at –20°C being heated to boiling point and beyond is shown below.



When the ice at –20°C is heated, the temperature rises to 0°C as it absorbs thermal energy. The temperature then remains constant while the ice melts even though heating continues. Once all of the ice has melted, the temperature of the water begins to rise steadily until it reaches 100°C. At this point, heating continues but the temperature remains constant while all of the water turns into steam. If the steam is contained and heating continues, the temperature will begin to rise steadily once again.

Key ideas

1. Pure substances have characteristic melting and boiling points.
2. While a substance changes state, its temperature remains constant.
3. Once all of the substance has completely changed state, the temperature will start to rise again if heating continues.

Change of state in terms of molecular behaviour

The kinetic theory or particle model can be used to explain each change of state. When a substance in solid state is heated, the atoms or molecules vibrate at an increased rate and gain kinetic energy. This means that the temperature increases. When the melting point is reached, the atoms or molecules have sufficient kinetic energy to break the bonds between them and start to slide over one another. As heating continues, the thermal energy is used to overcome the forces of attraction between the atoms or molecules until the solid is completely converted into a liquid.

Since the thermal energy is used to break bonds and increase the distance between the atoms or molecules, a change in temperature is not observed as the average kinetic energy of the particles hasn't increased. This heat energy used is known as **latent heat**. Latent means 'hidden'.

Once the change of state is complete, the potential energy of the atoms or molecules increases and the temperature rises. The kinetic energy of the particles also increases.

When the boiling point is reached, the thermal energy supplied is once again used to break bonds between the liquid atoms or molecules. The particles gain sufficient kinetic energy to escape the liquid as vapour (or gas state).

If the substance in gaseous state is heated further, the temperature increases due to the gas particles gaining kinetic energy (mostly in the form of translational kinetic energy).

The reverse argument applies if a gas **condenses** to a liquid and then **solidifies**/**freezes** to a solid.

Evaporation and boiling in terms of the particle model

The atoms or molecules of a liquid have a range of kinetic energies. Some have kinetic energies that are considerably larger than the average. If these particles are near the surface of the liquid, they can overcome the attractive forces of other atoms or molecules and escape the body of the liquid.

Evaporation is the term used when a substance changes from a liquid to a gas at a temperature below boiling point and occurs at the surface of the liquid.

Since the atoms or molecules with highest kinetic energies have escaped the liquid, the average kinetic energy of the remaining particles will be smaller. Since temperature is a measure of the average kinetic energy of the particles, the temperature decreases. This is why evaporation has a cooling effect.

Humans perspire on a hot day. As the perspiration evaporates from the skin, it will decrease the thermal energy of the body. As a result, the person's body temperature decreases.

Boiling also involves a substance changing from a liquid to a gas. It takes place at a temperature that is characteristic to a substance and occurs throughout the liquid.

Latent heat

The heat energy absorbed or released when a material changes state is called latent heat.

The amount of latent heat required (Q) depends upon the nature of the substance (specifically, its latent heat (L)) and the mass of the substance m, and is calculated using $Q = mL$.

The latent heat of a substance is defined as the thermal energy required to change one kilogram of a substance from one state to another without a change in temperature.

$$Q = mL$$

where Q = thermal energy absorbed or released in Joules (J)

m = mass of the substance changing state in kilograms (kg)

L = latent heat of the substance in J kg^{-1}

There are three forms of latent heat:

Latent heat of fusion L_f	Latent heat of vaporisation L_v	Latent heat of sublimation L_s
The latent heat of fusion of a substance is defined as the thermal energy required to change one kilogram of a substance from solid state to liquid state without a change in temperature.	The latent heat of vaporisation of a substance is defined as the thermal energy required to change one kilogram of a substance from liquid state to gaseous state without a change in temperature.	The latent heat of sublimation of a substance is defined as the thermal energy required to change one kilogram of a substance from solid state to gaseous state without a change in temperature. ***Carbon dioxide and iodine are two common substances that undergo sublimation.***

WATER

$$L_f = 3.34 \times 10^5 \text{ J kg}^{-1}$$

$$L_v = 2.26 \times 10^6 \text{ J kg}^{-1}$$

During the change of state from a gas to a liquid (**condensation**) or from a liquid to a solid (**freezing/solidification**) heat is released due to the formation of bonds between atoms or molecules.

Some substances change from solid to gas (**sublimation**) or from gas to solid (**deposition**) without going through a liquid phase.

3

Worked examples

Useful data

water $L_f = 3.34 \times 10^5$ J kg^{-1}

water $L_v = 2.26 \times 10^6$ J kg^{-1}

$c_{water} = 4.18 \times 10^3$ J kg^{-1} K^{-1}

$c_{ice} = 2.1 \times 10^3$ J kg^{-1} K^{-1}

1. Calculate the thermal energy needed to melt 100 g of ice at 0.00°C or 273 K.

   $Q = mL = 0.1 \times 3.34 \times 10^5 = 3.34 \times 10^4$ J

2. (a) Calculate the thermal energy required to convert 250 g of water at 18°C completely to steam.

   $Q = Q_{raise\ temp\ to\ 100} + Q_{vaporise}$

   $Q = mc\Delta T + mL_v$

   $Q = 0.25 \times 4180\ (100 - 18) + 0.25 \times 2.26 \times 10^6$

   $Q = 6.5 \times 10^5$ J

   (b) A kettle is rated at 1200 W. Calculate the time taken for the kettle to convert the water at 18°C to steam in minutes.

   $Q = Pt \quad \therefore \quad t = \frac{Q}{P} = \frac{6.5 \times 10^5}{1200} = 540\text{s} = 9.0 \text{ minutes}$

3. 20 g of water at room temperature (22°C) is frozen to produce ice at 0.0°C. Calculate the amount of thermal energy released during this process.

   $Q = Q_{lower\ temp\ to\ 0} + Q_{solidify}$

   $Q = mc\Delta T + mL_f$

   $Q = 0.02 \times 4180\ (22) + 0.02 \times 3.34 \times 10^5$

   $Q = 8.5 \times 10^3$ J

? Science inquiry practical

The latent heat of fusion of ice

Method

1. Measure the mass of a calorimeter using electronic scales.
2. Fill the calorimeter about halfway with warm water (around 30°C).
3. Measure the mass of the calorimeter and water using electronic scales.
4. Calculate the mass of water by subtracting the mass of the calorimeter from the combined mass of the calorimeter and the water.
5. Measure the initial temperature of the warm water.
6. Dry a few small pieces of ice and place them in the water.
7. Continually stir the mixture and continue adding pieces of ice until the temperature drops to between 5°C and 10°C.
8. Record the temperature of the water once all of the ice has melted.
9. Measure the combined mass of the calorimeter containing the water and the melted ice.
10. Calculate the mass of the ice by subtracting the combined mass of calorimeter, water and melted ice from the original mass of water in the calorimeter.

Data

Mass of calorimeter	
Mass of calorimeter and water	
Initial temperature of warm water	
Mass of warm water	
Mass of calorimeter, water and melted ice	
Mass of ice	
Final temperature of water and melted ice	

Calculation

$$Q_{released\ by\ warm\ water} = Q_{melt\ ice} + Q_{increase\ the\ temperature\ of\ the\ melted\ ice}$$

$$m_{warm\ water}\, c_{warm\ water}\, \Delta T_{warm\ water} = m_{ice}\, L_{ice} + m_{melted\ ice}\, c_{melted\ ice}\, \Delta T_{melted\ ice}$$

$$\therefore\ L_{ice} = \frac{m_{warm\ water}\, c_{warm\ water}\, \Delta T_{warm\ water} - m_{melted\ ice}\, c_{melted\ ice}\, \Delta T_{melted\ ice}}{m_{ice}}$$

Perform your calculation here:

Questions

1. Why does the ice need to be dry?
2. Why is it important to stir the mixture?
3. Calculate the percentage error for your experimental value for the latent heat of fusion of ice and comment on the accuracy.

Exercises

3.1 Heat and temperature

1. Describe the difference between thermal energy and heat.

2. (a) Use the space below to sketch a graph that represents the range of kinetic energies of the particles in a substance.

   (b) The substance is cooled. On the same set of axes, represent the new range of kinetic energies of the particles.

3. Explain why thermal energy increases with temperature.

4. Convert the following temperatures.
   (a) 30°C to °F
   (b) 40°C to K
   (c) 50 K to °C
   (d) 100°F to °C

5. (a) Define the term absolute zero.

   (b) State the temperature value for absolute zero in Kelvin and degrees Celsius.

6. Define the term temperature and explain why it is said to determine the direction of heat flow.

7. State the condition required for the flow of heat to stop.

8. The diagram below shows a warm heat bag being used to relieve neck pain

Explain why the heat bag will cool down after being in contact with your body for an extended period of time.

9. Explain how a jumper helps keep you warm.

10. The diagram below shows a metal spoon resting in a cup of hot tea.

Explain why a metal spoon that has been resting in a hot cup of tea is too hot to place in your mouth.

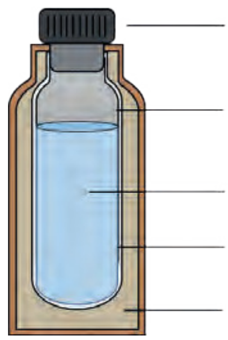
11. A gas stove cooker is shown in the diagram below.

(a) Describe how the flame at the back of a gas oven helps heat the air inside the oven.

(b) You are baking a cake with a friend. Your friend urges you not to open the oven door or the cold air will get into the oven. Discuss the problem with this statement.

12. The adjacent diagram shows a vacuum flask.

It consists of a thick plastic screw-top and double metal walls that are evacuated (all air is removed). The flask is silvered on the inside.



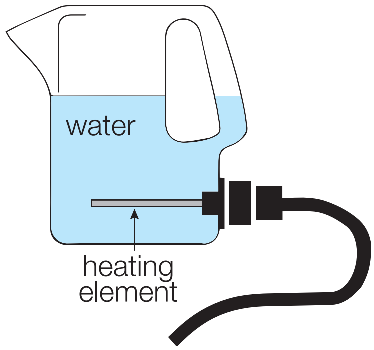
(a) Name the transfer process by which heat flows through the metal.

(b) Name the transfer process by which heat flows through the vacuum.

(c) Suggest and explain a reason for using a plastic screw-top to seal the flask instead of a metal screw top.

(d) A vacuum flask is used to keep drinks such as coffee hot. Describe why a hot drink such as coffee remains hot for a long period of time in a vacuum flask.

13. An electric kettle is shown in the adjacent diagram.



(a) Name the transfer process by which heat flows from the heating element to the water in the kettle.

(b) Explain how the process of convection heats the water. Draw a convection current in the pictured kettle.

(c) Explain, in terms of the particle theory, why the outer plastic casing of the kettle gets hot.

14. The diagram below shows a common cork used to seal a bottle.

Explain why such a cork is hard to remove from a hot bottle but is easier to remove once the bottle cools.

15. Use the particle model to explain why the expansion in liquids is generally larger than the expansion in solids.

16. Summarise a possible procedure for demonstrating that a gas will expand when it is heated.

17. This question requires a longer response.

In answering the question that follows you should:

- *communicate your knowledge clearly and concisely*
- *use physics terms correctly*
- *present information in an organised and logical sequence*
- *include information that is relevant to the question.*

Pressure cookers are popular kitchen items because they cook food faster than traditional stove top cookers. The main parts of a pressure cooker are illustrated in the diagram below.

The heating element is located near the base of the cooker not the top of the cooker.

Explain how the heating element placed at the base of the cooker heats the contents of the cooker (which includes a significant amount of liquid) and why a design with the heating element at the top of the cooker would be inefficient

3.2 Specific heat capacity

Useful data

$L_{f\ ice} = 3.34 \times 10^5$ J kg^{-1}

$L_{v\ water} = 2.26 \times 10^6$ J kg^{-1}

$c_{water} = 4.18 \times 10^3$ J Kg^{-1} K^{-1}

$c_{iron} = 450$ J kg^{-1} K^{-1}

$c_{lead} = 130$ J kg^{-1} K^{-1}

1. Define the term specific heat capacity.

2. A lump of lead experiences a temperature increase of 60 K when it absorbs 5.0×10^3 J of thermal energy. Determine the temperature change that the same lump of lead would experience if it absorbs 2.0×10^4 J of thermal energy.

3. (a) Calculate the thermal energy that an electric kettle transfers to 500.0 g of water in raising the temperature from 20.0°C to boiling point.

   (b) Calculate the power rating of the kettle if it can boil the water in 1 minute and 15 seconds.

4. A 75 g iron nail is heated to 130°C in a flame. It is dropped on a block of ice. The nail quickly loses 1.23×10^3 J of thermal energy. Determine the final temperature of the nail.

5. 1.50 kg of water at 323 K is mixed with 1.20 kg of water at 365 K. Show that the equilibrium temperature of the water is 342 K.

6. 200 g of lead is heated in a 700°C flame for several minutes. It is then placed in 250 g of water until thermal equilibrium is reached. This temperature is 26°C.

(a) Determine the initial temperature of the water to two significant figures.

(b) State the assumption that you have made in calculating your answer.

7. A student collects experimental data for determining the specific heat capacity of a metal X. The student's data is listed below.

(a) Use the data to calculate the specific heat capacity of metal *X*.

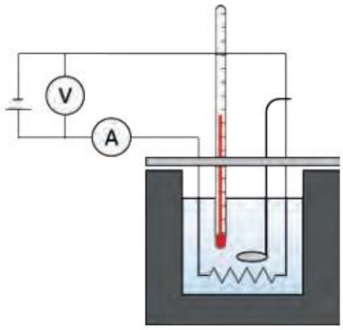
mass of metal X = 50.0 g
mass of water in copper calorimeter = 100.0 g
mass of copper calorimeter = 100.0 g
initial temperature of metal X = 100.0°C
initial temperature of water in the calorimeter = 15.0°C
final temperature of water in the calorimeter = 19.0°C
c_{water} = 4180 J kg^{-1} K^{-1}
c_{copper} = 385 J kg^{-1} K^{-1}

(b) Describe the significance of the value obtained in part (a).

8. A student immerses a 200 W heating element in a calorimeter.

The student uses the element to heat 100 g of water for different amounts of time and records the temperature change experienced by the water.

The table below summarises the results of the experiment.



Heating time (seconds)	0	30	60	90	120	150
Change in temperature ΔT (°C)	0	14	30	43	58	72

(a) State the independent variable for this experiment.

(b) State the dependent variable for this experiment.

(c) Plot a suitable graph for the results on the graph page.

(d) Calculate the gradient of the line (include the units).

(e) State the relationship between the two variables and write the equation of the line.

(f) Use your value of the gradient to calculate the specific heat capacity of water to two significant figures.

(g) If the power rating of the heating element was not known, describe how it could be determined using the circuit shown in the diagram.

(h) Describe one likely source of error in the results that were collected. Classify it as random or systematic.

(i) Describe one improvement that could be made to the method so that the effect of random errors may be reduced.

(j) State any evidence that the effects of random errors in this experiment are minimal.

9. The diagram below shows a saucepan being heated on an electric cooktop. The saucepan contains 1.25 L of water at 21.0°C. The heating element has a power rating of 1.80 KW.

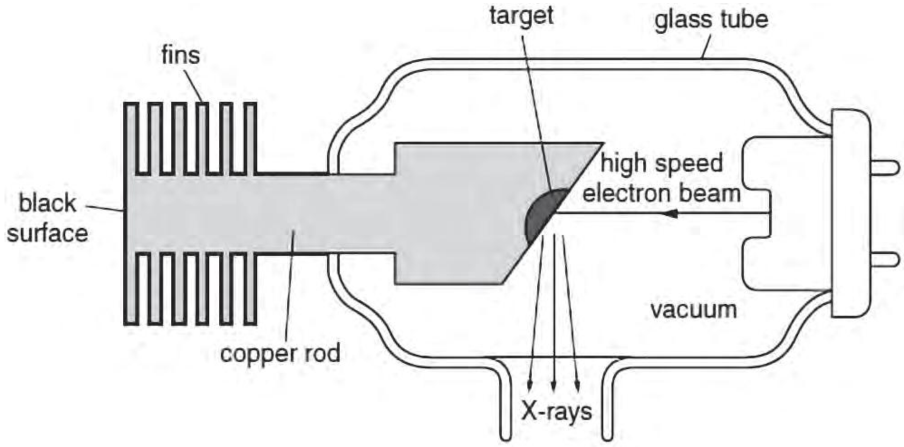
(a) Calculate the time it would take to boil the water using this heating element. Express your answer in minutes.

(b) Cooktops often have several heating elements. They are not all of the same size.

The diagram below shows such a cooktop.

In terms of saving energy when cooking, suggest one advantage in designing cooktops with heating elements that have a different size.

10. The diagram below shows an X-ray tube. X-rays are produced when a high-speed electron beam strikes a target. A large amount of heat energy is produced due to the collisions. The cooling fins contain water that circulates through them to draw heat away from the target. This ensures that the X-ray tube does not overheat and melt. A copper rod connects the target and the cooling fins.



(a) Suggest a reason for choosing copper for the rod that connects the target and the cooling fins.

(b) State the main method of heat transfer which heats the water in the cooling fins.

(c) The cooling fins are black and are designed with spaces between them.

Explain the advantage of black cooling fins with spaces between them in drawing heat away from the target.

(d) The cooling fins of a particular X-ray tube are filled with 25.0 mL of water. The cooling fins draw heat energy away from the target at an average rate of 9.35×10^4 Js^{-1}.

An X-ray image is taken with this X-ray tube. The tube is in operation for 1.00×10^{-1} s in taking the X-ray image.

If the cooling fins do not transfer heat energy to the air, show that the increase in temperature of the water in the cooling fins would be 89.5ºC in taking this X-ray image.

3.3 Change of state

Useful data

$L_{f\ ice} = 3.34 \times 10^5$ J kg^{-1}

$L_{v\ water} = 2.26 \times 10^6$ J kg^{-1}

1. Distinguish between latent heat of fusion and latent heat of vaporisation.

2. Calculate the thermal energy needed to melt 5.0 kg of ice at 273 K.

3. Show that the thermal energy required to convert 2.00×10^3 g of ice at 0.00°C to steam at 1.00×10^2 °C is 6.02×10^6 J.

4. A kettle can boil 0.50 kg of water at room temperature (22°C) and convert half the mass to steam in 3.0 minutes.

   (a) Determine the power rating of the kettle.

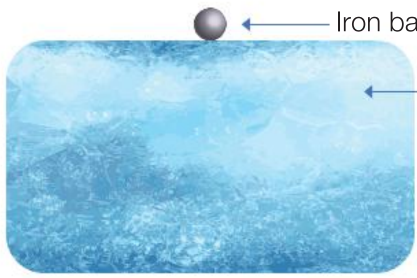
   (b) Explain what this power rating means.

5. You are cooking pasta in boiling water. Explain whether the pasta will cook faster if you increase the size of the flame used to heat the pot.

6. Calculate the thermal energy released from your body when you melt 80.0 g of ice at 0.00°C on your hand. ***Hint:*** the ice melts and then reaches thermal equilibrium with your body (37.0°C).

7. You are at the beach on a very hot day. Explain why you cool down when you wrap your wet towel around your body.

8. An iron ball bearing of mass 0.300 kg is heated from 20.0°C to 100.0°C by placing it in a beaker of boiling water for several minutes. The ball bearing is then placed onto a large block of ice at 0.00°C.

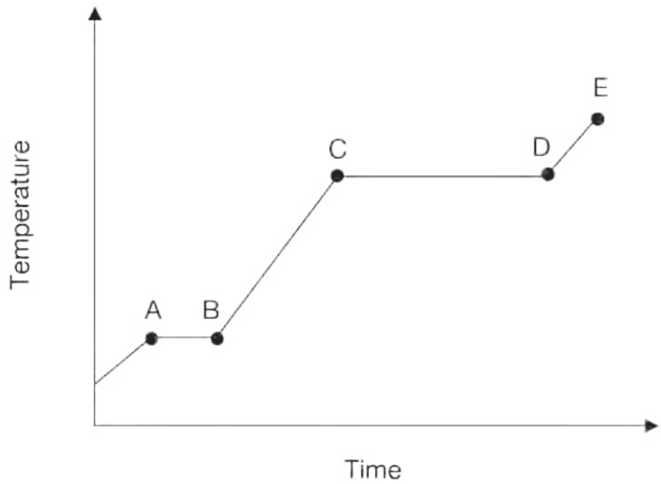


(a) Given the specific heat capacity of iron is 450 J kg^{-1} °C^{-1} that 32.3 g of ice that will melt.

(b) State any assumption made in answering part (a).

9. 2.00×10^6 J of heat energy is supplied to 2.00 L of water at 70.0°C. Determine the mass of steam produced.

10. The diagram below is a heating curve, which represents how the temperature of a solid substance changes as it is heated.



(a) State the section of the graph that represents the substance completely in

(i) liquid state

(ii) gaseous state

(b) State the section of the graph that represents the substance while it is

(i) melting

(ii) vaporising

(c) Clearly indicate the melting point of the substance on the graph.

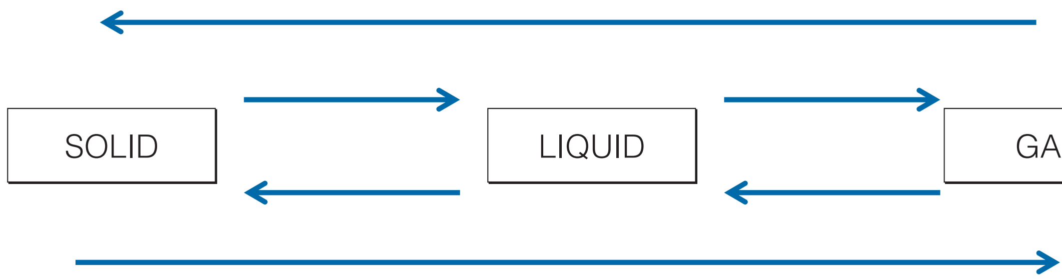
(d) Clearly indicate the boiling point of the substance on the graph.

(e) Explain why the temperature of a substance remains constant while it is changing state even though heating continues.

11. Describe the difference between evaporation and boiling.

12. Explain why a scalding burn (from boiling water) is not as severe as a steam burn.

13. Add labels for the name given to each change of state represented by the arrows on the diagram below.



14. A plastic water bottle is filled with 480 g of water at 22°C. The bottle is placed in a freezer that removes heat energy from the water causing it to freeze. The temperature of the ice when the bottle is removed from the freezer is –5.0°C.

The diagram below shows the plastic water bottle containing the ice.

(a) Using the data listed below and the information in the question, show that the amount of heat energy removed from the water is 2.1×10^5 J.

Specific heat capacity of water = 4200 J kg^{-1} K^{-1}

Specific latent heat of fusion of water = 3.3×10^5 J kg^{-1}

Specific heat capacity of ice = 2200 J kg^{-1} K^{-1}

(b) As the water freezes, it is noted that the plastic bottle becomes deformed bulging out at the base. Explain this observation.

Topic 4: Energy and momentum

4.1 Energy

Science understanding

1. The work done on an object is equivalent to the change in energy of that object. When a force is applied to an object causing a displacement over a distance, work is done.
    - Explain work in terms of an applied force.
    - Solve problems using $W = \Delta E$ and $W = Fs$ where the displacement is parallel to the force.
2. Energy exists in a number of different forms.
    - Describe different forms of energy including kinetic, elastic, gravitational potential, rotational kinetic, heat, and electrical.
3. Energy can be transferred from one object to another or transformed into different forms of energy.
    - Describe examples of energy being transferred from one object to another.
    - Describe examples of energy being transformed.
    - Explain qualitatively the meaning and some applications of various forms of energy, including kinetic energy and potential energy.
    - Solve problems using $E_k = \frac{1}{2}mv^2$ and $E_P = mgh$.
    - Describe energy transfers between objects and within different mechanical systems.
4. Energy is conserved when transferred from one object to another in an isolated system.
    - Solve problems using the conservation of energy.
    - Describe and explain the energy losses that occur in systems involving energy transfers.
5. Power is defined as the rate at which work is done and is equivalent to the rate at which energy is used.
    - Solve problems using $P = \frac{W}{t}$ and $P = Fv$.
    - Interpret solutions in context

Energy is the ability to do something or cause change.

The **SI unit** of energy is the **Newton-metre** and is called the **Joule.**

An object or system either has energy or it does not. Direction is not relevant. Therefore, energy is not a vector quantity, it is a **scalar quantity**.

Work

When a force is applied to an object and causes a displacement, we say work is done. Consider pushing a supermarket trolley. You do more 'work' (use more energy) if you have to push harder (e.g. the trolley is heavy) or if you have to push the supermarket trolley a long distance.

Work done is defined as the product of the displacement created by the force and the component of force parallel to the displacement.

$$W = Fs$$

Where W = work done in Joules (J)

s = displacement in metres (m) in the direction of the force

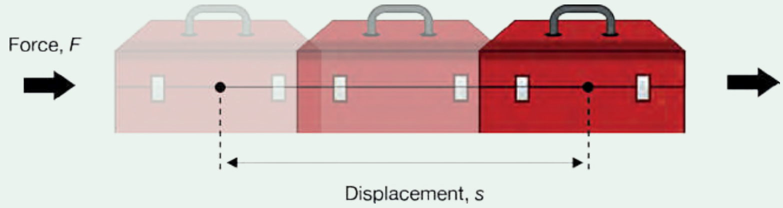
F = the component of force in the direction of the displacement

In general, whenever an object or system experiences a change in energy, work is said to be done. The work done on an object or system is equivalent to the change in energy of that object or system. We revisit this concept again later in the chapter and use it to define energy more formally.

Energy is the ability to do work.

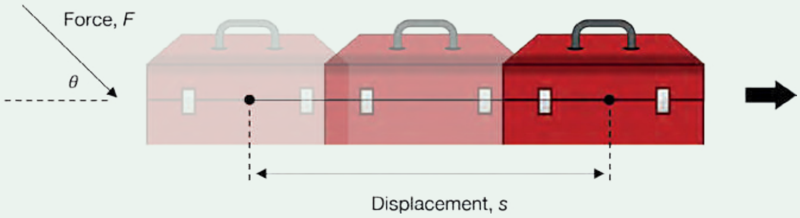
Extra understanding

CASE 1 The displacement is parallel to the force



W=Fs

CASE 2 The displacement is not parallel to the force



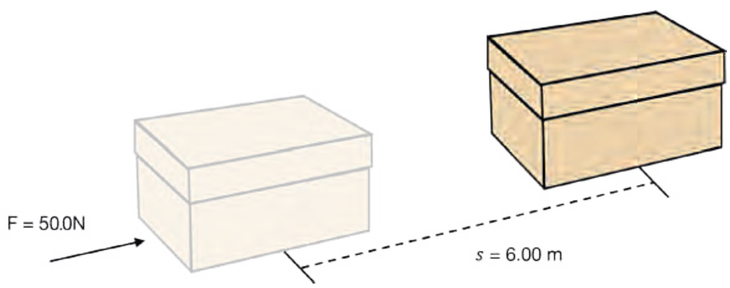
From figure 4.1.1, it can be seen that the component of force parallel to the displacement (F_H) is given by *Fcosθ.* It follows that the work done is given by:

W=Fscosθ

Figure 4.1.1

Worked examples

1. A 50.0 N force acts to move a 3.00 kg box 6.00 m across a smooth floor as shown in the diagram below. The frictional forces are negligible.



Calculate the work done in moving the box 6.00 m.

$W = Fs = 50 \times 6 = 3.00 \times 10^2\ J$

2. A car pulls a caravan along a straight horizontal road. The tension in the coupling between the car and the caravan is 1.00×10^3 N. The caravan is towed for 2.00 hours at an average speed of 60.0 kmh^{-1}.

(a) Calculate the displacement of the caravan while it is being towed.

$s = vt = \frac{60}{3.6} \times (2 \times 60 \times 60) = 1.20 \times 10^5\ m$ in the direction that the caravan moves

(b) Calculate the work done by the car's motor after 2.00 hours.

$W = Fs = 1000 \times 1.2 \times 10^5 = 1.20 \times 10^8\ J$

3. A 8.0 tonne truck can accelerate at a rate 1.2 ms^{-2}. Calculate the work done by the motor in moving the truck 1.0 km.

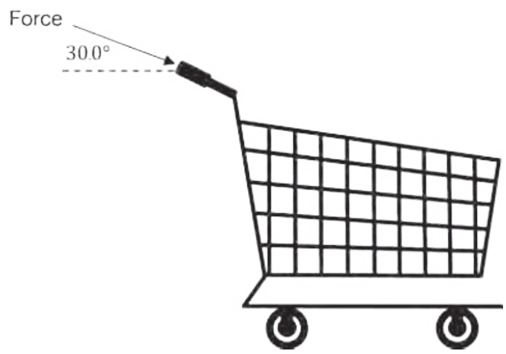
$W = Fs = mas = 8000 \times 1.2 \times 1000 = 9.6 \times 10^6\ J$

4. An object gains 2.5×10^4 J of energy when a force acts on it over a distance of 5.0 m. Calculate the magnitude of the force acting on the object.

The gain in energy is equivalent to the work done.

$W = Fs\ \therefore\ F = \frac{W}{s} = \frac{2.5 \times 10^4}{5} = 5.0 \times 10^3\ N$

5. A child pushes a supermarket trolley 8.00 m with a force of 120 N at 30.0° to the horizontal as shown.



Calculate the work done in moving the trolley 8.00 m.

$W = F s \cos\theta = 120 \times 8 \times \cos 30 = 831\ J$

Different forms of energy

Energy exists in a number of different forms.

Different forms of energy are described in the table that follows. Potential energy is energy that is stored and cannot do any work until it is released.

Type of energy	Description
Kinetic	The energy associated with any moving object. Since most objects that we deal with in this course travel in a straight line, we are dealing with translational kinetic energy. This is covered mathematically later in this chapter.
Rotational kinetic	The energy associated with any rotating object e.g. a rotating tyre, or a CD in a CD player. Consider a ball being thrown: it may have both translational kinetic energy and rotational kinetic energy. In Topic 3, we discussed the particles of a substance such as a gas having translational, rotational and vibrational kinetic energy.
Elastic potential	The energy possessed by a stretched or compressed material such as a spring or elastic band.
Gravitational potential energy	Gravitational potential energy is the energy possessed by an object due to its height above the ground. This is covered mathematically later in this chapter.
Thermal/heat	The energy possessed by moving atoms and molecules. Recall that thermal energy is defined as the combined potential and kinetic energies that come from the vibration of particles within an object. Heat is the thermal energy that is absorbed, released or transferred between objects. It involves a flow of thermal energy.
Electrical	The energy possessed by moving charges that make up an electric current.
Electromagnetic	The energy possessed by electromagnetic radiation such as microwaves, visible light, X-rays, ultraviolet light and gamma rays.
Nuclear	The energy released during nuclear reactions. For example, when uranium is split by a neutron, energy is released in the form of kinetic energy of the products. This process is called fission.
Sound	The energy possessed by vibrating air or matter molecules.
Chemical potential	The energy possessed by the electronic structure of atoms and molecules. It is the energy associated with foods and fuels.

4

Energy transformations

Energy can be transferred from one object to another or transformed into different forms of energy.

1. Energy being transferred from one object to another.

Examples include:

- The work done on a cricket ball when you hit a cricket ball is transformed into the kinetic energy of the ball.
- The work you do on your school bag to lift it will become the gravitational potential energy of your school bag.
- The work you do on an elastic band in stretching it becomes the elastic potential energy of the elastic band.
- As seen in Topic 3, heat can be transferred by conduction from an object at a higher temperature to another object at a lower temperature when the two objects are in contact.
- During a collision between a moving ball and a stationary ball, the moving ball will impact some or all of its kinetic energy to the stationary ball.

2. Energy being transformed into different forms of energy.

Examples include:

- Solar cells convert electromagnetic energy into electrical energy.
- Photosynthesis is the process by which green plants use the Sun's energy to make food in the form of sugar. The process of photosynthesis therefore converts electromagnetic energy into chemical potential energy.
- A battery converts chemical potential energy into electrical energy.
- A microphone converts sound energy into electrical energy.
- A pendulum converts gravitational potential energy into kinetic energy and vice versa as it swings.

Helpful online resource

'Energy forms and changes' https://phet.colorado.edu/

Kinetic energy

Consider a moving object. If it collides with another object it is likely to cause damage or change the speed of the object it collides with. By definition, it possesses energy because it can do work. This type of energy is called kinetic energy and its value depends on two factors: the speed and mass of the moving object.

Figure 4.1.2 shows a car colliding with a wall. The car possesses a large amount of kinetic energy and is able to do work on the wall. This results in a significant amount of damage to the wall (and window). The car is also damaged because the wall does work on the car.

Figure 4.1.2

Kinetic energy is the energy possessed by a moving object.

$$E_k = \frac{1}{2}mv^2$$

where E_k is the kinetic energy in Joules (J)
m is the mass in kilograms (kg)
v is the speed of the object in ms^{-1}

Worked examples

1. (a) Calculate the kinetic energy possessed by a 11.0 mg fly, moving with a speed of 18.0 ms^{-1}.

$$E_k = \frac{1}{2}mv^2 = \frac{1}{2}(11 \times 10^{-6})(18)^2 = 0.00178\,J$$

(b) Calculate the speed with which a 30.0 kg child would need to walk in order to have the same kinetic energy as the fly in part (a). (Answer in ms^{-1} and kmh^{-1}.)

$$E_k = \frac{1}{2}mv^2 \therefore v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 0.00178}{30}} = 0.0109\ ms^{-1} = 0.0392\ kmh^{-1}$$

2. Two masses A and B have speeds 20 ms^{-1} and 40 ms^{-1} respectively. If the masses possess the same kinetic energy, determine the ratio of mass A to mass B.

$$E_k = \frac{1}{2}mv^2$$

$$\frac{E_{kA}}{E_{kB}} = \frac{\frac{1}{2}m_A v_A^2}{\frac{1}{2}m_B v_B^2} = \frac{m_A 20^2}{m_B 40^2} \therefore \frac{m_A}{m_B} = \frac{E_{kA}}{E_{kB}}\frac{40^2}{20^2} = 4$$

Gravitational potential energy

When an object is lifted, it gains energy. We know this because it has the ability to do work, especially if it falls on top of another object.

This type of energy is called gravitational potential energy. Its magnitude depends on how high an object is lifted and the mass of that object.

Figure 4.1.3 shows a person carrying several boxes. The boxes possess gravitational potential energy which can do work if they fall.

Figure 4.1.3

Gravitational potential energy is the energy possessed by an object due to its height in a gravitational field.

$$E_P = mgh$$

where E_P is the gravitational potential energy in Joules (J)

m is the mass in kilograms (kg)

g is the gravitational acceleration = 9.80 ms^{-2} on Earth

h is the vertical position of the object in metres (m)

4

Worked examples

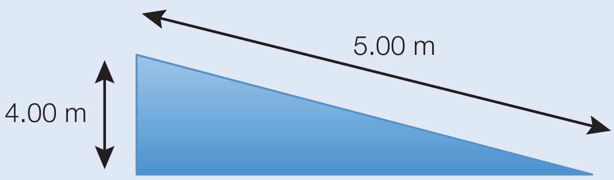
1. Calculate the gravitational potential energy possessed by a 15.0 kg box raised 3.00 m above the ground.

   $E_P = mgh = 15 \times 9.8 \times 3 = 441\ J$

2. Determine the height from which a 500 g object should be dropped in order for it to impart 100 J of energy to another object resting on the floor.

   $E_p = mgh \quad \therefore \quad h = \frac{E_p}{mg} = \frac{100}{0.5 \times 9.8} = 20.4 = 20\text{ m}$

3. Consider a 60.0 kg woman walking 5.00 m up a staircase. The vertical height reached at the top of the staircase is 4.00 m. Calculate the gravitational potential energy gained by the woman.



   $E_P = mgh = 60 \times 9.8 \times 4 = 2.35 \times 10^3\ J$

The law of conservation of energy

Energy is conserved when transferred from one object to another in an isolated system.

The law of conservation of energy states that energy cannot be created nor destroyed, it can only be converted from one form into another.

Consider the following cases:

1: A change in an object's kinetic energy

Work is done when an object gains kinetic energy. For instance, the work done by the engine of a vehicle provides the vehicle with kinetic energy. If we apply the law of conservation of energy and we consider the system to be **isolated from outside forces**, then it follows that the gain in kinetic energy of the vehicle is equal to the work done by the engine of the vehicle. That is, all of the work done by the engine is transformed into kinetic energy. This is illustrated by Figure 4.1.4.

Figure 4.1.4

Alternatively, work is done in slowing or stopping an object which already has kinetic energy. For a vehicle, work is done by the braking system unless the vehicle collides with another object such as a wall. If we apply the law of conservation of energy and we consider the system to be **isolated from outside forces**, then it follows that the loss in kinetic energy of the vehicle is equal to the work done. This is illustrated by Figure 4.1.5.

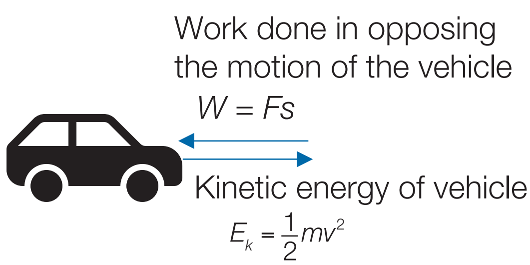


Figure 4.1.5

Work done = gain or loss in kinetic energy = ΔE_k

2: A change in an object's gravitational potential energy

Work is done whenever an object is lifted through a vertical height *h*. This results in the object gaining gravitational potential energy. If we apply the law of conservation of energy and we consider the system to be **isolated from outside forces**, then it follows that the gain in gravitational potential energy of the object is equal to the work done on the object in lifting it. That is, all of the work done in lifting the object is transformed into gravitational potential energy. This is illustrated by Figure 4.1.6.

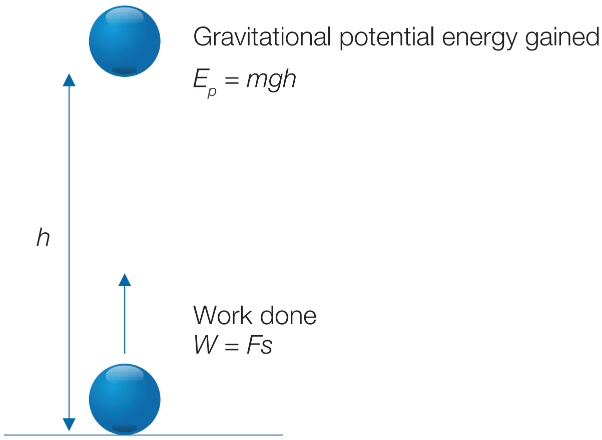


Figure 4.1.6

Alternatively, when an object falls through a vertical height *h*, the Earth's gravitational field does work on the object and it gains kinetic energy. If we apply the law of conservation of energy and we consider the system to be **isolated from outside forces**, the kinetic energy gained by the object is equal to the gravitational potential energy that it 'lost'. That is, all of the gravitational potential energy initially possessed by the object is transformed into kinetic energy. This is illustrated by Figure 4.1.7.

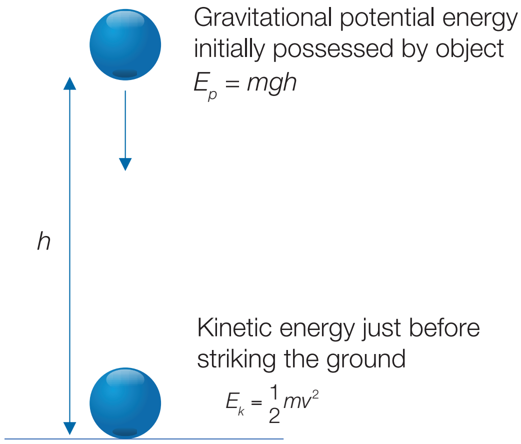


Figure 4.1.7

Gravitational potential energy gained or lost ΔE_g = loss or gain in kinetic energy = ΔE_k

Helpful online resource

https://phet.colorado.edu/sims/html/energy-skate-park-basics/latest/energy-skate-park-basics_en.html

https://phet.colorado.edu/en/simulation/legacy/energy-skate-park

Extra understanding

Your teacher may be able to demonstrate energy transfers using a steam engine, combustion engine or other similar engines.

In addition your teacher may demonstrate the relationship between power and mechanical advantage.

4

Worked examples

1. An arrow is fired with a vertical velocity of 100 ms^{-1}.

   (a) Describe the main energy transformation that occurs from the time the arrow is fired to the time that it reaches its maximum height.

   As the arrow is fired it possesses kinetic energy. As it rises, the kinetic energy is converted into gravitational potential energy. The higher the arrow rises, the more kinetic energy is converted into gravitational potential energy. Once it reaches maximum height, all of the kinetic energy originally possessed by the arrow is completely converted into gravitational potential energy.

   (b) Use the law of conservation of energy to determine the height reached by the arrow. Describe and explain any assumption that you have made.

   $$E_{K_{when\ fired}} = E_{p_{top\ of\ flight}}$$

   $$\frac{1}{2}mv^2 = mgh$$

   $$h = \frac{v^2}{2g} = \frac{100^2}{2 \times 9.8} = 510\ m$$

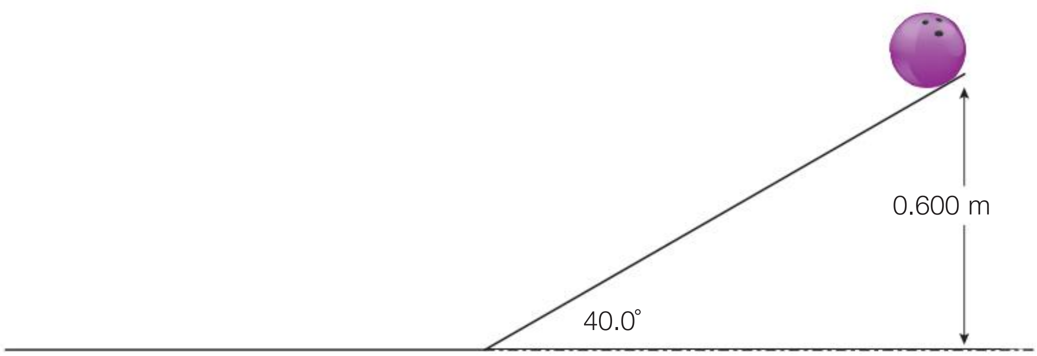
   The assumption made is that there is no energy lost in other ways, such as heat (due to air resistance).

   (c) Check your answer to part (b) using kinematics (i.e. the equations of motion).

   $$v^2 = v_o^2 + 2as$$

   $$s = \frac{v^2 - v_o^2}{2a} = \frac{0^2 - 100^2}{2 \times -9.8} = 510\ m$$

2. Consider a bowling ball of mass 3.00 kg held at rest at the top of the incline plane shown below. The incline plane makes an angle of 40.0° with the horizontal. Frictional forces acting on the bowling ball can be considered negligible.



   (a) The bowling ball is released. Describe the main energy transformation that occurs in this situation.

   When the ball is released it possesses gravitational potential energy. As it moves down the incline plane, the gravitational potential energy is converted into kinetic energy. Once the ball reaches the bottom of the incline plane, all of the gravitational potential energy it originally possessed is completely converted into kinetic energy.

   (b) Use the law of conservation of energy to determine the speed of the bowling ball at the bottom of the incline plane.

   $$E_{K_{bottom}} = E_{p_{top}}$$

   $$\frac{1}{2}mv^2 = mgh$$

   $$v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 0.6} = 3.43\ ms^{-1}$$

   NB: It should be noted that some of the kinetic energy of the ball would in the form of rotational kinetic energy. Since rotational dynamics is not part of this course, it has been assumed that all of the kinetic energy of the ball is translational. The actual speed of the ball at the bottom of the incline plane would be less than the value calculated if the rotational kinetic energy were taken into account.

3. Consider the bowling ball described in question 2. Frictional forces acting on the bowling ball were considered negligible. This question assumes that a frictional force of 4.00 N acts on the ball.

(a) Determine the work done by the ball in overcoming friction as it moves down the incline plane.

Length of the incline plane: $\sin 40 = \frac{0.6}{s} \therefore s = \frac{0.6}{\sin 40} = 0.933\ m$

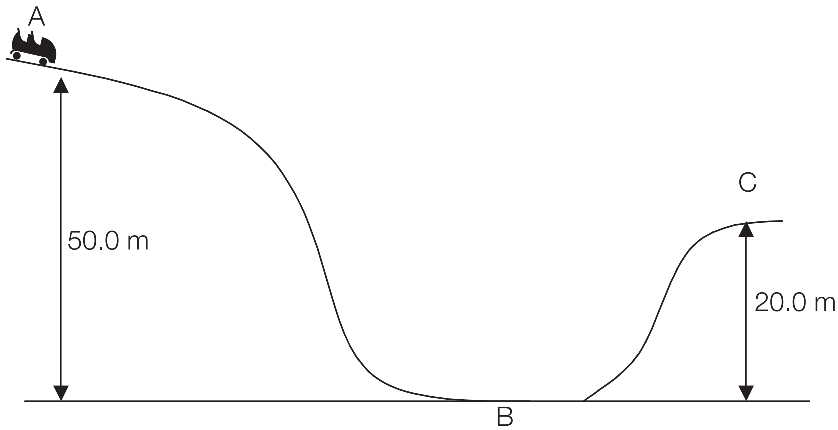
Work done: $W = Fs = 4 \times 0.933 = 3.73\ J$

(b) Determine the speed of the ball at the bottom of the incline plane (take into account the frictional force calculated above).

Energy available to be converted into $E_k = mgh - 3.73 = 3 \times 9.8 \times 0.6 - 3.73 = 13.91\ J$

$E_k = \frac{1}{2}mv^2 \therefore v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 13.91}{3}} = 3.05\ ms^{-1}$

4. Consider a roller coaster cart on the frictionless track shown below. The cart moves from position A to B and then proceeds to position C.



(a) Assuming that the cart starts from rest at position A, determine the speed of the cart at position B.

$E_{kB} = E_{pA}$ *Law of conservation of energy*

$\frac{1}{2}mv^2 = mgh$

$v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 50} = 31.3\ ms^{-1}$

(b) Determine the speed of the cart at position C.

$E_{totalA} = E_{pc} + E_{kc}$

$mgh_A = mgh_c + \frac{1}{2}mv_c^2$

$gh_A = gh_c + \frac{1}{2}v_c^2$

$v_c = \sqrt{2(gh_A - gh_c)} = \sqrt{2(9.8 \times 50 - 9.8 \times 20)} = 24.2\ ms^{-1}$

(c) If the cart is given an initial speed of 10.0 ms^{-1} at position A, show that the speed of the cart at position B would be 32.9 ms^{-1}.

Total energy at A: $E_p + E_k = mgh_A + \frac{1}{2}mv_A^2$

It follows that $mgh_A + \frac{1}{2}mv_A^2 = \frac{1}{2}mv_B^2$

Therefore $gh_A + \frac{1}{2}v_A^2 = \frac{1}{2}v_B^2 \therefore v_B = \sqrt{2(gh_A + \frac{1}{2}v_A^2)} = \sqrt{2(9.8 \times 50 + \frac{1}{2} \times 10^2)} = 32.9\ ms^{-1}$

5. A cyclist and his bicycle have a mass of 85 kg. The cyclist can accelerate from rest at a rate of 2.5 ms^{-2} over a distance of 100 m.

   (a) Calculate the cyclist's gain in kinetic energy.

   Using the law of conservation of energy, the kinetic energy gained by the cyclist is equal to the work done.

   $W = E_{kgained} = Fs = mas = 85 \times 2.5 \times 100 = 2.1 \times 10^4\ J$

   (b) Calculate the final speed of the cyclist.

   $E_k = \frac{1}{2}mv^2 \quad \therefore \quad v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 2.1 \times 10^4}{85}} = 22\ ms^{-1}$

6. A 130 g dart is thrown with a speed of 15 ms^{-1} at a dartboard. In stopping, the dart penetrates the board 4.0 mm.

   (a) Calculate, with reason, the work done by the dartboard in stopping the dart.

   Using the law of conservation of energy, the work done by the dartboard in stopping the dart is equal to the dart's loss in kinetic energy.

   $W = E_{k\ lost} = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.13 \times 15^2 = 15\ J$

   (b) Calculate the magnitude of the average force on the dart.

   $W = Fs \quad therefore \quad F = \frac{W}{s} = \frac{15}{4 \times 10^{-3}} = 3800\ N$

   (c) Calculate the magnitude of the average acceleration of the dart.

   $a = \frac{F}{m} = \frac{3800}{0.13} = 2.9 \times 10^4\ ms^{-2}$

Power

We were introduced to power in Topic 2. It was defined as the rate at which energy is transformed.

Power can be calculated by using the equation $P = \frac{W}{t}$.

The unit for power is the Watt where 1W = 1Js^{-1}.

All electrical devices have a power rating; a kettle with a power rating of 1200 W uses 1200 J of electrical energy every second. A kettle with a power rating of 2000 W is a more powerful kettle and transforms electrical energy into thermal energy more quickly.

Now consider two cars. What do we mean when we say that one is more powerful than the other?

If both cars accelerate to 100 kmh^{-1} but one takes ten seconds while the other only takes seven seconds, then the second car is said to be more powerful than the first. In other words, the more powerful car can transform the chemical potential energy of the fuel into kinetic energy of the car more quickly.

Similarly, consider two weightlifters. What do we mean when we say that one is more powerful than the other? If both can lift a mass of 100 kg above their heads but one takes three seconds while the other only takes two seconds, then the second is said to be more powerful than the first. In other words, the more powerful weightlifter can transform chemical potential energy into the gravitational potential energy of the weights more quickly.

Power is defined as the rate at which work is done.

Power is equivalent to the rate at which energy is used.

$$P = \frac{W}{t} = \frac{\Delta E}{t}$$

the unit for power is the Watt (W) or Js^{-1}

P = Power (W)

W = work (J)

t = time (s)

Worked examples

1. A 2.00 tonne car accelerates from rest to a speed of 100 kmh^{-1} in 5.80 s.

   (a) Determine the increase in the car's kinetic energy.

   $$E_{K_{gained}} = \frac{1}{2}mv^2 = \frac{1}{2} \times 2 \times 10^3 \times \frac{100}{3.6}^2 = 7.71 \times 10^5\ J$$

   (b) Determine the power delivered by the car.

   $$P = \frac{\Delta E}{t} = \frac{7.71 \times 10^5}{5.8} = 1.33 \times 10^5\ W$$

2. A kettle converts 30 000 J of electrical energy to thermal energy in 40 s. Calculate the power rating of the kettle.

   $$P = \frac{\Delta E}{t} = \frac{30000}{40} = 750\ W$$

3. (a) An electrical heater is rated at 1200 W. Explain what this means.

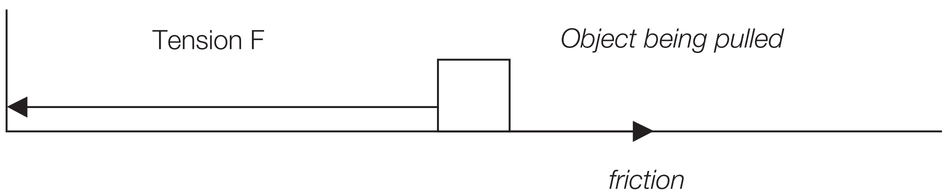
   1200 W is the power rating of the heater. This means that the heater converts 1200 J of electrical energy to thermal energy every second.

   (b) Determine the electrical energy used/converted in one hour of use. Express your answer in KJ.

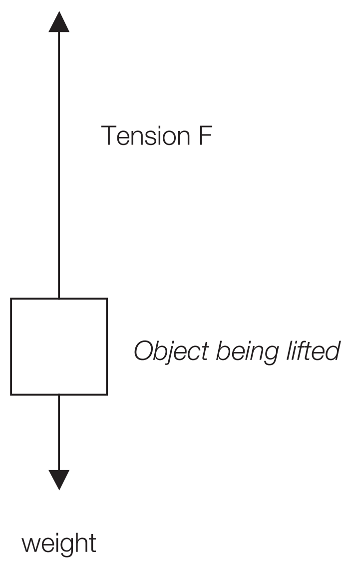
   $$P = \frac{\Delta E}{t} \therefore \Delta E = Pt = 1200 \times (60 \times 60) = 4.3 \times 10^6\ J = 4.3 \times 10^3\ KJ$$

The relationship between power and speed

Consider an object being pulled at a constant speed along the ground by a string. The tension in the string will cause the object to move with a constant speed if its magnitude is equal to the opposing frictional force between the object and the ground.



Similarly, consider an object being lifted at a constant speed. The magnitude of the tension in the string must be equal to the weight of the object.



The power of the device moving or lifting the object is given by $P = \frac{W}{t} = \frac{Fs}{t} = Fv$

The relationship between power and speed is given by: $\boldsymbol{P = Fv}$

where F is the force in Newtons and v is speed in ms^{-1}

4

Worked example

A tractor exerts a force of 2000 N when pulling an object behind it with a constant speed of 3.0 ms^{-1}. Calculate the power delivered by the tractor.

$P = Fv = 2000 \times 3 = 6000\ W$

Efficiency

The concept of efficiency was introduced in Topic 2. Efficiency can be calculated using the equation:

$$efficiency = \frac{useful\ energy\ /\ power\ output}{total\ energy\ /\ power\ input} \times 100$$

Worked example

1. A forklift truck uses 1.40×10^5J of energy to lift a 2.00×10^3 kg object through a height of 3.50 m.

   (a) Calculate the useful work done by the forklift truck.

   $work = E_{p\ gained} = mgh = 2 \times 10^3 \times 9.8 \times 3.5 = 6.86 \times 10^4\ J$

   (b) Calculate the efficiency of the forklift truck.

   $$efficiency = \frac{useful\ energy}{total\ energy} = \frac{6.86 \times 10^4}{1.4 \times 10^5} = 0.49$$

   i.e. 49% efficiency

Science as a human endeavour – example

An **electric motor** converts electrical energy into mechanical energy. An example is a water pump which converts electrical energy into the kinetic energy of moving water. Electric motors are used in machinery and many household devices.

The electric motor is responsible for a large amount of the electricity consumed worldwide. Advancements in design have made electric motors more efficient. Higher efficiency usually means that the performance of a motor is better. However, the purchase cost is higher. As a consequence, less efficient designs may be chosen even though the long-term running cost may be higher.

One method of increasing efficiency is by using **power source regeneration**. An electric motor will act as a generator to produce electricity when it decelerates or slows down. Traditionally this electrical energy was converted into heat and released. A power source regeneration system returns this electrical energy to the system so less electricity is consumed overall. Not only is the running cost reduced but the impact on the environment is also reduced.

Similarly, regenerative brakes make use of the loss in kinetic energy as a car brakes. Instead of the kinetic energy being converted to thermal energy and released, the kinetic energy is converted back into electrical energy and used to recharge the car battery. This not only slows the vehicle down but also causes the motor to work as a generator to produce electricity, Regenerative brakes are common in hybrid and fully electric vehicles where efficiency is very important.

Traditional brakes use brake pads that rely on friction to slow down a vehicle. These produce heat that is energy lost or wasted. Having said that, hybrid and fully electric vehicles have a traditional braking system as a back up.

? Further inquiry

A heat engine converts heat energy into another form. The energy transformations for a heat engine are represented by the arrow diagram below.

chemical energy → thermal energy → mechanical energy or work done

A traditional motor vehicle engine converts the chemical potential energy in petrol or gas to heat energy. This heat energy is then converted into kinetic energy to move the vehicle.

The energy transformations for a coal or gas power plant are represented by the arrow diagram below.

chemical energy → thermal energy → mechanical energy or work done → electrical energy

Heat engines (e.g. motor vehicle engines or fossil-fuel power plants) use fossil fuels or derivatives from a fossil fuel. They are not 100% efficient. In fact, efficiency is often between 30% and 40%. Heat energy is lost to the environment during the processes required to produce the mechanical energy.

Research ways in which heat engines can be more efficient.

? Science inquiry practical

Some ideas:

1. Design and conduct individual or group experiments to determine the efficiency of different systems involving energy transfers, e.g. different roller coaster systems.
2. Design and build a 'gravity car' – a car that uses a falling weight to transfer energy and rotate the wheels. Test or compare the power or efficiency of the car with others in the class.
3. Investigate the motion of pendulums, demonstrating the law of conservation of energy.
4. Test the conservation of energy by recording and measuring objects falling from different heights and recording their speed as they hit the ground.

Extra understanding

Your teacher may demonstrate the relationship between power and mechanical advantage using simple machines.

4.2 Momentum

Science understanding

1. Momentum is a property of moving objects, which depends on their mass and velocity.
2. Momentum can be expressed mathematically as $\vec{p} = m\vec{v}$.
3. Momentum may be transferred from one object to another when a force acts over a time interval.
4. The rate of change of momentum of an object with respect to time is equal to the net force acting upon the object. This can be expressed mathematically as: $\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$.
5. The impulse of an object is equal to $F\Delta t$, and consequently equals the change in momentum.
   - Use Newton's Second Law in the form $\vec{F} = m\vec{a}$ to derive the formula: $\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$
   - Solve problems involving changes in momentum and impulse (for one dimension).
   - Draw and interpret graphs of force vs time.
6. In an isolated system, the total momentum is conserved.
   - Use the conservation of momentum to solve problems in a variety of contexts.
7. An elastic collision is one in which the total initial kinetic energy equals the total final kinetic energy. In an inelastic collision some kinetic energy is transformed.
   - Describe the difference between an elastic collision and an inelastic collision using examples.
   - Solve problems involving one-dimensional collisions, using $E_k = \frac{1}{2}mv^2$ and $\vec{p} = m\vec{v}$.
   - Describe the energy transformations during inelastic collisions.
8. Undertake experiments to investigate the conservation of energy or conservation of momentum.

Momentum

Momentum is a property of moving objects, which depends on their mass and velocity.

Momentum is defined as the product of an object's mass and velocity.

Momentum can be expressed mathematically as:

$$\vec{p} = m\vec{v}$$

where *m* is the mass in kilograms (kg) and *v* is the velocity in ms^{-1}.

Since velocity is a ***vector quantity***, so is momentum.

The units of momentum are $kgms^{-1}$ or sN (shown later in chapter).

Worked example

Calculate the momentum of a 50.0 g ball thrown at 72.0 kmh^{-1} in an easterly direction.

$$\vec{p} = m\vec{v} = 0.05 \times \frac{72}{3.6} = 1.00\ kgms^{-1}\ east$$

Proportionality

Momentum is proportional to the mass of the object and it's velocity. This can be expressed as $p \propto mv$.

This means that the momentum changes by the same factor as the factor by which the mass or velocity is changed. For example, if the mass doubles so does the momentum. If the velocity is made ten times larger, the momentum becomes ten times larger. If the mass doubles and the velocity becomes ten times larger the momentum of the object becomes *2 × 10 = 20* times larger.

Newton's second law in terms of a change in momentum

Momentum may be transferred from one object to another when a force acts over a time interval.

The rate of change of momentum of an object with respect to time is equal to the net force acting upon the object.

This can be expressed mathematically as:

$$\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$$

where $\vec{F}$ is the force in Newtons and $\Delta\vec{p}$ is the change in momentum in $kgms^{-1}$ or sN.

Unit of momentum

Since $\Delta\vec{p} = \vec{F}\Delta t$ it follows that the units of momentum can be expressed as sN.

Derivation

Newton's second law can be expressed as the time rate of change in momentum.

$$\vec{F} = m\vec{a} = m\left(\frac{\vec{v}_f - \vec{v}_i}{\Delta t}\right) = \frac{m\vec{v}_f - m\vec{v}_i}{\Delta t} = \frac{\vec{p}_f - \vec{p}_i}{\Delta t} = \frac{\Delta\vec{p}}{\Delta t}$$

The focus in Stage 1 should be on one-dimensional situations.

Two-dimensional situations are studied in Stage 2 Physics. *© SACE 2018*

4

Worked examples

1. A 60.0 kg athlete increases his speed from 2.00 ms^{-1} to 9.00 ms^{-1} in 10.0 s.

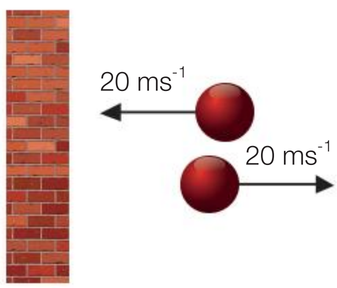
(a) Calculate the magnitude of the athlete's change in momentum.

$\Delta p = mv_f - mv_i = 60 \times 9 - 60 \times 2 = 420\ kg\ ms^{-1}$

(b) Calculate the magnitude of the force required to produce this change in speed.

$F = \frac{\Delta p}{\Delta t} = \frac{420}{10} = 42.0\ N$

2. A 300 g ball collides with a wall and rebounds at 90° to the wall without a loss in speed.



(a) Calculate the change in velocity $\Delta\vec{v}$, of the ball.

$\Delta\vec{v} = \vec{v}_f - \vec{v}_i = 20 \rightarrow - 20 \leftarrow = 20 \rightarrow + 20 \rightarrow = 40 ms^{-1} \rightarrow$ (i.e. 90° away from the wall)

(b) Determine the change in momentum $\Delta\vec{p}$, of the ball.

$\Delta\vec{p} = m\Delta\vec{v} = 0.3 \times 40 = 12\ kgms^{-1} \rightarrow$

(c) Calculate the force $\vec{F}$, that the ball exerts on the wall, if the collision takes 0.04 s.

$\vec{F}_{ball} = \frac{\Delta\vec{p}_{ball}}{\Delta t} = \frac{12}{0.04} = 300\ N \rightarrow$

Using Newton's Third Law, $\vec{F}_{wall} = -\vec{F}_{ball} = 300\ N \leftarrow$ (i.e. 90° towards the wall)

Impulse

Since $F = \frac{\Delta p}{\Delta t}$, it follows that $F\Delta t = \Delta p$

The product $F\Delta t$ is called the impulse of the force.

Impulse is equal to the change in momentum. It is defined as the product of force and the time over which the force acts.

Graphs of force versus time

A force vs time graph can be used to show how the force acting on an object changes with time. Figure 4.2.1 represents a constant force acting on an object. According to the law of conservation of energy, the work done on the object is transformed into its kinetic energy. That is, the object gains velocity and therefore momentum. A change in momentum constitutes an impulse. The area under the graph represents the product $F\Delta t$ or impulse.

Figure 4.2.2 represents an increasing force acting on an object. The area under the graph will still represent impulse.

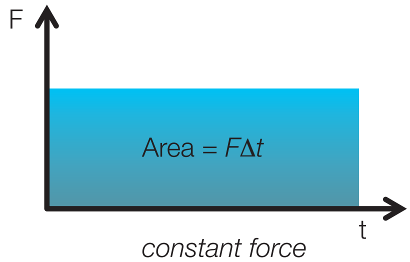


Figure 4.2.1

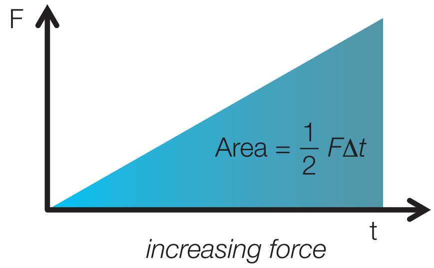


Figure 4.2.2

Worked examples

1. A force of 90.0 N acts on an object for 5.50 s. Calculate the magnitude of the impulse of the force.

   impulse $= F\Delta t = 90 \times 5.5 = 495$ *sN*

2. A 1600 kg vehicle travelling with a speed of 15 ms^{-1} collides with a stobie pole and stops in 2.2 s.

   (a) Calculate the magnitude of the impulse of the force acting.

   impulse $= \Delta p = mv_f - mv_i = 1600 \times 0 - 1600 \times 15 = -2.4 \times 10^4$ *sN*

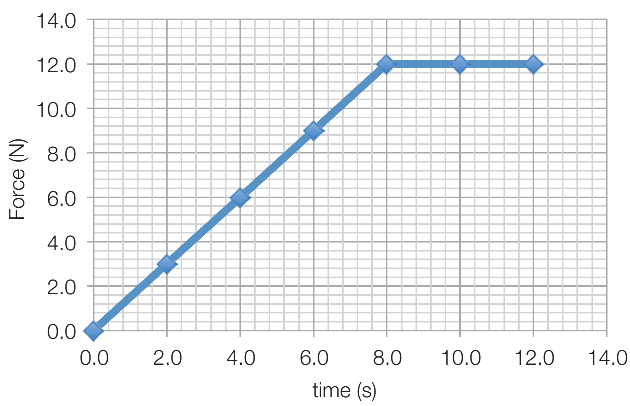
   The magnitude of the impulse is 2.4×10^4 sN

   NB: The negative indicates that the change in momentum is in the opposite direction to the original motion of the vehicle.

   (b) Calculate the magnitude of the force acting on the vehicle.

   $impulse = F\Delta t \quad \therefore \quad F = \frac{impulse}{\Delta t} = \frac{2.4 \times 10^4}{2.2} = 1.1 \times 10^4 N$

3. The graph shown below shows how the force on an object changes over a 12.0 s period of time.



   Calculate the impulse delivered by the force over 12.0 seconds.

   $Impulse = area\ under\ graph = \frac{1}{2} \times 12 \times 8 + 12 \times 4 = 96\ sN$

Applications

1. Why is it better to bend your knees as you land from a jump than to land with your legs in a straight and rigid position?

   When a person lands, they experience a change in momentum or impulse over a given time. If you bend your knees while landing, the change in momentum occurs over a longer period of time. Since $F = \frac{\Delta p}{\Delta t}$, the greater the time over which the change in momentum occurs, the smaller the force on your knees. This will hurt less and/or is less likely to cause injury.

2. Why does a cricket player trying to hit a 'six' follow through on a swing of the bat?

   The aim of the cricket player is to increase the momentum of the ball. As the bat hits the ball, the ball experiences a change in momentum or impulse. The strength of the player limits the magnitude of the force that they can exert as they swing the bat. Since $\Delta p = Ft$, increasing the contact time will increase the impulse and hence change in momentum of the ball. The ball is more likely to travel a greater distance.

Science as a human endeavour

Some ideas:

1. Explore applications in which an understanding of maximising the time during which the force acts leads to an increase in speed. Examples include: long rowing strokes, use of a woomera for throwing.
2. Evaluate ways in which increasing the gain in speed through maximising the force applied is used in sport science. Examples include: force applied with tennis racquets or golf clubs, kicking balls, and other ball sports. Design a new piece of equipment.

Extra understanding

Car safety features

Air bags help save lives during a collision. While the car is moving, the car and its occupants have a certain momentum. When a collision occurs, the car stops but the occupants continue moving forward in accordance with Newton's First Law. A change in momentum occurs to bring the occupants to rest. If the occupants strike a hard surface such as the steering wheel, their change in momentum occurs over a short time interval. An air bag causes the same change in momentum to occur over a longer period of time. Since the force experienced is inversely proportional to the time taken to stop, the force experienced by the occupants is reduced.

Science as a human endeavour

Road accidents cause death and injury. According to the Australian government's Department of Infrastructure and Regional Development, the estimated economical cost of motor vehicle accidents is $27 billion per annum. This department started keeping records in 1925 and since then there have been over 187 000 recorded deaths due to car accidents on our roads.

Thanks to the advancements in car safety features, road trauma has decreased over the past 40 years or so. This is despite the fact that more cars are present on our roads. The number of recorded road deaths has decreased from approximately 3800 in 1970 to approximately 1200 in 2015.

Socially, car accidents effect not only individuals but others around them. The death of a family member may lead to the loss of a carer, or the loss of income, for that family. These circumstances can lead to anxiety and or depression. If a family member is injured or becomes disabled, the effect may be similar. The injured individual may lose short or long-term employment, and other members of the family may need to leave work to care for the individual. This can resulting in financial and/or emotional strain. It is not uncommon for family units to break down.

Further inquiry

Research and analyse other safety mechanisms of modern vehicles that use concepts of impulse and momentum.

? Science inquiry practical

Some ideas:

1. Compare how difficult it is to stop objects of different masses and speeds.
2. Design an egg casing/container for eggs. Use the container to drop eggs and investigate the concept of impulse.

The law of conservation of momentum

The law of conservation of momentum states that in an isolated system where no external forces act, the total momentum before an interaction is equal to the total momentum after an interaction.

An **isolated system** is one in which no unbalanced forces act. This means that the effects of forces such as friction and air resistance are negligible. The objects therefore move with constant velocity within the system.

If the system is not isolated, the law of conservation of momentum does not hold true.

Another way of stating the law of conservation of momentum is to say that the total momentum of an isolated system remains constant or unchanged.

Elastic and inelastic collisions

An elastic collision is one in which the total initial kinetic energy equals the total final kinetic energy.

In an inelastic collision some kinetic energy is transformed into other forms of energy.

Helpful online resource

'Collisions Lab' https://phet.colorado.edu/en/simulation/legacy/collision-lab

Everyday examples

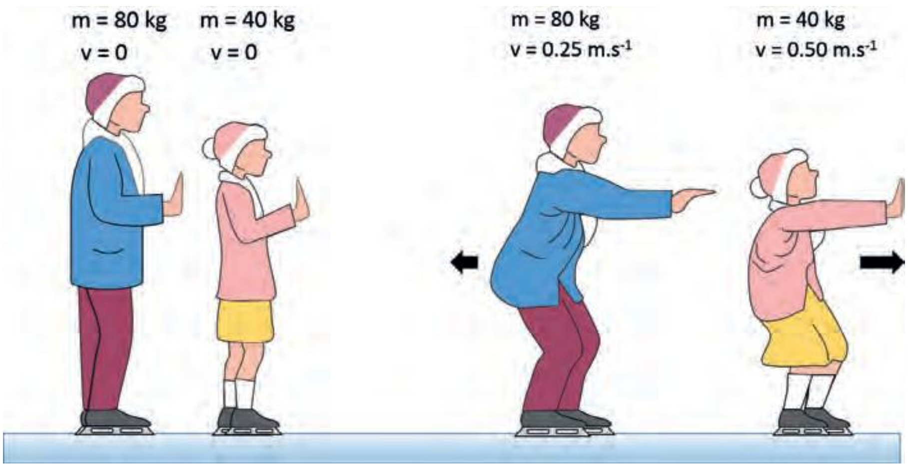


Figure 4.2.3

Figure 4.2.3 shows a man and his daughter standing still on ice. Their ice skates will reduce friction significantly when they move. The system can therefore be considered an isolated system. The total initial momentum of the man and his daughter is zero because they are standing still. When the man pushes his daughter forward she gains momentum. The diagram shows the girl's mass to be 40 kg and her speed to be 0.50 ms^{-1}. Her momentum is therefore $p = mv = 40 \times 0.5 = 20$ *sN* to the right. The diagram also shows that the man has a speed of 0.25 ms^{-1} to the left after he has pushed his daughter. Given the man's mass is 80 kg, he has gained a momentum of $p = mv = 80 \times 0.25 = 20$ *sN* to the left. That is, the man gains an equal momentum in the opposite direction to his daughter. The total final momentum of the man and his daughter is zero. The total momentum of the system has not changed i.e. momentum is conserved.

Figure 4.2.4 shows a blue van of mass 1800 kg travelling with a speed of 15.0 ms^{-1}. It collides with a stationary car. After the collision the two vehicles combine and travel as one mass.

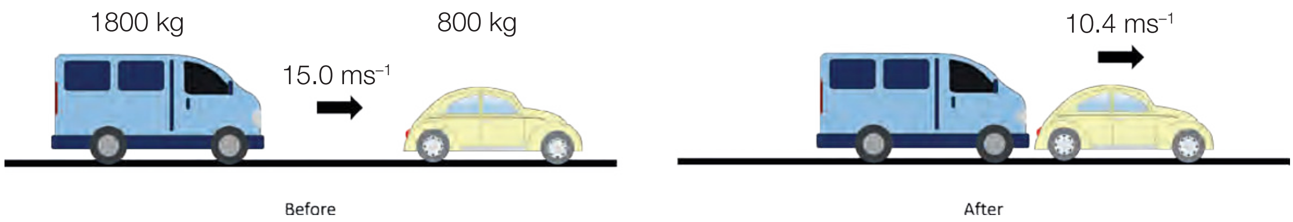
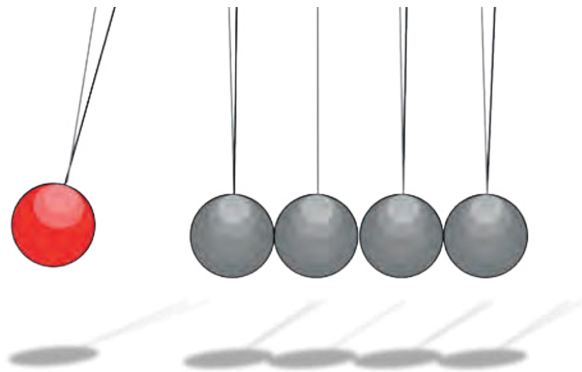


Figure 4.2.4

Assuming the system is isolated, the total momentum of the blue van and the yellow car will remain constant. The total initial momentum of the system is the momentum of the blue van before the collision because the yellow car is stationary ($p = mv = 1800 \times 15 = 27\ 000$ *sN* to the right). The total final momentum of the system is given by the product of the mass of the combined cars and their velocity ($p = mv = 2600 \times 10.4 = 27\ 000$ *sN* to the right).

Newton's cradle



Newton's cradle consists of five stationary balls hanging so that they make contact with one another. If you lift and release the first ball without disturbing the other four, it will hit the row of stationary balls and stop. At the same time, the first ball at the opposite end swings up.

This is because the balls are in contact and the momentum of the first ball is conserved. The momentum of the first ball is transferred to the second ball which transfers the momentum to the third ball. The transfer of momentum continues until it is transferred to the last ball. This causes the last ball to swing upwards.

The conservation of energy also applies. The gravitational potential energy of the first ball that was lifted is converted into kinetic energy as it swings to hit the row of stationary balls. The kinetic energy is transferred from the first ball to the last ball until the last ball in the row swings up to the same height that the first ball was lifted.

? Science inquiry practical

The type of investigations will depend on the type of equipment available at your school.

Some suggestions:

- Conduct experiments involving collisions, using a range of recording equipment, such as motion sensors and video. Confirm the law of conservation of momentum and/or determine whether the collisions are elastic.
- Use data and photographs from simulated accidents to make reasonable assumptions about their causes.
- Design and investigate collisions with minimal friction, using an air track and a range of recording equipment.
- Analyse video footage of explosions to further understand momentum in two dimensions.
- Investigate non-contact collisions by attaching magnets to trolleys.

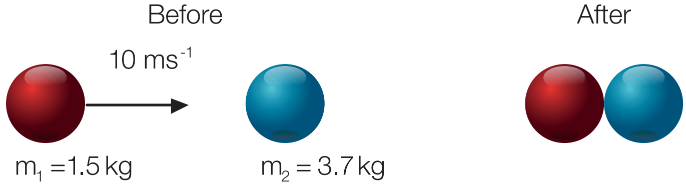
Science as a human endeavour

Some ideas

- Assess the technical and practical challenges associated with the development of spacecraft and the ways in which the conservation of momentum may be applied to spacecraft.
- Analyse the effect of the conservation of momentum in traffic accidents and therefore determine factors that may have led to a collision. Evaluate the social and economic consequences of traffic accidents.

Worked examples

1. The diagram below shows a 1.5 kg ball moving with a velocity of 10 ms^{-1} colliding with a stationary ball of mass 3.7 kg. After the collision, the balls stick together.



(a) Determine the combined velocity of the balls after the collision.

Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

$m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = m_T\vec{v}_f$

$1.5 \times 10 \rightarrow + 0 = 5.2 \times v_f$

$15 \rightarrow + 0 = 5.2 \times v_f$

$\therefore \ v_f = \frac{15 \rightarrow}{5.2} = 2.9 \ ms^{-1} \rightarrow$ i.e. $2.9 \ ms^{-1}$ to the right

(b) State the assumption you have made in answering part (a).

The system is isolated i.e. no external forces act. This allows the law of conservation of momentum to apply.

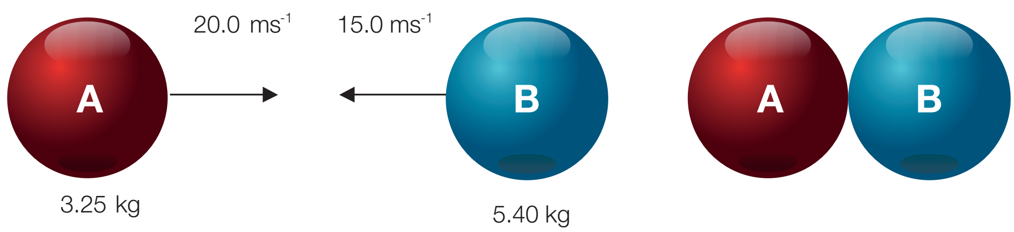
(c) Determine whether the collision is elastic.

$E_{ki} = \frac{1}{2}m_1v_1^2 + \frac{1}{2}m_2v_2^2 = \frac{1}{2} \times 1.5 \times (10)^2 + \frac{1}{2} \times 3.7 \times 0^2 = 75 \ J$

$E_{kf} = \frac{1}{2}m_Tv^2 = \frac{1}{2} \times 5.2 \times (2.9)^2 = 22 \ J$

The total final kinetic energy is not equal to the total initial kinetic energy. The collision is not elastic.

2. Consider the 'head on' collision shown below. The objects collide on a smooth, almost frictionless surface and stick together after the collision.



before the collision *after the collision*

(a) Determine the combined velocity of the objects after the collision.

Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

$m_A\vec{v}_{Ai} + m_B\vec{v}_{Bi} = m_{A+B}\vec{v}_{(A+B)f}$

$3.25 \times 20 \rightarrow + 5.4 \times 15 \leftarrow = 8.65 \times v_{(A+B)f}$

$65 \rightarrow + 81 \leftarrow = 8.65 \times v_{(A+B)f}$

$\therefore \ v_{(A+B)f} = \frac{16 \leftarrow}{8.65} = 1.85 \ ms^{-1} \leftarrow$ i.e. $1.85 \ ms^{-1}$ to the left

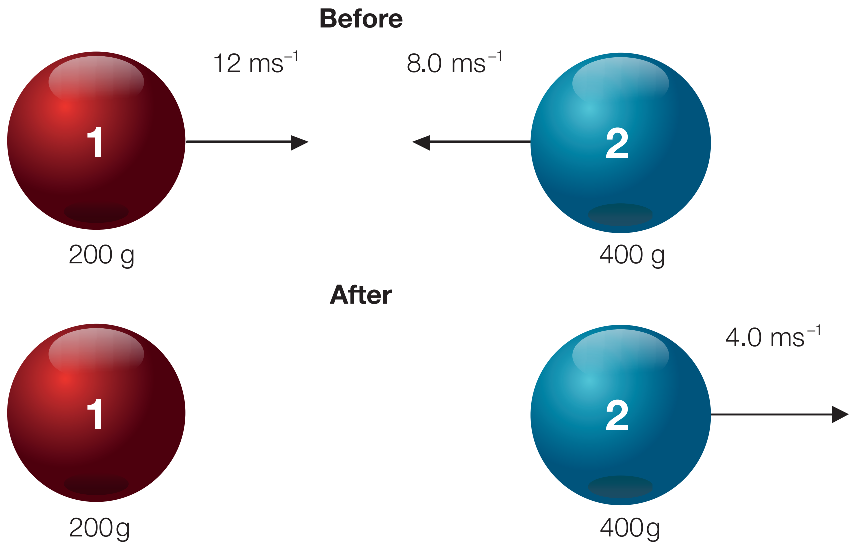
(b) Determine whether the collision is elastic.

$E_{ki} = \frac{1}{2}m_Av_A^2 + \frac{1}{2}m_Bv_B^2 = \frac{1}{2} \times 3.25 \times (20)^2 + \frac{1}{2} \times 5.4 \times 15^2 = 1260 \ J$

$E_{kf} = \frac{1}{2}m_{A+B}v_{(A+B)f}^2 = \frac{1}{2} \times 8.65 \times (1.85)^2 = 14.8 \ J$

The total final kinetic energy is not equal to the total initial kinetic energy. The collision is not elastic.

3. Two balls, 1 and 2, collide head on as shown below. The collision takes place on a smooth surface. The velocity of ball 2 after the collision is shown on the diagram below.



(a) Calculate the velocity of ball 1 after the collision.

Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

$m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = m_1\vec{v}_{1f} + m_2\vec{v}_{2f}$

$0.2 \times 12 \rightarrow + 0.4 \times 8 \leftarrow = 0.2 \times v + 0.4 \times 4 \rightarrow$

$2.4 \rightarrow + 3.2 \leftarrow = 0.2 \times v + 0.4 \times 4 \rightarrow$

$0.8 \leftarrow = 0.2 \times v + 1.6 \rightarrow$

$0.8 \leftarrow - 1.6 \rightarrow = 0.2 \times v$

$v = \frac{2.4 \leftarrow}{0.2} = 12\ ms^{-1} \leftarrow$

i.e. *12 ms⁻¹* to the left

(b) State any assumption that you have made in answering part (a).

The system is isolated i.e. no external forces act. This allows the law of conservation of momentum to apply.

(c) Determine whether the collision is elastic.

$E_{ki} = \frac{1}{2}m_1v_{i1}^2 + \frac{1}{2}m_2v_{2i}^2 = \frac{1}{2} \times 0.2 \times (12)^2 + \frac{1}{2} \times 0.4 \times 8^2 = 27\ J$

$E_{kf} = \frac{1}{2}m_1v_{1f}^2 + \frac{1}{2}m_2v_{2f}^2 = \frac{1}{2} \times 0.2 \times (12)^2 + \frac{1}{2} \times 0.4 \times 4^2 = 18\ J$

The total final kinetic energy is not equal to the total initial kinetic energy. The collision is not elastic.

4. A 3.00 kg rifle is fired. A 3.80 g bullet leaves the rifle with a velocity of 235 ms⁻¹.

(a) Sketch a diagram that illustrates the situation before and after the rifle is fired.

before the rifle is fired *after the rifle is fired*

(b) Explain, in terms of momentum, why the rifle recoils or 'kicks back'.

When the bullet is fired, it gains momentum. According to the law of conservation of momentum, the total momentum of a system remains unchanged in an isolated system. Since the total initial momentum of the rifle and the bullet is zero, this means that the total final momentum must be zero. The rifle therefore gains the same momentum as the bullet but in the opposite direction. This causes the rifle to recoil.

(c) Calculate the recoil velocity of the rifle.

$$m_{B+R}\vec{v}_{(B+R)i} = m_B\vec{v}_{Bf} + m_R\vec{v}_{Rf}$$

$$0 = 3.8\times10^{-3}\times 235 \rightarrow +3v$$

$$0 = 0.893 \rightarrow +\ 3v$$

$$0.893 \leftarrow\ = 3v$$

$$v = \frac{0.893\leftarrow}{3} = 0.298\ ms^{-1}\leftarrow$$

i.e. 0.298 ms^{-1} in the opposite direction to the bullet

Exercises

4.1 Energy

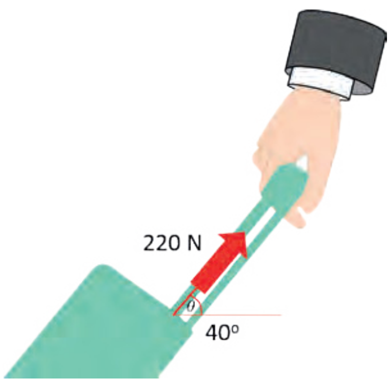
1. (a) Define the term ‘work done’.

(b) A child pulls a toy car with a force of 15.0 N over a distance of 2.00 m. Calculate the work done by the child.

(c) State the energy gained by the toy car.

2. A 3.00×10^3 kg truck can accelerate at a rate of 1.57 ms^{-2}. Calculate the work done by the motor in moving the truck 1.00 km.

3. A man pulls a suitcase 300 m through an airport terminal with a force of 220 N at 40.0° to the horizontal as shown in the diagram below.



(a) Calculate the work done in pulling the suitcase.

(b) Describe how reducing the angle at which the suitcase is pulled affects the amount of work done.

4. A force of 480 N acts on an object transferring 7.2×10^3 J of energy to the object. Calculate the displacement that results.

5. Describe the following forms of energy:

(a) electrical

(b) sound

(c) chemical potential

6. Use arrow diagrams to describe the main energy transformation involved in each case:

(a) a loud speaker

(b) a hair dryer

(c) a person running up a staircase with a constant speed

(d) a slingshot used to fire a rock horizontally

7. Describe the energy transformations involved when a person dives off a diving board into a swimming pool.

8. (a) Define the term ‘kinetic energy’.

(b) State the two factors that affect the amount of kinetic energy possessed by a body.

(c) State and explain the relationship between kinetic energy and each factor that affects it.

9. Calculate the kinetic energy of a Boeing 747-400 aeroplane with a mass of 3.90×10^5 kg cruising at a constant speed of 950 kmh^{-1}.

10. Calculate the kinetic energy of a 1000 kg adult great white shark swimming at a top speed of 40 kmh^{-1}.

11. A 60.0 kg woman possesses 5.80×10^2 J of kinetic energy as she is jogging. Calculate her average jogging speed.

12. (a) Define the term ‘gravitational potential energy’.

(b) The world’s tallest bungee jump is 233 m from the Macau Tower in China.

Calculate the gravitational potential energy possessed by a bungee jumper with mass 75.0 kg.

(c) State and explain the difference in the gravitational potential energy possessed by the bungee jumper if the jump was made possible on the Moon.

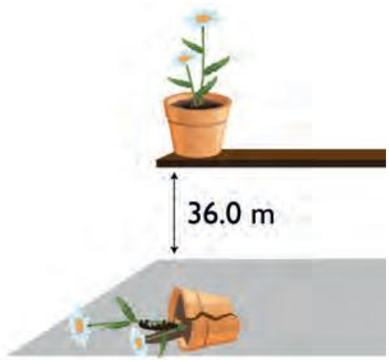
13. Determine the height to which a 10.0 kg object needs to be raised in order for it to possess the same kinetic energy as the woman jogging in question 11.

14. (a) A 250 g arrow is fired with a speed of 160 ms^{-1} towards a tree. Calculate the kinetic energy of the arrow.

(b) The arrow strikes and penetrates the tree to a depth of 8.00 cm. Determine the force that the tree exerts on the arrow when stopping it.

(c) State, with reason, the force that the arrow exerts on the tree.

15. (a) A pot plant is dropped from the window of a building 36.0 m above the ground.



Use energy principles to determine the speed of the pot plant on impact with the ground.

(b) Describe the energy changes that occur from the time that the pot plant is released to its impact with the ground.

(c) In terms of energy transformation, explain why the pot smashes on impact with the ground and does not bounce.

16. (a) A force of 285 N acts to move a 12.0 kg object 3.50 m. Calculate the work done.

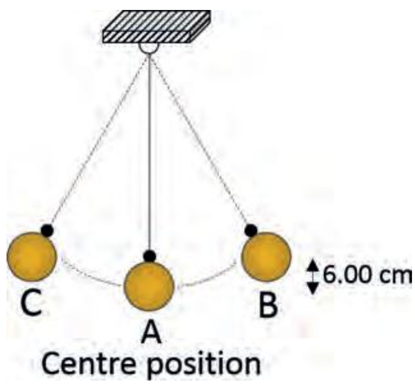
(b) Assuming that the object starts at rest, calculate the speed gained by the object.

17. A ball is thrown vertically into the air with a velocity of 20.0 ms^{-1}.

(a) Describe the energy changes that the ball experiences as it rises to reach maximum height.

(b) Use energy concepts to show that the height reached by the ball is 20.4 m.

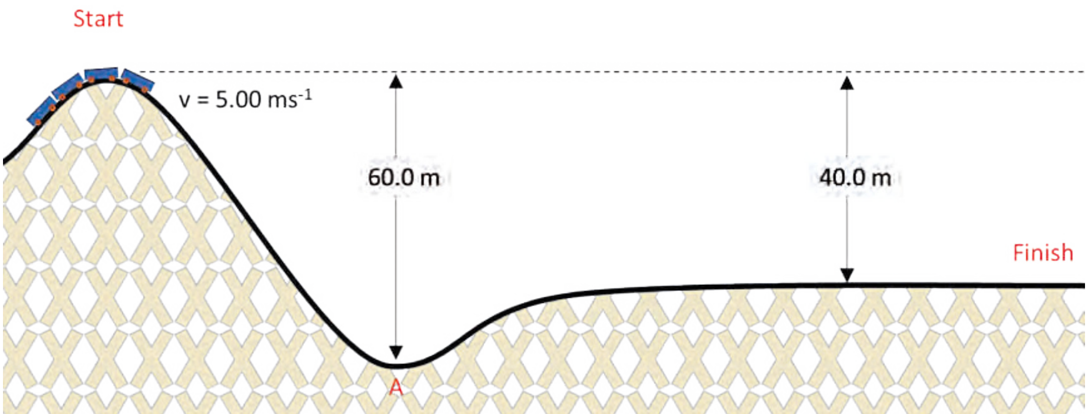
18. Consider the pendulum below. The bob is raise to position B, 6.00 cm above the centre position at A and released from rest at position B.



(a) Determine the speed of the bob at position A.

(b) State with reason the speed at position C.

19. The diagram below shows a roller coaster cart moving along a roller coaster. At the position marked ‘Start’, the roller coaster cart has a speed of 5.00 ms^{-1}. The cart them moves to the ‘Finish’ having passed through position A. Friction between the cart and the track can be considered negligible.



(a) Determine the speed of the cart at position A.

(b) Determine the speed of the cart at the finish.

20. A single scull rowing boat and its rower has a mass of 66.0 kg. The boat can reach a speed of 5.00 ms^{-1} in 2.40 s.

(a) Calculate the increase in the boat’s kinetic energy.

(b) Determine the power developed by the rower.

21. A 60.0 W globe is operated for 8.00 hours during an average day. Calculate the electrical energy used by the globe in this time.

22. (a) A motor uses 9.3 KJ of energy to lift a 350 kg box of goods. Determine the height to which the motor lifts the box.

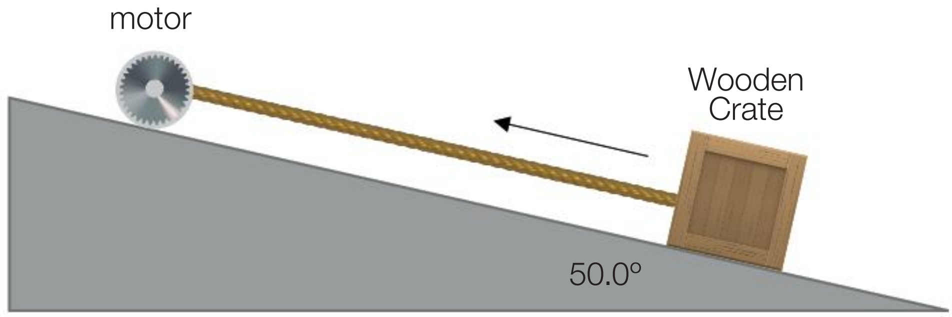
(b) The motor takes 12 seconds to lift the box through this height. Show that the power developed by the motor is 780 W.

23. A student pulls a desk with a force of 120 N at a constant speed of 0.35 ms^{-1}. Calculate the power developed by the student.

24. A boat anchor on a chain that has been raised out of the water by an electric motor is pictured below. The motor lifted the anchor out of the water with a constant speed and has an output power of 2400 W. A tension of 6.3 kN was maintained in the chain while lifting the anchor.

Calculate the speed at which the anchor was lifted out of the water.

25. The diagram below shows a 40.0 kg wooden crate being pulled up an incline plane at an angle of 50.0° to the ground. The wooden crate is attached to a motor via a rope. The motor pulls the wooden crate a distance of 10.0 m up the incline plane. A frictional force of 30.0 N acts to oppose the motion of the wooden crate.



(a) Show that the vertical distance through which the wooden crate is lifted is 7.66 m.

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(b) Calculate the useful work done by the motor in lifting the wooden crate a vertical distance of 7.66 m.

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(c) Calculate the actual work done by the motor in lifting the wooden crate through a vertical distance of 7.66 m.

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(d) Calculate the efficiency of the motor.

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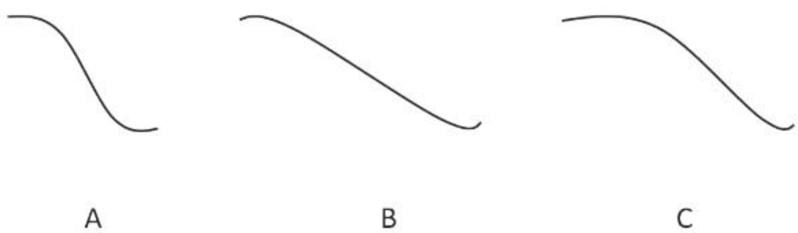
26. Consider the three playground slides (slippery dips) A, B and C shown below.



Assuming that the friction along each of the slides is negligible, explain which of the slides, if any at all, produces the greatest speed at its base.

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....

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27. This question requires a longer response.

In answering the question that follows you should:

- *communicate your knowledge clearly and concisely*
- *use physics terms correctly*
- *present information in an organised and logical sequence*
- *include information that is relevant to the question.*

Legend has it that while Isaac Newton was sitting under a tree, an apple dropped on his head leading him to the idea of the force due to gravity.

In terms of energy transformations, discuss why the apple falling on Newton's head from a greater height (i.e. a taller tree) could cause pain or potential injury.

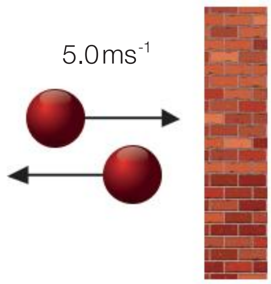
4.2 Momentum

1. Calculate the momentum $\vec{p}$ of a 30.0 kg German shepherd running with a velocity of 8.00 ms^{-1} in a northerly direction.

2. Calculate the magnitude and direction of the momentum of a 2.00 tonne van travelling with a velocity of 80.0kmh^{-1} in a southerly direction.

3. Calculate the speed of a 0.625 kg basketball which has a momentum of 3.50 kg ms^{-1}.

4. A 35 g ball collides without loss in speed with a wall as shown in the diagram below.



(a) State the change in speed Δv, of the ball.

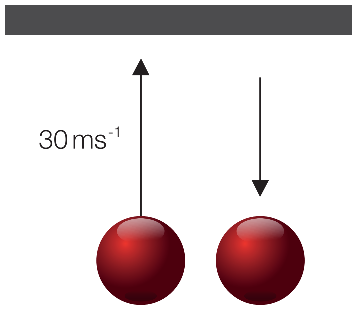
(b) Calculate the change in velocity $\Delta\vec{v}$, of the ball.

(c) Calculate the change in momentum, $\Delta\vec{p}$ of the ball.

(d) If the ball is in contact with the wall for 0.050 s, calculate the force $\vec{F}$ that the wall exerts on the ball.

(e) Determine the force, $\vec{F}$, that the ball exerts on the wall.

5. A gas molecule of mass 4.80×10^{-27} kg collides with the wall of a container with a speed of 30.0 ms^{-1}. The gas molecule is in contact with the wall for 1.50 μs and rebounds elastically.



(a) Calculate the magnitude and direction of the change in momentum of the gas molecule.

(b) Calculate the magnitude and direction of the force on the gas molecule.

(c) State the magnitude and direction of the force on the wall of the container.

6. The image below shows a motorised wooden go-cart. A force of 1.5×10^2 N acts on the go-cart for 5.0 s. The mass of the go-cart and the rider is 95 kg.

(a) Calculate the magnitude of the impulse of the force acting on the go-cart.

(b) Calculate the change in speed of the go-cart.

7. A supermarket trolley experiences an impulse of 2.50×10^3 sN when a force is applied for 4.00 s.

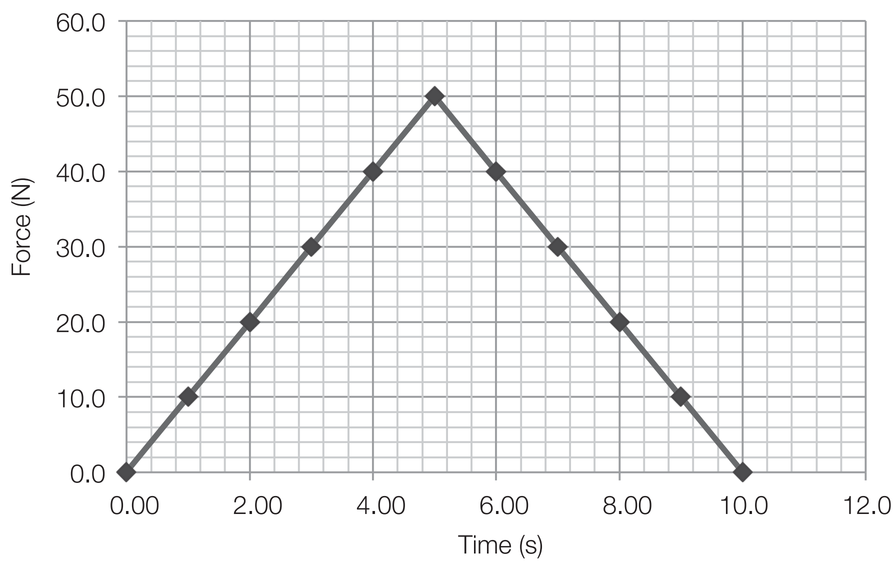
(a) Calculate the magnitude of the force acting on the supermarket trolley.

(b) If the supermarket trolley and its contents have a mass of 50.0 kg, calculate the magnitude of the acceleration of the supermarket trolley.

8. Explain why it hurts a boxer less if they follow through on a punch.

9. In terms of momentum, explain why a tennis player can hit a ball with greater speed if they follow through on a shot.

10. The graph illustrated below shows how the force acting on a 5.00 kg object varies over a 10.0 s period of time.



(a) Calculate the impulse delivered by the force acting over the 10.0 s.

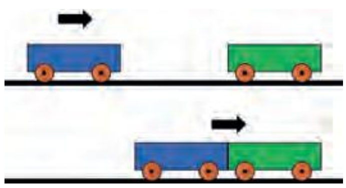
(b) The object was initially at rest. Calculate its speed after 10.0 s.

11. Show that the relationship between kinetic energy and momentum is given by $E_k = \frac{p^2}{2m}$

12. A 2.8×10^3 kg railway carriage travelling with a velocity of 4.0 ms^{-1} collides with a stationary railway carriage of mass 3.2×10^3 kg. The carriages link together after the collision as shown in the diagram below.

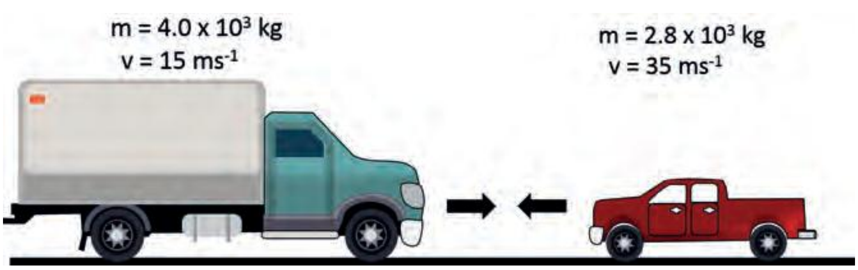
before

after



Determine the common velocity of the carriages after the collision.

13. A truck of mass 4.0×10^3 kg travelling with a velocity of 15 ms^{-1} to the right collides with and sticks to a smaller truck of mass 2.8×10^3 kg travelling with a velocity of 35 ms^{-1} to the left. Assume the system is isolated.



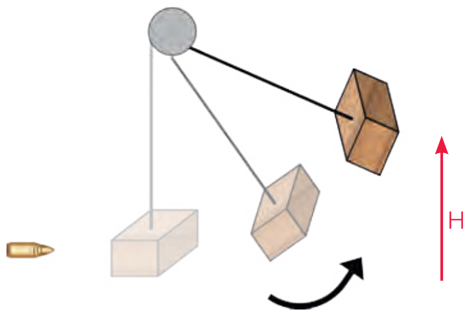
Show that the velocity of the trucks after the collision is 5.6 ms^{-1} to the left.

14. Two ice skaters travelling in opposite directions collide. Mary has a mass of 55.0 kg and is skating with a velocity of 5.00 ms^{-1}, while Jane has a mass of 60.0 kg and is skating with a velocity of 4.00 ms^{-1}. After the collision, Mary has a velocity of 1.00 ms^{-1} in the opposite direction that she was originally travelling.

(a) Explain the significance of the collision occurring on ice.

(b) Calculate Jane's velocity after the collision.

15. A 30.0 g bullet is fired with a velocity of 100 ms^{-1} into a 200 g block of wood which is suspended from a long rope. The bullet penetrates the block and they move off together as one mass as shown in the diagram.



The block swings in a circular path and rises to a height H above its original position.

(a) Calculate the speed with which the bullet and the block move off together.

(b) Calculate the kinetic energy of the bullet and the block.

(c) Determine the height *H*, to which the block rises.

16. Mickey's Fun Wheel is an enormous Ferris wheel with a twist. It is located at Disney California Adventure Park.

The carriages are referred to as gondolas and carry up to eight people. Some gondolas are fixed to the rim of the wheel while others slide along the interior curves of a loop as the wheel turns. The height of a gondola at the top of the wheel is 48.8 m.

A gondola holding eight people has a mass of 590 kg.

(a) Calculate the gravitational potential energy of the gondola at the top of the wheel.

(b) If an accident were to occur and the gondola fell from the top of the wheel, show that the maximum speed with which the gondola would strike the ground is 30.9 ms^{-1}.

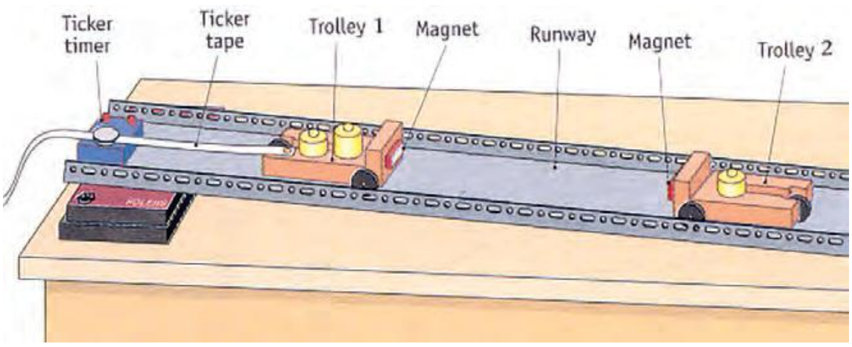
(c) Calculate the maximum magnitude of the momentum of the gondola as it strikes the ground.

(d) The gondolas are designed to crush slightly when a force is exerted on them. Why would this feature be an advantage in the unfortunate event that a gondola falls from the wheel while the ride is in operation?

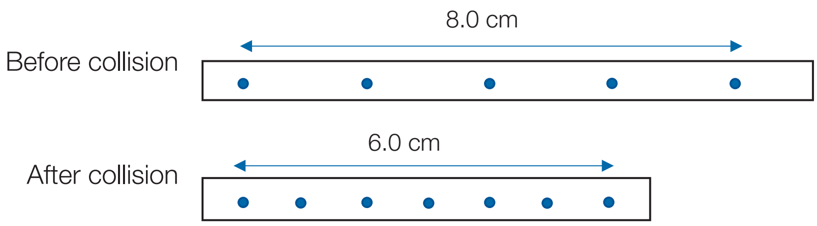
17. A student uses the apparatus show in the diagram below to determine whether momentum is conserved during a collision.

Trolley 1 is attached to a ticker timer tape which is threaded through a ticker timer.

When Trolley 1 is released, it moves down the runway and collides with Trolley 2 which is stationary. The ticker timer produces a series of dots on the tape. The time between the dots is 0.020 s. The speed of Trolley 1 before and after the collision can be determined from the ticker timer tape that results. The student varied the mass of the trolleys by adding masses to them and conducted three trials.



(a) The ticker timer tape for Trial 1 is shown below.



Calculate the speed of Trolley 1 before and after the collision.

(b) The table shown below summarises the results of the experiment.

Add the speed of Trolley 1, before and after the collision to the table.

	Trial 1	**Trial 2**	**Trial 3**
mass of Trolley 1 (kg)	0.20	0.20	0.31
mass of Trolley 2 (kg)	0.22	0.33	0.41
Initial speed of Trolley 1 (ms^{-1})		1.43	1.26
Final speed of trolleys (ms^{-1})		0.55	0.54

(c) Use the data for Trial 2 to determine whether momentum is conserved for this trial.

(d) Describe one improvement to the method that could result in more accurate data for the speed of the trolleys.

(e) Comment on the number of trials conducted by the student.

Topic 5: Waves

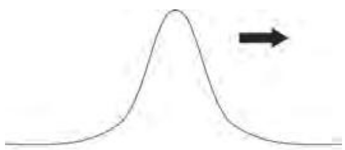
5.1 Wave model

Science understanding

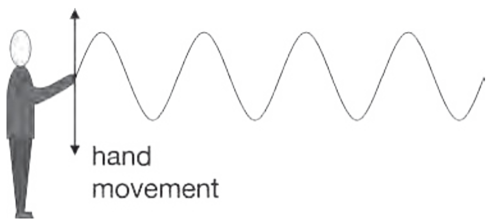
1. Waves are periodic oscillations that transfer energy from one point to another.
2. In longitudinal waves the direction of oscillation is parallel to the direction of travel of the wave.
3. In transverse waves the direction of oscillation is perpendicular to the direction of travel of the wave.
   - Represent transverse waves graphically and analyse the graphs.
   - Describe waves in terms of measurable quantities, including amplitude, wavelength (λ), frequency (f), period (T), and velocity (v).
   - Solve problems using:
     – $f = \frac{1}{T}$
     – $v = f\lambda$

Waves

A **single vibration** results in a **pulse**. If you shake a running hose up and down in a single action, a single moving pulse is produced.



A **wave** is created by a **continuous vibration**. If you shake a running hose continuously in a vertical direction, a snake-like pattern or continuous wave results. This type of wave is called a transverse wave and will be discussed later in the chapter.



The particles of the medium through which the wave travels will vibrate. The **medium** is the material through which the wave travels. In this case, the medium is water.

Waves transfer energy without transferring matter

Consider a cork in a tub of water. When you dip your finger vertically in and out of the water, some distance from the cork, you will produce a wave that causes the cork to vibrate (or oscillate) up and down as indicated in Figure 5.1.1. The cork does not move forward with the wave. This simple demonstration illustrates that waves transfer energy from one point to another without transferring matter.

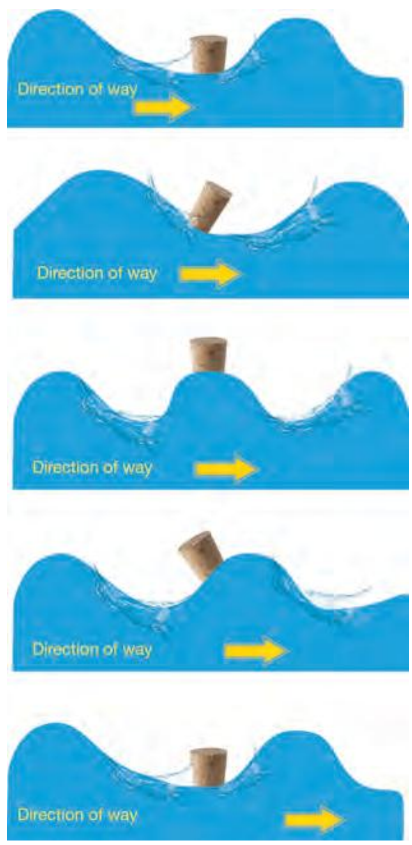


Figure 5.1.1

Waves are periodic oscillations that transfer energy from one point to another.

Helpful online resource

Watch this video. It discusses how waves can transfer energy without transferring matter.

https://www.youtube.com/watch?v=LyxLxx3xifo

Activity

Using slinky springs to demonstrate wave phenomena

Most school laboratories have slinky springs similar to the one shown in figure 5.1.2.

Figure 5.1.2

1. A student needs to hold each end of the spring.
2. Extend the spring.
3. One student holds their end firmly against the ground while the other student vibrates their end of the spring back and forth in a single vibration along the ground and towards the other student. The vibration is parallel to the direction of travel of the wave that is created. This produces a **longitudinal** pulse.
4. This time one student holds their end firmly against the ground while the other student vibrates their end of the spring up and down along the ground in a single vibration. The vibration is perpendicular to the direction of travel of the wave that is created. This is a **transverse** pulse. Its height is referred to as its **amplitude**.
5. Next tie a ribbon half way along the slinky spring. Send a transverse pulse along the spring. Describe the motion of the ribbon.
6. Send a larger transverse pulse down the spring. What do you need to do to create a larger pulse? What is the relationship between the energy of the pulse and its **amplitude**.
7. Send another transverse pulse down the spring.
   (a) What do you notice about the speed of the wave?
   (b) What do you notice about the wave as it reflects at the other ‘fixed’ end?
8. Send a transverse pulse down the spring simultaneously from each end of the spring so that their orientations are identical. What do you notice when the pulses meet?
9. Send a transverse pulse down the spring simultaneously from each end of the spring so that their orientations are inverted. What do you notice when the pulses meet?

Types of waves

1. Longitudinal waves

A longitudinal wave is wave in which the vibrations (or oscillations) are parallel to the direction of travel of the wave or wave propagation.

A longitudinal wave travels as a series of compressions and rarefactions.

An example of a longitudinal wave is sound.

Longitudinal waves can be represents diagrammatically in different ways.

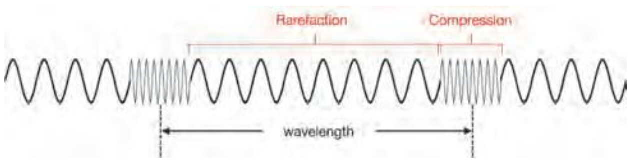
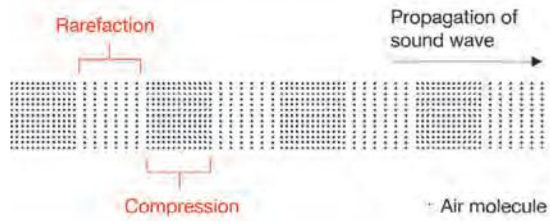
 *Figure 5.1.3*	 *Figure 5.1.4*
This diagram represents a longitudinal wave in a slinky spring.	This diagram represents a longitudinal soundwave in air.

Figure 5.1.5 shows a general representation of a longitudinal wave.

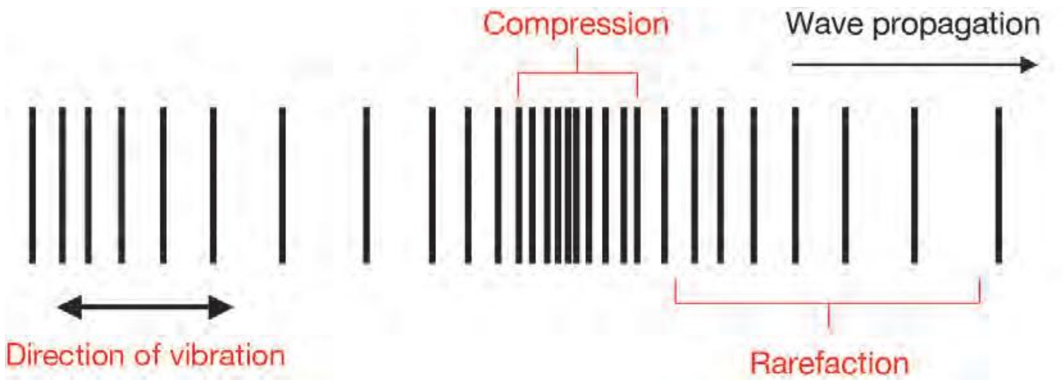


Figure 5.1.5

Compressions are positions of maximum pressure (the particles of the medium are close together) and **rarefactions** are positions of minimum pressure (the particles of the medium are spread out).

2. Transverse waves

A transverse wave is wave in which the vibrations (or oscillations) are perpendicular to the direction of wave propagation.

A transverse wave travels as a series of crests and troughs.

Light is an example of a transverse wave, so are water waves

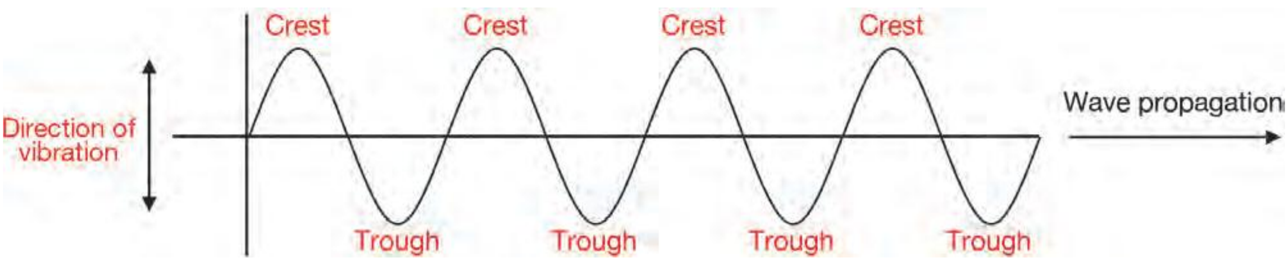


Figure 5.1.6

Crests are the peaks of the wave or positions of maximum positive displacement and **troughs** are the lowest point on the wave or positions of maximum negative displacement. Several crests and troughs are illustrated in figure 5.1.6.

Wave characteristics

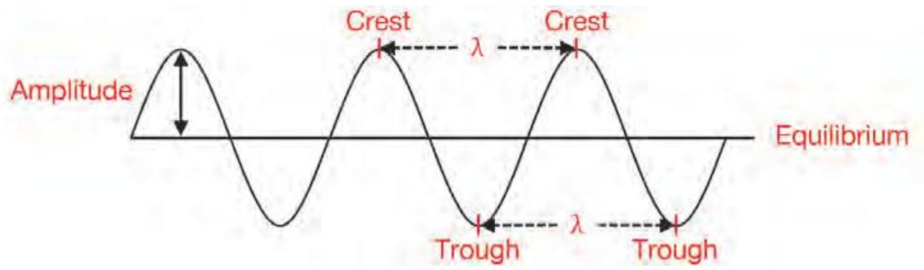


Figure 5.1.7

The table shown below, summarises measurable quantities of a wave. Some of these quantities are labelled on figure 5.1.7.

Characteristic	Symbol	SI unit	Definition
Displacement	s	*metre* *m*	The position of the particles relative to the mean or equilibrium position.
Amplitude	A	*metre* *m*	The ***maximum displacement*** of the particles from the mean or equilibrium position.
Frequency	f	*Hertz* *Hz*	The number of wave oscillations (or vibrations) per second or the number of waves passing a point in the medium per second.
Period	T	*second* *s*	The time taken for one complete wave oscillation.
Wavelength	λ	*m*	The distance between two points on the wave that are in phase (i.e. moving in the same direction with the same speed). This is the same as the distance between two points on the wave that have the same displacement from the equilibrium position. The wavelength of a transverse wave is the distance between two consecutive crests or troughs and the wavelength of a longitudinal wave is the distance between two consecutive compressions or rarefactions.
Wave velocity	v	ms^{-1}	The displacement of the wave per unit time.

5

The relationship between frequency and period

Consider a wave with a frequency of 10 Hz. This means that there are 10 complete wave oscillations per second. The time taken for one wave oscillation is $\frac{1}{10}$ s.

This means that the frequency and period of a wave are the inverse of one another.

$$T = \frac{1}{f}$$

The relationship between frequency, wavelength and wave speed

For ***ONE*** wave

$$v = \frac{s}{t} = \frac{\lambda}{T} = f\lambda$$

$$v = f\lambda$$

For light this equation can be expressed as:

$$c = f\lambda$$

Where ***c = speed of light = 3.00 × 10*** ^{8} ***ms*** $^{-1}$

Representing transverse waves graphically

1. Displacement-time graphs

The displacement of a wave can be graphed as a function of time as shown in figure 5.1.8.

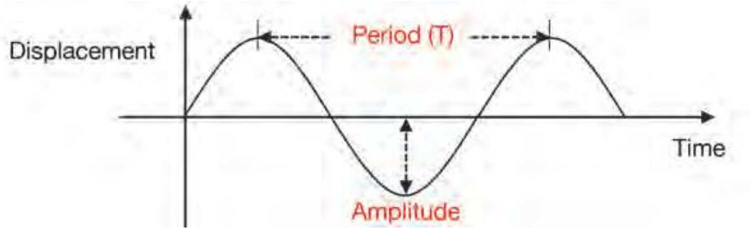


Figure 5.1.8

The amplitude and period of the wave are shown in figure 5.1.8. The period of the wave is the time interval between any two points on the wave that are in phase e.g two consecutive crests or two consecutive troughs.

2. Displacement-position graphs

The displacement of a wave can be graphed as a function of distance or position as shown in figure 5.1.9.

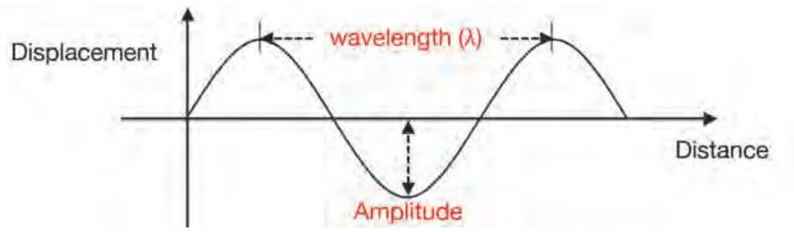


Figure 5.1.9

The amplitude and wavelength of the wave are indicated on the diagram. The wavelength of the wave is the distance between any two points on the wave that are in phase e.g two consecutive crests or two consecutive troughs.

Helpful online resource

Phet – Sound and Waves.

https://phet.colorado.edu/en/simulation s/category/physics/sound-and-waves

Worked examples

1. A child sitting on a jetty measures the wavelength of some passing waves to be 60.0 cm. They find that 5 waves pass in 10.0 s. Calculate the

(a) period of the waves.

$$T = \frac{10}{5} = 2.00s$$

(b) frequency of the waves.

$$f = \frac{1}{T} = \frac{1}{2} = 0.500Hz$$

(c) speed of the waves.

$$v = f\lambda = 0.5 \times 0.6 = 0.300ms^{-1}$$

2. Calculate the period of a wave if it has a speed of 8.0 ms^{-1} and a wavelength of 3.0 m.

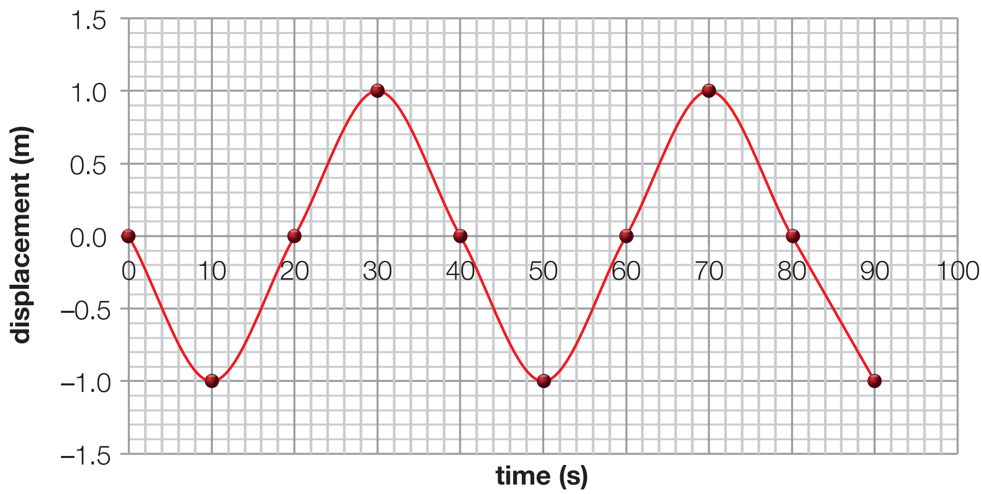
$$v = f\lambda \qquad \therefore \quad f = \frac{v}{\lambda} = \frac{8}{3} = 2.66Hz$$

$$T = \frac{1}{f} = \frac{1}{2.66} = 0.38s$$

3. Laser light travels at a speed of 3.00×10^8 ms^{-1}. A laser beam is reflected from a satellite high in the atmosphere and takes 0.24 s to return to Earth. Calculate the height of the satellite above the Earth's surface.

$$v = \frac{s}{t} \quad \therefore \quad s = vt = 3 \times 10^8 \times \frac{0.24}{2} = 3.6 \times 10^7 m$$

4. The wave represented by the graph show below has a speed of 1.50 ms^{-1}.



(a) State the amplitude of the wave and the displacement of a point on the wave after 16 s.

The amplitude 1.0 m and the displacement at 16 s is -0.5 m

(b) State the period of the wave.

40 s

(c) Calculate the frequency of the wave.

$$f = \frac{1}{T} = \frac{1}{40} = 0.025 Hz$$

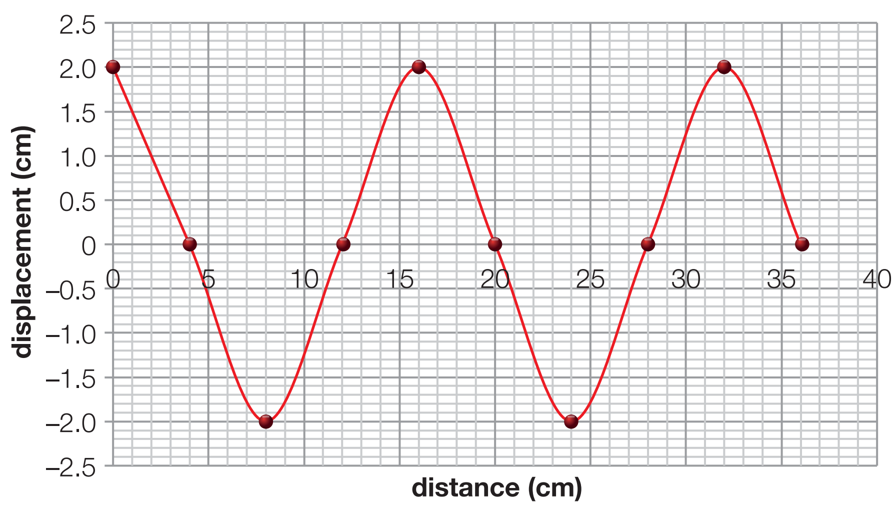
(d) Calculate the wavelength of the wave.

$$v = f\lambda \quad \therefore \quad \lambda = \frac{v}{f} = \frac{1.5}{0.025} = 60m$$

(e) Calculate the distance travelled by the wave in 2.0 minutes.

Waves travel with constant speed $s = vt$ =1.5 × 120 = 180 m

5. The displacement against distance graph for a wave of frequency 3.0 Hz is shown below.



(a) State the wavelength of this wave.

16 cm

5

(b) State the displacement of particles along the wave at 4 cm and 30 cm.

0 cm and 1.2 cm

(c) Calculate the speed of the wave.

$v = f\lambda = 3 \times 0.16 = 0.48\ ms^{-1}$

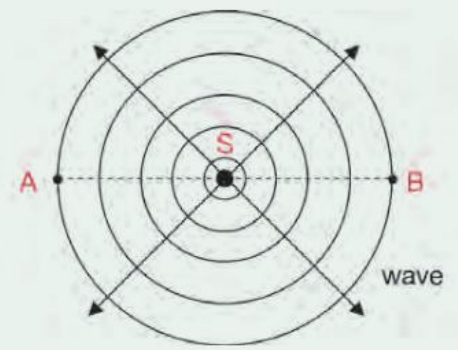
(d) Calculate the period of the wave.

$T = \frac{1}{f} = \frac{1}{3} = 0.33\ s$

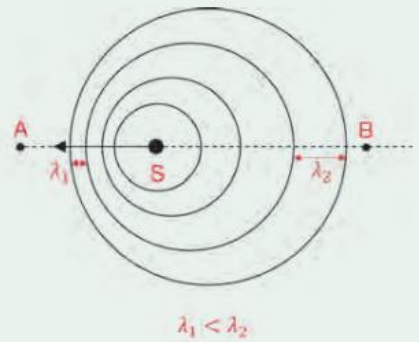
Extra understanding

Doppler effect for sound

Sound waves spread radially from a source S in all directions. The frequency or pitch of the sound heard by two observers A and B is the same.



If the source creating the sound waves now moves to the left towards observer A, the frequency heard by A increases. This is because the waves bunch up in front of the moving source. This reduces the wavelength and therefore increases the frequency ($f \alpha \frac{1}{\lambda}$).



The frequency or pitch heard by observer B decreases. This is because the waves spread out behind the source. This increases the wavelength and decreases the frequency. This shift in frequency is called the ***Doppler Effect***.
A similar effect occurs if the observer is moving and the source of sound is stationary.

The Dopper effect is the change in frequency of a sound as it moves relative to an observer.

The Doppler effect is evident when a fire truck or ambulance passes you. As the vehicle approaches, the pitch or frequency increases, as the vehicle passes you, the frequency decreases.

Helpful online resource

Sonic Boom

A sonic boom is a loud explosive sound created when an object such as an aeroplane travels faster than the speed of sound. *Watch this video to learn more about sonic boom.*

https://www.youtube.com/watch?v=-d9A2oq1N38

? Science inquiry practical

Some ideas for student investigations

1. Investigate sound and vibrations, e.g. tuning fork in water, speaker cone.
2. Analyse wave representations using technology, such as oscilloscopes or smartphone apps.
3. Measure sound levels and relate them to the amplitude of the waves.
4. Explore the relationships between the frequency and period of oscillators (such as pendulums and springs), and investigate factors that affect these quantities (such as string length).
5. Investigate velocity of various waves (sound, seismic, light) in various media (air, water, solids).

Science as a human endeavour

Research one of the following applications of the Doppler effect and ascertain the economic, social, and environmental impacts.

1. Detecting red-shift and blue-shift stars
2. Radar guns
3. Doppler radar
4. Reading weather patterns using a stationary transmitter in weather station and moving object, e.g. storm system
5. Using sound waves to produce image of heart (Doppler Echocardiogram).

5.2 Mechanical Waves

Science understanding

1. Mechanical waves such as sound and seismic waves transfer energy through a physical medium.
2. The natural frequency is the rate at which an object vibrates when it is disturbed by an outside force.
3. A forced vibration occurs when a wave forces an object to vibrate at the same frequency as the wave.
4. Resonance is the large-amplitude vibration that occurs in the object when the forced vibration is the same as its natural frequency.
   - Explain a range of wave-related phenomena, including echoes, refraction, and resonance, using the mechanical wave model.
   - Use the principle of superposition of waves to explain a range of interference phenomena, including standing waves and beats.

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Mechanical waves

Chapter 5.1 has already discussed the fact that a wave transfers energy through a medium. **Mechanical waves** are waves that **travel through a physical medium**, whether it be a solid, liquid or gas. Sound waves are mechanical waves. They need a medium i.e. do not travel through a vacuum. This is easily illustrated by the activity outlined below.

Activity

The bell Jar

Most schools have a bell jar similar to that shown in Figure 5.2.1. An electric bell can be heard ringing inside the jar which is covered with a glass dome. When a pump is used to remove air from inside the jar, a near vacuum is created. As the air is pumped out the volume of the sound produced by the bell inside the jar decreases until it can no longer be heard.

This simple demonstration illustrates the fact that sound needs a medium or that **sound does not travel through a vacuum**.

The fact that we can see the bell, with, or without air in the jar, indicates that **electromagnetic waves (or light) can travel in both a physical medium or a vacuum**.

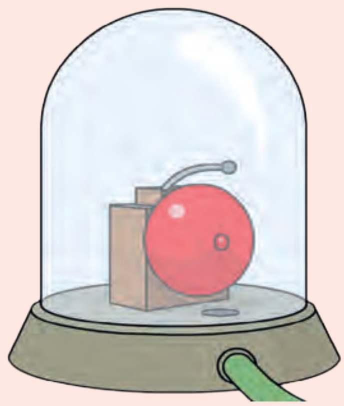


Figure 5.2.1

Resonance

All materials have a natural frequency at which they vibrate.

The natural frequency is the rate at which an object vibrates when it is disturbed by an outside force.

If a system is forced to vibrate at a frequency other than its natural frequency, the vibration is referred to as a **forced vibration**.

A forced vibration occurs when a wave forces an object to vibrate at the same frequency as the wave.

Resonance is the large-amplitude vibration that occurs in the object when the forced vibration is the same as its natural frequency.

Examples of resonance

1. The Tacoma Narrows bridge in Washington collapsed in 1940 approximately four months after it was completed. The wind caused the bridge to vibrate at its natural frequency. Resonance caused an increase in the amplitude of the vibrations and the concrete bridge eventually collapsed.

   Figure 5.2.2 shows a section of the Tacoma Narrows Bridge vibrating. Figure 5.2.3 shows a section of the bridge collapsing.

Figure 5.2.2

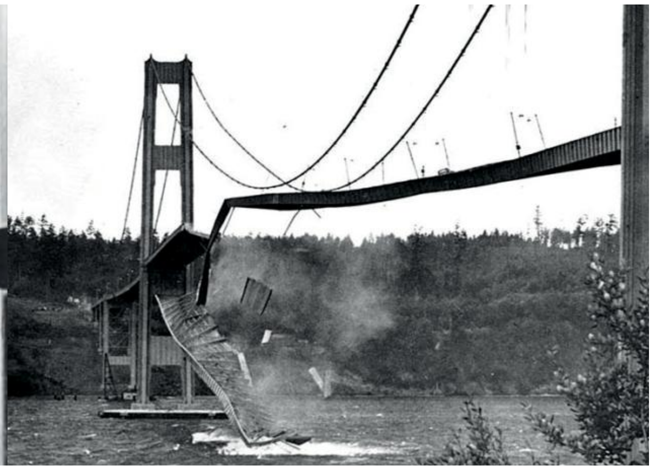


Figure 5.2.3

Helpful online resource

The collapse of the bridge was captured on film. Watch the bridge collapse at:

https://www.youtube.com/watch?v=j-zczJXSxnw

2. Resonance occurs in the sound box of a musical instrument. The forced vibration of the air inside the sound box (due to say a violin bow vibrating the strings) causes the air to resonate. This increases the amplitude of the sound waves, which results in a louder or amplified sound.

   Figure 5.2.4 is an image of a violin. The body of the violin acts as a sound box and makes the sound audible.

Figure 5.2.4

3. The moving parts of machinery can cause the machinery to vibrate at its natural frequency. This can cause the machinery to resonate. The increase in amplitude of the vibrations can cause severe damage.
4. A car being driven across a bumpy road can force engine parts or the car itself to vibrate at its natural frequency. This will cause resonance. The increase in the amplitude of the vibrations can cause severe damage to the motor or cause the car body to vibrate violently, making the car ride very bumpy .

Extra understanding

1. Watch the ‘the singing rod’: https://www.youtube.com/watch?v=zrBgRsD9uXY
2. Your teacher may also demonstrate the tuning of a guitar using resonance.
3. Watch the ‘singing goblet: http://www.physicsclassroom.com/class/sound/Lesson-4/Natural-Frequency

Wavefronts and rays

Figure 5.2.5 shows plane or straight waves. The top edge of the crests is marked in red and is referred to as a wavefront. The distance between two consecutive wavefronts is one wavelength (λ). Figure 5.2.6 is a top-down view of the plane waves. A ray has been added to this diagram and represents the direction of travel of the wave.

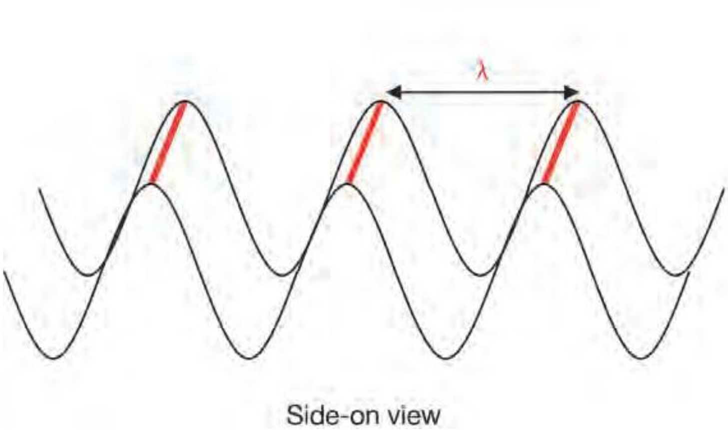


Figure 5.2.5

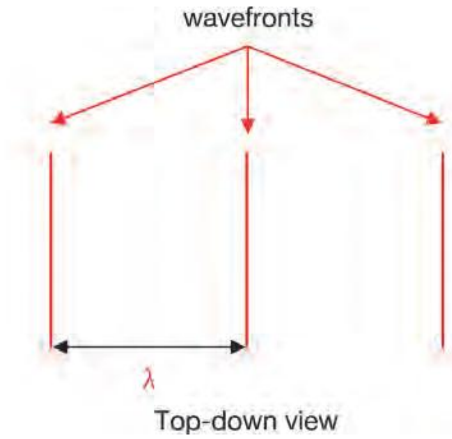


Figure 5.2.6

Pictured above - plane (straight wave fronts). These can be produced when a straight piece of wood or plastic is dipped in and out of water.

A ***wavefront*** is the leading edge of a wave and represents the line joining points on the wave that are in phase.

Rays indicate the direction that a wave travels and are at 90° to the wavefronts.

Activity

The ripple tank

The ripple tank (Figure 5.2.6) can be used to demonstrate wave phenomena such as reflection and refraction.

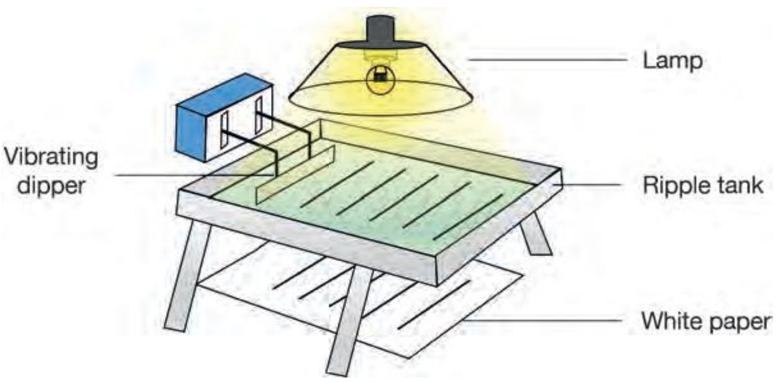


Figure 5.2.6

Reflection

1. Produce plane waves using a straight dipper.
2. Use a plastic or wooden barrier to reflect the waves at an angle. Describe the reflected waves.

Result

Figure 5.2.7 shows several incident and reflected wavefronts and an incident and reflected ray. The results lead to the law of reflection.

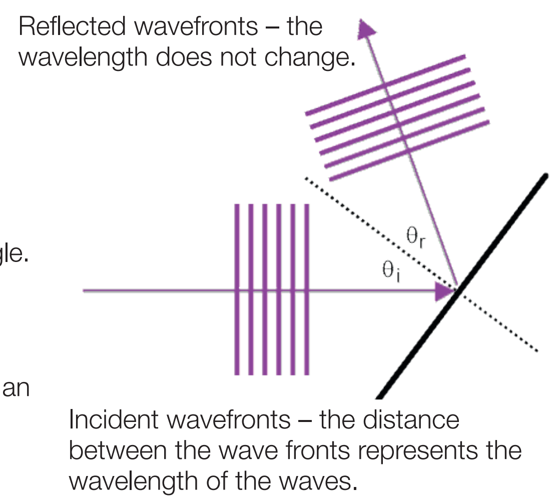


Figure 5.2.7

The ***law of reflection states***:

1. The angle of incidence *i*, is equal to the angle of reflection *r*.

2 The incident ray, the normal and the reflected ray all lie in the same plane.

The **normal** is a line drawn perpendicular to the surface.

The **incident ray** represents the direction that the incoming wave is travelling.

The **reflected ray** represents the direction that the reflected (bouncing) wave is travelling.

i is the angle between the normal and the incident ray.

r is the angle between the normal and the reflected ray.

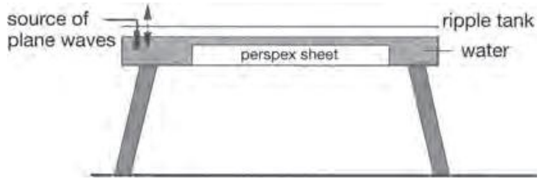


Figure 5.2.8

Refraction

1. Use a piece of perspex or thin wooden to create a shallow area of water as shown in Figure 5.2.8.
2. Produce plane waves using a straight dipper. Direct the waves so that they arrive parallel to the barrier.
3. Describe any change in the wavelength and speed of the waves as they enter the shallow water.
4. Now change the angle at which the waves strike the barrier. Describe any change in the wavelength, speed and direction of the waves as they enter the shallow water.

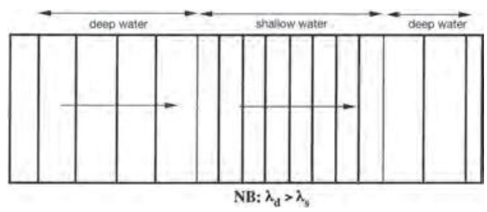


Figure 5.2.9

Result

Figure 5.2.9 shows the change in the wavelength as the waves move from the shallow water to the deeper water.

The distance between the wavefronts decreases. This means that the wavelength decreases in the shallow water.

Since the **frequency** of the waves **does not change** but the wavelength is smaller, it follows that the **speed of the waves has decreased** in the shallow water ($v = f\lambda$).

In the example above, the angle of incidence is zero, and no **refraction or bending** occurs.

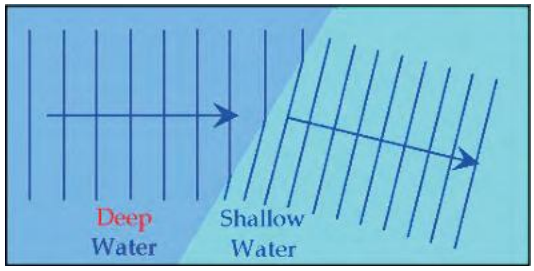


Figure 5.2.10

When the waves enter the shallow water at an angle, they bend towards the normal as shown in Figure 5.2.10.

Refraction is the change in direction of propagation of a wave due to a change in speed.

Reflection of sound – Echoes and reverberation

Hard surfaces such as glass and concrete will reflect sound waves.

If the time between the original sound and the reflection is long enough (approximately 0.1 s or more) then the original sound dies off and a second sound is heard. The second sound is referred to as an **echo**.

A reverberation is different to an echo. If the time between reflections is less than 0.1 s, instead of hearing a distinct echo, the original sound hasn't died off and upon receiving the reflection it seems the original sound is prolonged. This often happens in small rooms with dimensions 17 m or less. This is because the speed of sound is constant and approximately 340 ms^{-1}. If it travels a distance of 17 m to a wall and back, the total distance is 34 m and the time taken for the reflection is approximately 0.1 s ($v = \frac{s}{t}$ then $t = \frac{s}{v} = \frac{34}{340} = 0.10s$).

When multiple reflections are received the effect is more obvious. Reverberation can result in an increase in the ambient noise level and can result in the sound being blurred or garbled. Acoustic design is therefore important when designing concert halls, restaurants, classrooms, day care centres etc.

Your teacher can use a large isolated solid wall to demonstrate echoes and reverberation.

Extra understanding

1. Human frequency range

Your teacher may use a frequency modulator to vary the frequency of sound. You can determine the range of frequencies that you can hear. Ideally the human hearing range is 20 Hz to 20 000 Hz.

5

Helpful online resource

Test your hearing range.

http://onlinetonegenerator.com/hearingtest.html

Extra understanding

2. Bats and echo location

Bats are nocturnal and use echolocation to hunt for prey during the night. Bats can determine the distance between their location and that of their prey by the time it takes for high frequency sound waves to reflect from their prey. The frequency of the sound waves emitted by most bats is outside the human hearing range.

In addition bats can are smart enough to tell the difference between objects they need to avoid and their prey. Bats can tell if an object is to their left or right by comparing whether the sound returns to their left or right ear first. A bat's ear has many folds which help determine whether sound is returning from above or below the bat. The intensity of the retuning sound waves can also help a bat determine the size of an object. Smaller objects reflect less sound which means that smaller objects return a less intense signal. Bats can also determine the direction that an object is travelling. For example if their prey is moving away from the bat, the returning sound wave has a lower frequency while prey moving towards the bat return sound waves of a higher frequency.

Despite the common misconception that bats have poor vision, bats use echolocation along with visual signals to help produce an image of the their surroundings.

Superposition of waves

The principle of superposition was introduced in Subtopic 5.1 during the activity 'Using slinky springs to demonstrate wave phenomena'.

Consider two pulses 1 and 2 travelling in opposite directions as shown in figure 5.2.11. Each pulse has an amplitude of 1 unit. When the pulses meet, the amplitude of the resultant pulse doubles to 2 units. This is called **constructive superposition**.

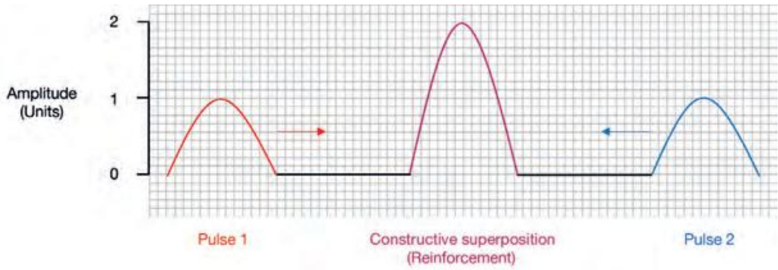


Figure 5.2.11

Now consider two pulses 1 and 2 travelling in opposite directions as shown in figure 5.2.12. One pulse has an amplitude of 1 unit and the other an amplitude of -1 unit. When the pulses meet, the amplitudes cancel and the resultant pulse has an amplitude of zero. This is called **destructive superposition**.

Figure 5.2.12

Finally consider two pulses 1 and 2 travelling in opposite directions as shown in figure 5.2.13.

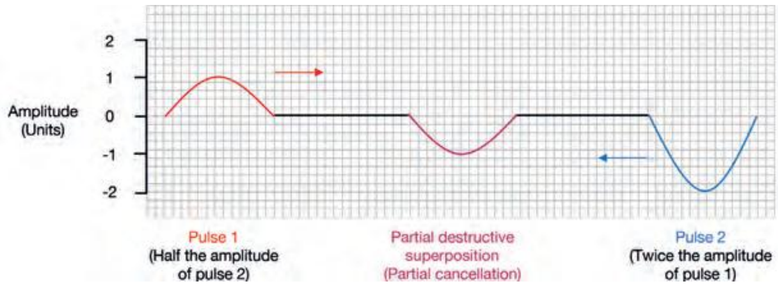


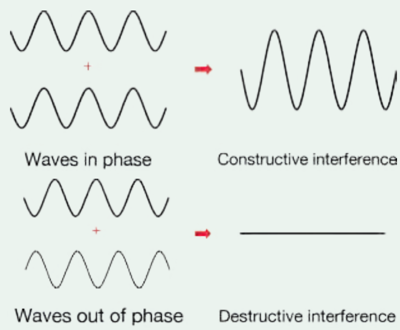
Figure 5.2.13

Pulse 1 has an amplitude of 1 unit while pulse 2 has an amplitude of -2 units. When the two pulses meet, the resulting pulse has an amplitude of -1 unit.

The principle of superposition states that whenever two waves meet in space, the amplitude of the resultant wave is a vector sum of the individual amplitudes of the original waves.

Extra understanding

Wave sources which produce waves with the same frequency and wavelength and maintain a constant phase relationship are called **coherent wave sources**. This means that both wave sources are producing identical waves.

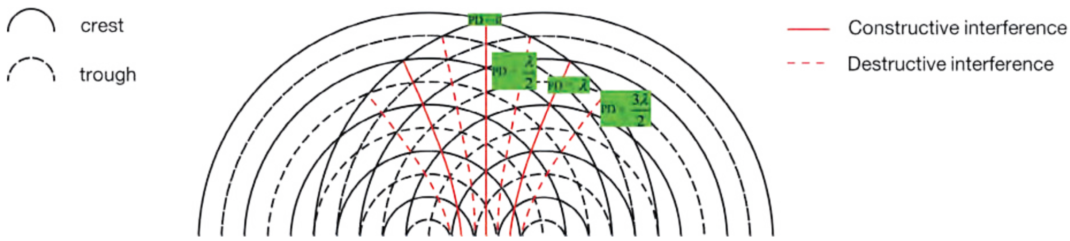


Transverse waves are said to **meet in phase** if the crest of one wave coincides with the crest of another or if the trough of one wave meets the trough of another. This means that when waves that are in phase meet, they undergo **constructive interference**. This results in a wave with twice the amplitude of the original waves.

Transverse waves are said to **meet out of phase** if the crest of one wave coincides with the trough of another. This means that when waves that are out of phase meet, they undergo **destructive interference**. This results in a wave of zero amplitude.

Two source interference

When two coherent wave sources overlap, an interference pattern results. Your teacher can demonstrate this using a ripple tank.



The curved lines that result join points at which the waves meet constructively or destructively. The path difference between waves from each source is the same along each curved line and its value is marked on the diagram as PD.

Path difference

Waves from each of the coherent sources travel different distances to the point were they meet and undergo superposition. This difference is called the **path difference** and is expressed in terms of wavelength.

For constructive interference

The path difference $PD = m\lambda$ $(m = 0, 1, 2, 3\ldots)$

Constructive interference occurs when the path difference is equal to an integral number of whole wavelengths.

For destructive interference

The path difference $PD = (m+\frac{1}{2})\lambda$ $(m = 0, 1, 2, 3\ldots)$

Destructive interference occurs when the path difference is equal to an odd number of half wavelengths.

Examples of two source interference

1 Water waves

Water waves are transverse. The interference pattern for water consists of a series of antinodal (positions of constructive superposition) and nodal lines (positions of destructive superposition). Figure 5.2.14 shows an interference pattern for water. It was produced using a ripple tank and projected onto a screen.

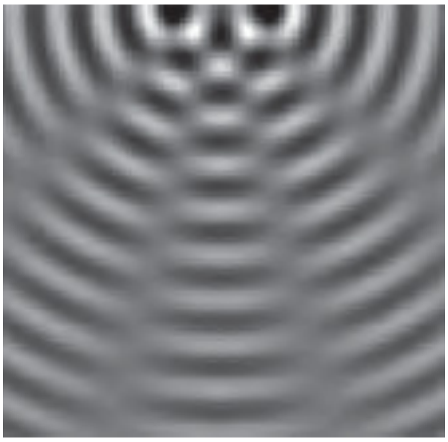


Figure 5.2.14

2 Light

In 1801 Thomas Young demonstrated that light displayed interference effects in a similar way to water waves. This provided experimental evidence for the wave nature of light.

The interference pattern for light consists of alternating bright and dark bands of equal width. The colour of the bright bands corresponds to the colour of the monochromatic light used. Figure 5.2.15 shows the interference pattern for sodium (yellow) light.

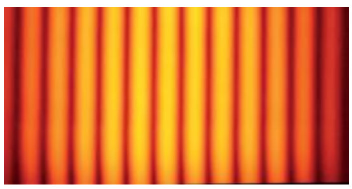


Figure 5.2.15

The path difference at any point on the screen will result in a bright or dark band.

If the path difference is $m\lambda$ (m = 0, 1, 2, 3…) the waves meet in phase and undergo constructive interference. This results in an increase in amplitude and light of maximum intensity i.e. a bright band.

If the path difference is $(m+\frac{1}{2})\lambda$ where m = 0, 1, 2, 3… the waves meet out of phase and undergo destructive interference.

This results in a decrease in amplitude to zero and light of minimum intensity i.e. a dark band.

3 Sound

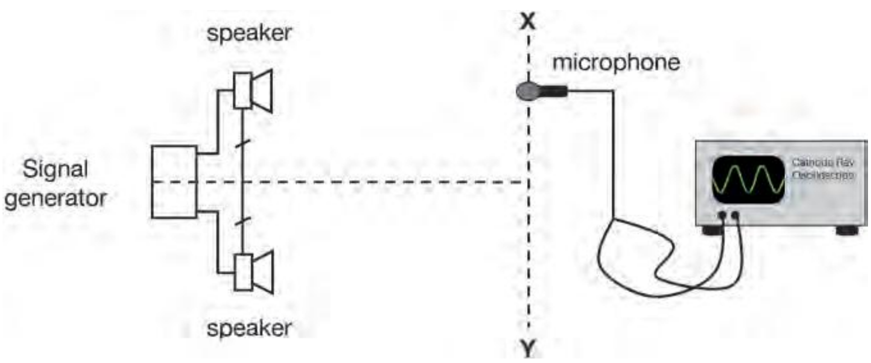


Figure 5.2.16

The arrangement illustrated in Figure 5.2.16 shows how the two source interference of sound can be demonstrated. The two speakers are placed about 50 cm apart and a sound signal of 600 Hz is produced by the frequency (or signal) generator. The two coherent sound sources interfere in the region in front of the speakers. When a microphone is moved from X to Y the signal on the cathode ray oscilloscope fluctuates from a high to low. Areas of low sound intensity (or low volume) correspond to areas of destructive superposition and areas of high sound intensity (high volume) correspond to areas of constructive superposition. An alternative is to walk slowly in a straight line from X to Y. The volume level will fluctuate.

4 Standing waves

A wave oscillator can be used to vibrate a piece of string attached to a fixed end as shown in figure 5.2.17.

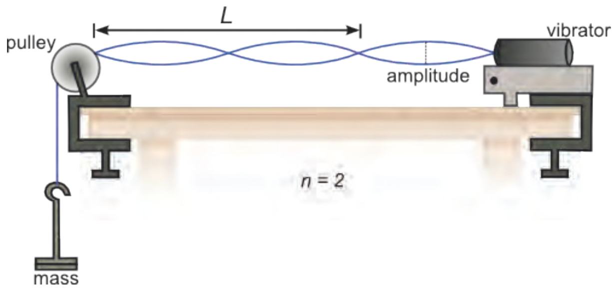


Figure 5.2.17

A wave travels along the string and when it reaches the fixed end, it is reflected and undergoes superposition with the forward moving wave. A pattern of 'stationary loops' form as shown in figure 5.2.18. This pattern is called a ***standing wave*** or ***stationary wave*** pattern. This is because the wave does not appear to move. If the frequency of the oscillator increases, more 'loops' form.

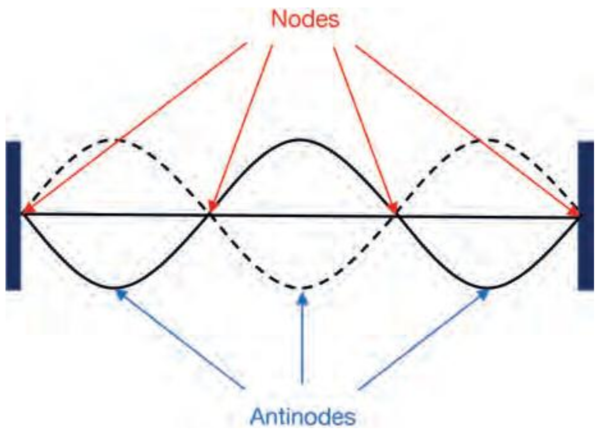


Figure 5.2.18

A standing wave pattern results when two waves with the same amplitude, frequency and wavelength travelling in the opposite direction meet and under go superposition. A standing wave does not transfer energy.

A standing wave consists of ***nodes*** (points of zero displacement) and ***antinodes*** (points of maximum displacement).

The distance between two adjacent nodes or antinodes is half a wavelength or $\frac{\lambda}{2}$.

The length of the string $l = n\frac{\lambda}{2}$ where $n = 1, 2, 3, \ldots$

Antinodes are positions of constructive superposition and have a maximum displacement of 2A (A is the amplitude of the original waves that interact). Nodes are points of destructive interference, which results in zero displacement.

Standing waves in strings

Consider a string of length l stretched between two fixed supports. When it is plucked at its centre, a standing wave is produced. The simplest vibration produced is called the ***fundamental*** or ***first harmonic***. This is the dominant vibration and pictured in figure 5.2.19.

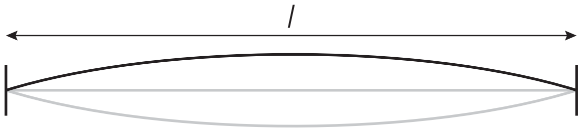


Figure 5.2.19

The fundamental frequency (first harmonic) can be calculated using:

$$v = f\lambda \quad \therefore \quad f_1 = \frac{v}{\lambda_1} = \frac{v}{2l}$$

The next simplest vibration is shown by figure 5.2.20 and is called the ***second harmonic***.

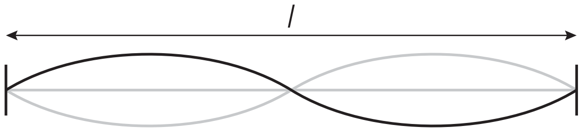


Figure 5.2.20

The second harmonic has a frequency given by: $v = f\lambda \quad \therefore \quad f_2 = \frac{v}{\lambda_2} = \frac{v}{l} = 2f_1$

The next simplest vibration is shown by figure 5.2.1 and is called the ***third harmonic***.

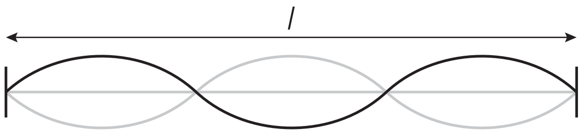


Figure 5.2.21

The third harmonic has a frequency given by: $v = f\lambda \quad \therefore \quad f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{2l}{3}} = \frac{3v}{2l} = 3f_1$

The pattern continues and the number of standing waves set up are infinite. The harmonics are integer multiples of the fundamental.

The ***n^th^ harmonic*** has a frequency given by: $f_n = nf_1$ *where* $n = 1, 2, 3, \ldots$

The human hearing range is 20 – 20 000 Hz. It follows that the number of audible harmonics is given by: $\frac{20000}{f_1}$

When the fundamental frequency is less than 20 Hz it is not audible and therefore subtracted from the value $\frac{20000}{f_1}$

The speed of a wave along a string

The speed of a travelling wave in a string depends on the tension (T) in the string and the mass per unit length (μ) of the string.

$$v = \sqrt{\frac{T}{\mu}} \quad \text{where } T = \text{tension (N) and } \mu = \frac{m}{l} \text{ kg m}^{-1}$$

These two equations can be combined to give $v = \sqrt{\frac{Tl}{m}}$

Recall

The length of the string $l = n\frac{\lambda}{2}$ where $n = 1, 2, 3, 4\ldots$

Worked examples

1. A wave travels along a 2.00 m length of wire with a speed of 60.0 ms^{-1}.

   (a) Sketch the fundamental and fifth harmonic produced by the string.

   (b) Calculate the frequency of the fundamental and fifth harmonic.

$$f_1 = \frac{v}{2l} = \frac{60}{2 \times 2} = 15Hz$$

$$f_5 = 5\,f_1 = 5 \times 15 = 75\text{Hz}$$

   (c) Calculate the number of audible harmonics produced.

$$\textit{Number of audible harmonics} = \frac{20000}{f_1} = \frac{20000}{15} = 1333$$

Since the fundamental is not audible, then the number of audible harmonics is 1332.

2. A string has a mass per unit length of 0.0200 kgm^{-1}. It is held at a tension of 10.0 N and plucked at its centre. Calculate the speed of the wave travelling along the string.

$$v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{10}{0.02}} = 22.4ms^{-1}$$

Air column closed at one end

Wind instruments produce sound when air is blown over a reed causing it to vibrate. The vibrating reed causes air in a pipe to resonate. Standing wave patterns similar to those for a string are created. Reflection from a fixed or closed end will always produce a ***node***, while the open end will allow maximum vibration and therefore result in an ***antinode***.

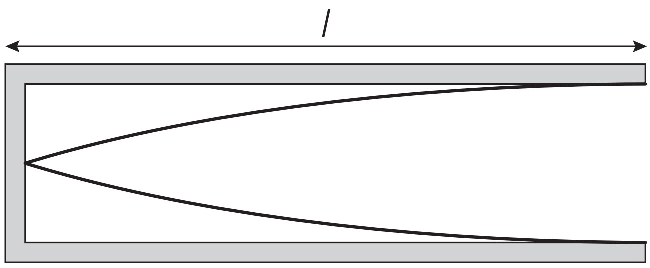


Figure 5.2.22

Figure 5.2.22 shows the standing wave pattern for the fundamental. The fundamental frequency (first harmonic) can be calculated using:

$$v = f\lambda \quad \therefore \quad f_1 = \frac{v}{\lambda_1} = \frac{v}{4l}$$

Here v is the speed of sound in air. This can be taken as 330 ms^{-1} but varies with humidity and temperature.

The next simplest vibration has the standing wave pattern shown in figure 5.2.23.

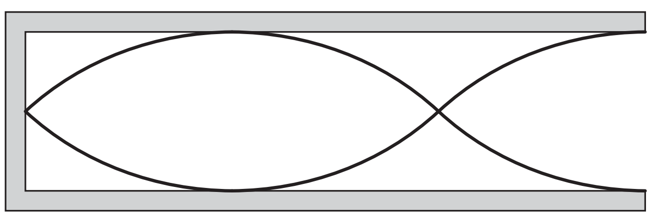


Figure 5.2.23

$$v = f\lambda \quad \therefore \quad f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{4l}{3}} = \frac{3v}{4l} = 3f_1$$

This has a frequency *three times* the fundamental (***third harmonic).***

The next simplest vibration has the standing wave pattern shown in figure 5.2.24.

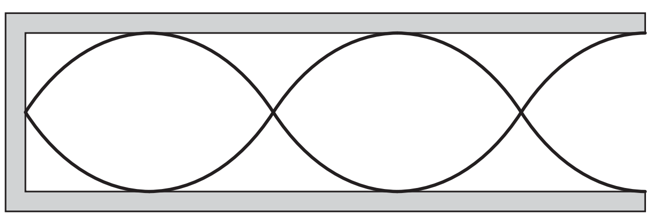


Figure 5.2.24

$$v = f\lambda \quad \therefore \quad f_5 = \frac{v}{\lambda_5} = \frac{v}{\frac{4l}{5}} = \frac{5v}{4l} = 5f_1$$

This has a frequency *five times* the fundamental (***fifth harmonic).***

Only the **odd harmonics** are produced with a frequency given by: $f_{2n-1} = (2n-1)\,f_1$ *where n = 1, 2, 3,...*

This means that there are only half as many audible harmonics ($\frac{20000}{2f_1}$).

The length of the pipe $l = (2n-1)\frac{\lambda}{4}$ where n = 1, 2, 3,...

Pipes – open at both ends

For a pipe or column of air open at both ends, a maximum vibration can occur at both ends of the pipe. This results in an ***antinode*** at both ends of the pipe.

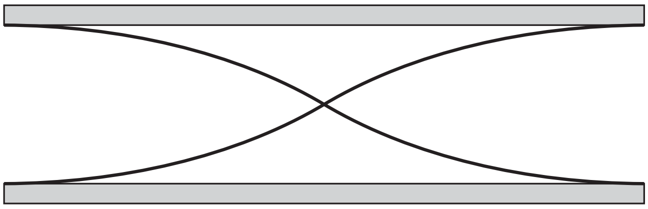


Figure 5.2.25

Figure 5.2.25 shows the standing wave pattern for the fundamental. The fundamental frequency can be calculated using:

$$v = f\lambda \quad \therefore \quad f_1 = \frac{v}{\lambda_1} = \frac{v}{2l}$$

The next simplest vibration has the standing wave pattern shown in figure 5.2.26.

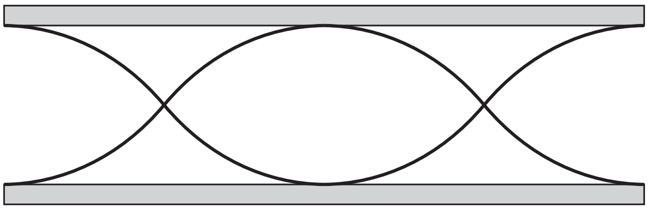


Figure 5.2.26

$$v = f\lambda \quad \therefore \quad f_2 = \frac{v}{\lambda_2} = \frac{v}{l} = 2f_1$$

This has a frequency twice the fundamental (***second harmonic).***

The next simplest vibration has the standing wave pattern shown in figure 5.2.27.

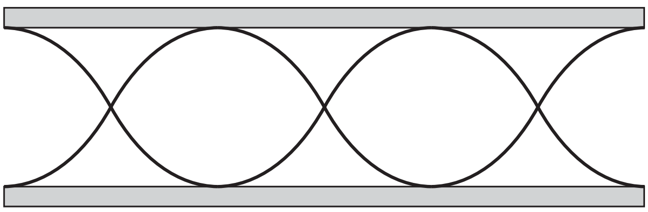


Figure 5.2.27

$$v = f\lambda \quad \therefore \quad f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{2l}{3}} = \frac{3v}{2l} = 3f_1$$

This has a frequency three times the fundamental (***third harmonic).***

The frequency of the harmonics are integer multiples of the fundamental.

The ***n***

The n^{th} **harmonic** has a frequency given by: $f_n = nf_1$ *where n = 1, 2, 3,...*

The length of the pipe $l = n\frac{\lambda}{2}$ *where n = 1, 2, 3,...*

Quality of sound

The number of audible harmonics produced will determine the quality of the sound. The greater the number of audible harmonics, the more melodic the sound will be. String instruments and those involving pipes open at both ends produce harmonics that are an integer multiple of the fundamental. The quality of sound is better than an instrument that has a pipe open at one end only because such a pipe only produces harmonics that are an odd multiple of the fundamental i.e. half as any audible harmonics.

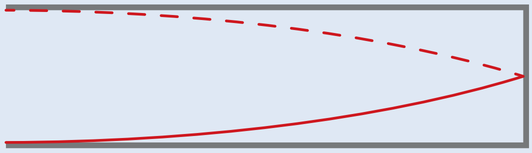
The source of the sound will also affect the quality. The purpose of a sound box is to produce resonance. This increases the amplitude and therefore volume. A wooden hand crafted violin produces better quality sound than a plastic or toy version made for children.

Worked examples

Standing waves in a pipe open at one end

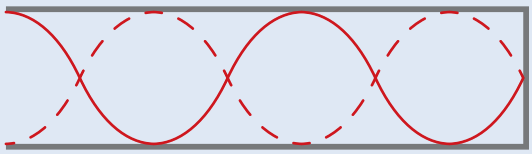
1. A pipe open at one end, has a length of 3.00 m. Take the speed of sound in air to be 330.0 ms^{-1} in answering the following questions.

   (a) Sketch and calculate the frequency of the fundamental.



$$f_1 = \frac{v}{4l} = \frac{330}{4 \times 3} = 27.5Hz$$

   (b) Sketch and calculate the frequency of the seventh harmonic.



$$f_7 = 7\,f_1 = 27.5 \times 7 = 193\text{Hz}$$

   (c) Calculate the number of audible harmonics produced by the pipe.

$$\textit{Number of audible harmonics} = \frac{20000}{2f_1} = \frac{20000}{2 \times 193} = 51$$

2. A column of air open at one end only produces a fifth harmonic with a frequency of 300 Hz. Take the speed of sound in the column of air to be 330 ms^{-1}.

   Calculate the length of the column of air to the nearest centimetre.

$$f_1 = \frac{f_5}{5} = \frac{300}{5} = 60Hz$$

$$f_1 = \frac{v}{4\ell} \quad \therefore \quad \ell = \frac{v}{4f_1} = \frac{330}{4 \times 60} = 1.38m = 138cm$$

Beats

Beats occur when waves of slightly different frequency meet and undergo superposition. This produces a periodic variation in volume or intensity because the waves are periodically in and out of phase.

Consider two sound sources interfering, one with a frequency of 50 Hz and the other with a frequency of 60 Hz. Figure 5.2.28 shows the two sounds waves interfering at t = 0 s and t = 0.1 s the waves meet in phase and undergo constructive superposition. This results in maximum wave intensity or volume. At t = 0.05 s the waves meet out of phase and undergo destructive superposition. This results in a minimum wave intensity or volume.

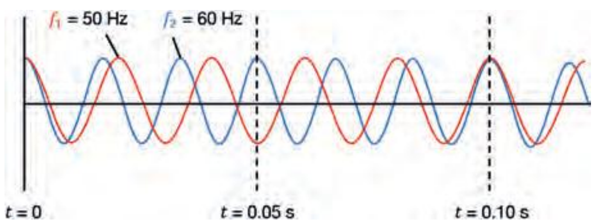


Figure 5.2.28

Figure 5.2.29 shows the resultant wave form. The time between maximum intensity or volume fluctuations is called the beat period.

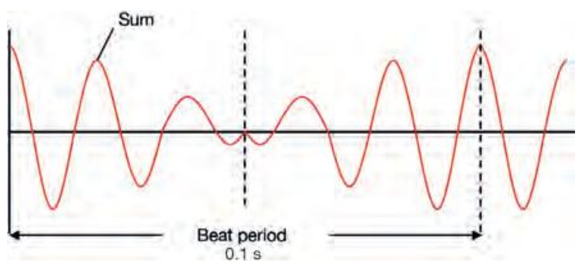


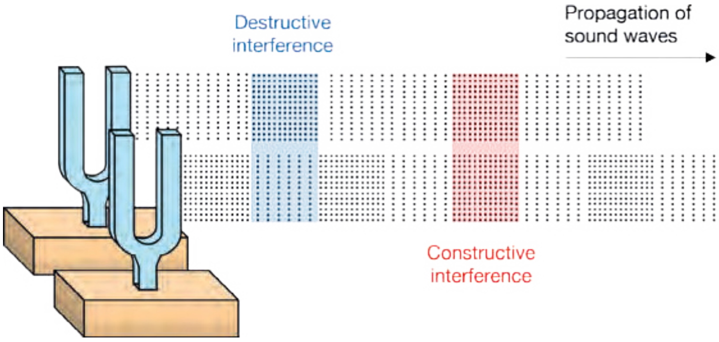
Figure 5.2.29

The cycle repeats every 0.1 s to produce a variation in intensity (or volume). The beat frequency is 10Hz.

The beat frequency is the difference in frequency of the two wave sources and represents the number of beats heard per second.

$$f_{beat} = |f_1 - f_2|$$

Activity



Place two identical tuning forks next to one another. If they are sounded simultaneously, a single frequency is heard. Change the frequency of one tuning fork by attaching a small piece of plasticine on the tuning fork. The two tuning forks will now produce a slightly different frequency. When the forks are sounded simultaneously beats will be produced.

Worked examples

Calculate the beat frequency when two tuning forks with frequencies 256 Hz and 258 Hz are sounded simultaneously.

$$f_{beat} = |f_1 - f_2| = |258 - 256| = 2Hz$$

? Science inquiry practical

Some possible ideas for student investigations:

1. The effect of different tensions or lengths on the vibrating frequency, using, for example, strings or air columns
2. The effect of the density of the medium on the speed of sound
3. Interference patterns in a ripple tank
4. The formation of standing waves in strings and pipes
5. The production of beats
6. The resonant frequency of an oscillator, such as a loudspeaker or spring, and the factors that affect the resonant frequency

Science as a human endeavour

Research one of the following contexts and evaluate the benefits, limitations, and ethical considerations of using technology:

1. voice recognition
2. medical imaging using ultrasound
3. sonar in submarines, depth sounders and locating fish
4. acoustic and building design
5. resonance in built structures
6. automated home systems.

5.3 Light

Science understanding

1. Light is the visible part of the electromagnetic spectrum – a spectrum that also includes radio waves, microwaves, infra-red, and ultraviolet radiations, X-rays, and gamma rays.
2. Electromagnetic waves can be modelled as a transverse wave that can travel through a vacuum.
3. Refraction is the change in direction of propagation of a wave as its speed changes.
4. Diffraction is the bending/spreading of waves as they pass through an aperture or past a sharp edge.
5. The plane of polarisation of an electromagnetic wave is the plane defined by the direction of travel and the oscillating electric field.

- Describe reflection and refraction, using the ray model of light.
- Explain a range of light-related phenomena, including reflection, refraction, total internal reflection, diffraction, and polarisation, using the wave model.

6. Undertake experiments to investigate reflection or refraction of light using different media.

The electromagnetic spectrum

The electromagnetic spectrum constitutes all forms of light.

Light travels with a ***constant speed*** of ***3.00×10^8 ms^{-1} in a vacuum.***

TV/RADIO MICROWAVES IR VISIBLE UV X-RAYS GAMMA

Decreasing wavelength or increasing frequency.

Figure 5.3.1

Visible light forms a small part of the electromagnetic spectrum which includes radio waves, microwaves, infrared, and ultraviolet radiations, X-rays, and gamma rays.

Electromagnetic waves can be modelled as a transverse wave that can travel through a vacuum. This model suggests that light consists of oscillating electric and magnetic fields. The electric and magnetic fields oscillate at right angles to one another and the direction of wave propagation.

Figure 5.3.2 represents an electromagnetic wave.

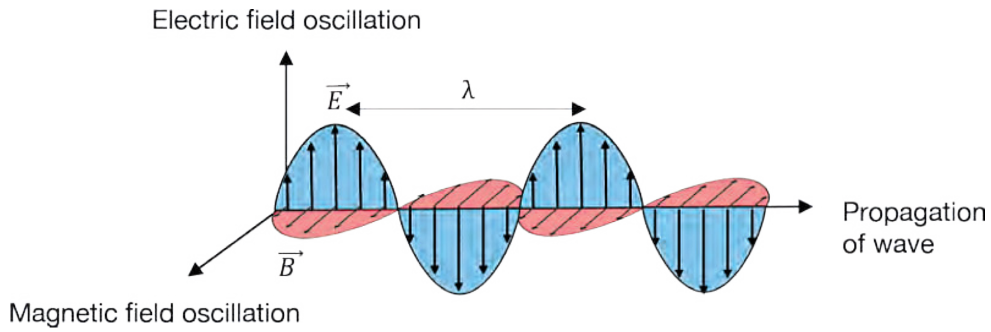


Figure 5.3.2

Extra understanding

Electromagnetic waves can travel through a vacuum.

Activity

Your teacher may demonstrate the transmission of a mobile phone signal through a vacuum using the bell jar.

Reflection of light

The reflection of water waves was investigated in subtopic 5.2 using a ripple tank. Reflection applies to light. When light reflects or bounces from a surface it obeys the law of reflection.

The ***law of reflection states***:

1. The angle of incidence *i*, is equal to the angle of reflection *r* i.e. $\angle i = \angle r$.
2. The incident ray, the normal and the reflected ray all lie in the same plane.

Figure 5.3.3 and figure 5.3.4 show the reflection of a single light ray from a surface.

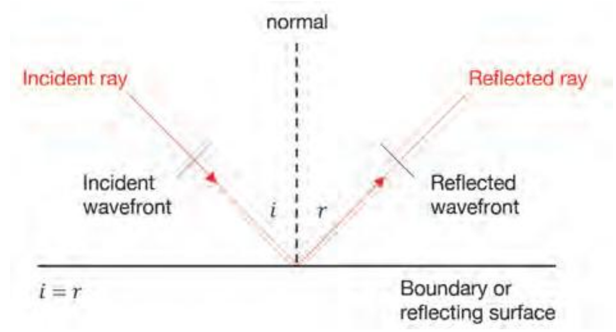


Figure 5.3.3

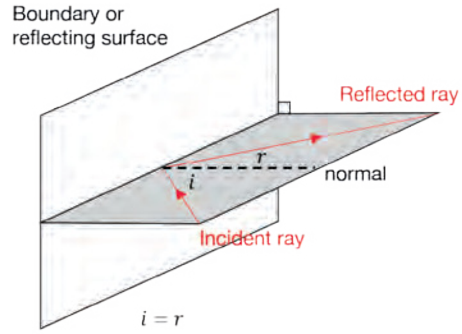


Figure 5.3.4

The normal is a line drawn perpendicular to the surface.

The ***incident ray*** represents the direction that the incoming wave is travelling.

The ***reflected ray*** represents the direction that the reflected wave is travelling.

i is the angle between the normal and the incident ray.

r is the angle between the normal and the reflected ray.

Activities

Reflection

These activities can be performed using a light box and various mirrors.

1. Lateral inversion

   Observe various letters in a plane (flat) mirror. What do you notice? Use the space below to sketch some letters as they appear in the mirror.

Result

You will notice that the letters become laterally inverted when viewed through a mirror.

Figure 5.3.5 shows the refection of the letter F in a plane mirror.

Figure 5.3.5

2. Regular and diffuse reflection
   - Use the ray box and a single slit to confirm the law of reflection for a single ray of light incident on a mirror.
   - Repeat this for multiple parallel beams of light.
   - Next, cover the mirror with aluminium foil that has been scrunched up and flattened again so that the surface is bumpy. Reflect a single beam and then multiple beams of light. What do you notice? Use the space below to record your results.

Result

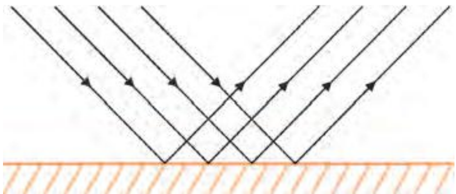


Figure 5.3.6

Figure 5.3.7

Light is reflected in a regular fashion when it s reflected from a smooth surface (figure 5.3.6). You will notice that the reflected rays are parallel. This results in a clear image being seen. When light is reflected from a rough surface such as paper (figure 5.3.7), a clear image can not form because the reflected light is scattered in different directions. This explains why you can see your reflection in a plane mirror but not in a piece of paper.

3. Concave and convex mirrors

   Use a multiple slit to produce several parallel beams of light. Reflect them from a concave and convex mirror.

   Use the space below to record your results.

5

4. Look at an object (e.g. a pencil tip) using concave and convex mirrors. Move the object toward and away from the mirror. Use the space below to describe what you notice.

Concave mirrors

Figure 5.3.8 shows parallel beams of light being reflected from a concave mirror.

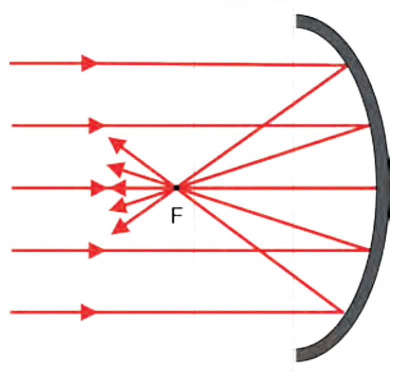


Figure 5.3.8

A **concave** mirror reflects rays of light so that they focus at a point in front of the mirror. This is called the focal point F. The distance between the mirror and the focal foint is called the focal length (*f*). Such mirrors are referred to as **converging** mirrors and are used in torches, telescopes and car headlights.

A ray diagram can be used to explain the appearance of the image in the mirror. This will depend on the distance between the object and the focal point. Figure 5.3.9 illustrates the result of placing the object at a distance from the mirror that is greater than two focal lengths. The image is inverted, reduced and real.

The difference between a **real image** and a **virtual image** is that a real image can be projected onto a screen while a virtual image cannot.

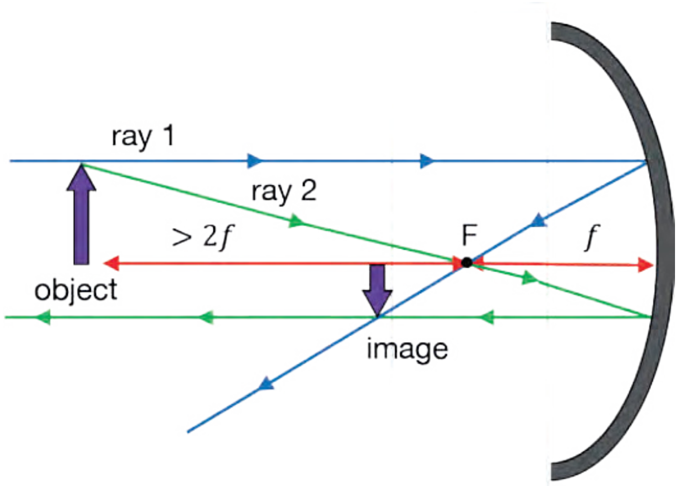


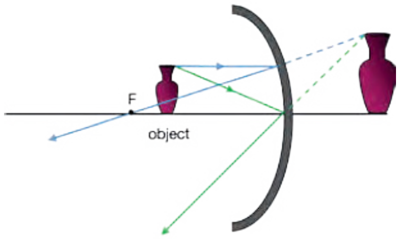
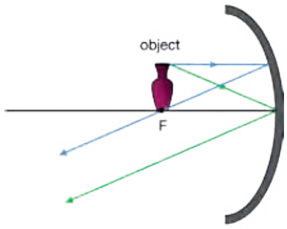
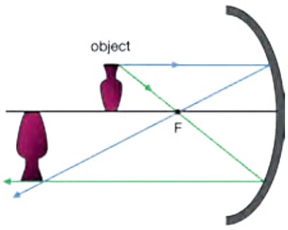
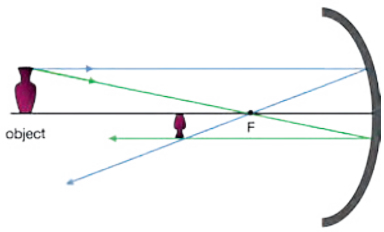
Figure 5.3.9

Helpful online resource

Drawing ray diagrams for concave mirrors

www.physicsclassroom.com/mmedia/optics/rdcma.cfm

The following table summarises the images formed.

Diagram	Distance (d) between object and focal point	Appearance of image in the mirror
	$0 \leq d < f$	Virtual, upright, enlarged
	$d = f$	No image
	$f < d < 2f$	Real, inverted, enlarged
	$d > 2f$	Real, inverted, reduced

Uses

Figure 5.3.10
make-up mirror

Figure 5.3.11
car headlight

Concave mirrors are particularly useful when you would like the image to be larger than the actual object e.g. a dentist's mirror, or make-up and shaving mirrors (figure 5.3.10).

Car headlights (figure 5.3.11) also use concave mirrors. The globe is placed at the focal point of the mirror and emits light in all directions. The rays of light that are reflected from the mirror, reflect forward to form a beam of many parallel rays.

Convex mirrors

Figure 5.3.12 shows parallel beams of light being reflected from a concave mirror.

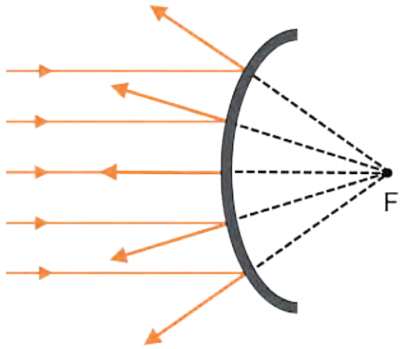


Figure 5.3.12

A **convex** mirror reflects rays of light so that they spread and appear to focus at a point (called the focal point, F) behind the mirror. They are referred to as **diverging mirrors**. Convex mirrors produce an image that is virtual, smaller than the object and upright.

A ray diagram (figure 5.3.13) can be used to explain the appearance of the image in the mirror.

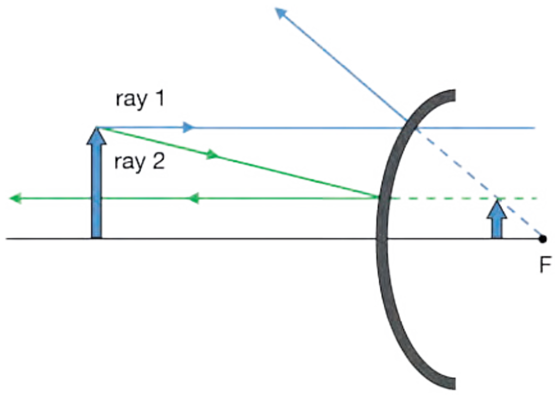


Figure 5.3.13

Helpful online resource

Drawing ray diagrams for convex mirrors

http://www.physicsclassroom.com/class/refln/Lesson-4/Ray-Diagrams-Convex-Mirrors

Uses

Figure 5.3.14

Supermarkets

Figure 5.3.15

Car side-view mirrors

Convex mirrors spread light. They are useful in creating a wide field of view and are used in supermarkets and in car side-view mirrors.

Refraction of light

Refraction is the change in direction of propagation of a wave as its speed changes.

Figure 5.3.16 shows a single ray of light in air entering and leaving a transparent medium. The ray can be seen bending towards the normal as it enters the medium and bending away from the normal as it leaves the medium. The medium is more optically dense than air. The light slows down once it enters the medium and speeds up once it leaves the medium. The change in speed causes the direction of the light to change.

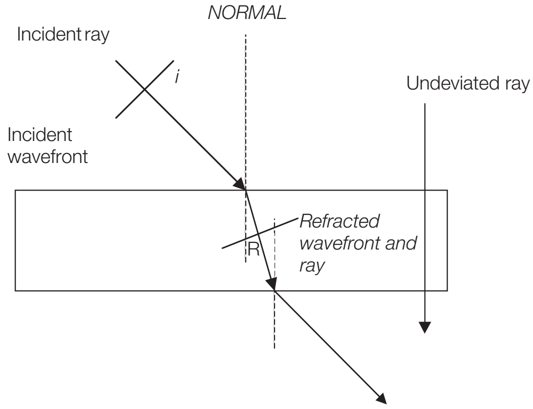


Figure 5.3.16

The speed changes as the light passes from one transparent medium into another due to a change in optical density.

The **normal** is a line drawn perpendicular to the surface.

The **incident** ray represents the direction that the incoming wave is travelling.

The **refracted** ray represents the direction that the refracted (bent) wave is travelling.

i is the angle of incidence or the angle between the normal and the incident ray.

R is the angle of refraction or the angle between the normal and the refracted ray.

Additional notes

1. If a ray of light is incident perpendicular to the surface (i.e. the angle of incidence is zero), it passes through the medium without deviation.
2. The ***frequency*** of the light ***does not change*** as the light pass from one medium into another.
3. If the **light passes into a more optically dense medium** (i.e. the speed decreases) it is bent or **refracted towards the normal**. An example is light entering glass.
4. If the **light passes into a less optically dense medium** (i.e. the speed increases) it is **bent or refracted away from the normal**. An example is light entering air from glass or water.
5. The same principles apply to all waves.

An example of refraction

Ever wondered why a pencil in a glass of water looks bent? Refer to figure 5.3.17 which shows the appearance of such a pencil.

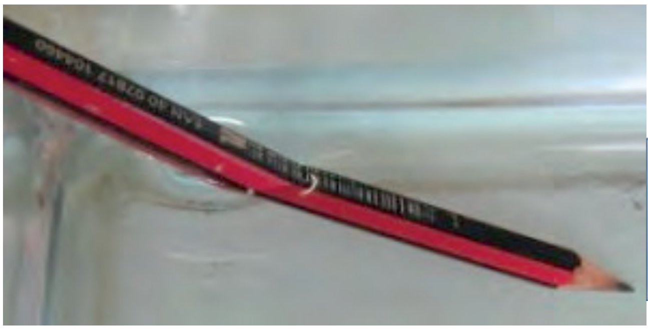


Figure 5.3.17

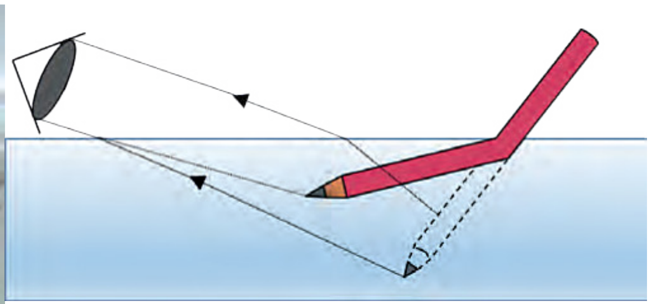


Figure 5.3.18

This phenomenon can be explained in terms of refraction. Figure 5.3.18 shows a ray diagram that helps explain this situation. Light leaves the pencil (say the tip) and travels towards our eye. The light bends away from the normal at the water-air boundary. Light travels in straight lines, so tracing the rays back, the tip appears higher than it actually is. The pencil looks bent.

Helpful online resource

Concepts of refraction can be explored using the simulation below:

https://phet.colorado.edu/en/simulation s/category/physics/light-and-radiation)

Snell's Law

Snell's Law states that the ratio of sine of the angle of incidence to the sine of the angle of refraction is a constant and equal to the ratio of the speed of the wave in the incident medium to the speed in the refracting medium.

$$\frac{\sin i}{\sin R} = \text{constant} = \frac{v_1}{v_2}$$

The constant in Snell's law is called the refractive index. It is a measure of the bending power of the medium for a wave incident from medium 1 to medium 2 or the ratio of the speed of the wave in the two media. In this case we will be talking about light but the law applies to other waves such as water and sound waves.

A vacuum does not bend light. When the bending power of a medium is compared to that of a vacuum, we call this the absolute refractive index.

Snell's law can be expressed mathematically as:

$$\frac{\sin i}{\sin R} = \frac{v_1}{v_2} = \frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$$

where

n_1 = absolute refractive index of medium 1

n_2 = absolute refractive index of medium 2

λ_1 = the wavelength in medium 1

λ_2 = the wavelength in medium 2

v_1 = the speed in medium 1

v_2 = the speed in medium 2

? Science inquiry practical

Determining Snell's Law experimentally

Snell's law can be expressed as:

$$\sin i = \text{constant} \times \sin R$$

where *i* is the angle of incidence and *R* is the angle of refraction.

The constant is the refractive index of the material that the light enters.

Aim: To verify Snell's Law and to find the refractive index of plastic graphically.

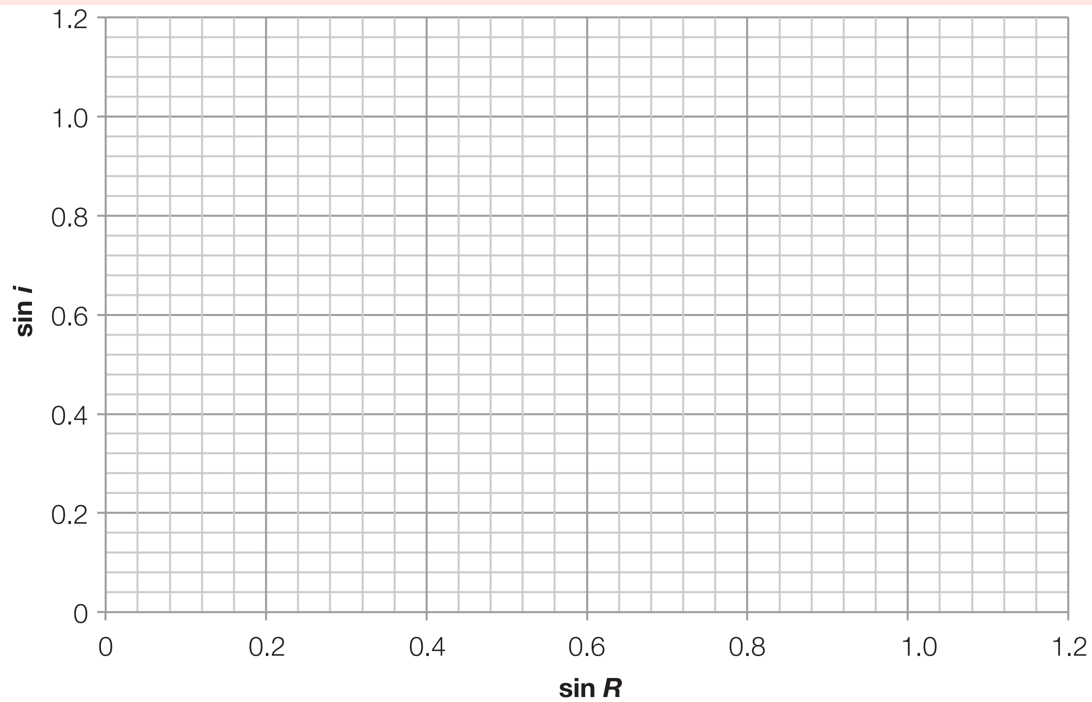
Equipment: Ray box, glass or plastic block, paper

Method:

1. Place a piece of white A4 paper on a bench.
2. Place a rectangular plastic block flat on the paper. Trace its outline with a sharp pencil.
3. Adjust the ray box to produce a single ray of light incident on the block. Mark this point and draw a normal at this point.
4. Trace the incident ray by marking two points on the ray. Now mark the point where the ray emerges from the block into air again.
5. Remove the block and draw in the incident and refracted rays.
6. Measure the angle of incidence *i* and the corresponding angle of refraction *R*.
7. Repeat for at least 5 angles of incidence.
8. Complete the table below.

i	***R***	**sin *i***	**sin *R***

9. Plot a graph of sin *i* against sin *R* with sin *i* on the vertical axis.
10. Draw a line of best fit for the plotted points.



5

Interpretation:

1. Does the graph verify Snell's Law?

2. Calculate the slope of the resulting line of best fit.

3. Write an equation for the straight line.

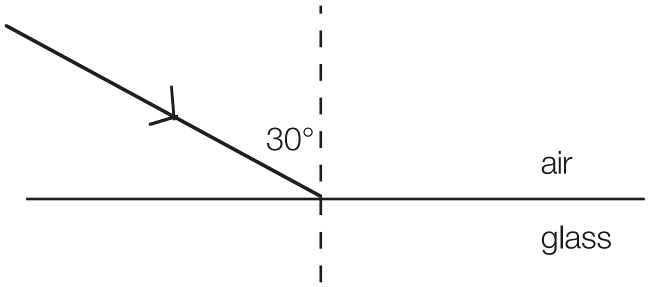
4. Use your equation to determine the refractive index of plastic.

5. Suggest two sources of error. Classify them as random or systematic.

6. Suggest two improvements to the method.

Worked examples

1. A ray of light of wavelength 6.0×10^{-7} m is incident from air into a block of glass with an angle of incidence of 30° as shown in the diagram below.



The refractive index of air is 1.0 and that of glass 1.5.

Calculate the

(a) angle of refraction.

$$\frac{\sin i}{\sin R} = \frac{n_2}{n_1} \quad \therefore \quad \frac{\sin 30}{\sin R} = \frac{1.5}{1} \quad \therefore \quad R = \sin^{-1}\left(\frac{\sin 30}{1.5}\right) = 19°$$

(b) angle of deviation of the incident ray.

30 – 19 = 11°

(c) speed of the light in the glass.

$$\frac{n_2}{n_1} = \frac{v_1}{v_2} \quad \therefore \quad \frac{1.5}{1} = \frac{3 \times 10^8}{v_2} \quad \therefore \quad v_2 = \frac{3 \times 10^8}{1.5} = 2.0 \times 10^8 \ ms^{-1}$$

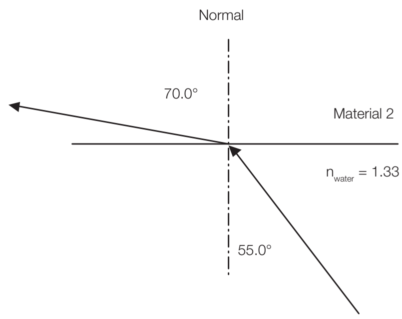
(d) wavelength of the light in the glass.

$$\frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2} \quad \therefore \quad \frac{1.5}{1} = \frac{6 \times 10^{-7}}{\lambda_2} \quad \therefore \quad \lambda_2 = \frac{6 \times 10^{-7}}{1.5} = 4.0 \times 10^{-7} \ m$$

(e) the frequency of the light.

$$v = f\lambda \quad \therefore \quad f = \frac{v}{\lambda} = \frac{3 \times 10^8}{6 \times 10^{-7}} = 5.0 \times 10^{14} Hz$$

2. A ray of light is incident from water into an unknown material as shown in the diagram below.



(a) What can you deduce about the optical density of material 2 relative to material 1?

The light is refracted away from the normal. Material 2 must be less optically dense than material 1.

(b) Calculate the refractive index of material 2.

$$\frac{\sin i}{\sin R} = \frac{n_2}{n_1} \quad \therefore \quad \frac{\sin 55}{\sin 70} = \frac{n_2}{1.33} \quad \therefore \quad n_2 = \frac{\sin 55 \times 1.33}{\sin 70} = 1.16$$

(c) Predict the outcome of progressively increasing the angle of incidence.

As the angle of incidence becomes larger, the angle of refraction increases. Eventually the angle of refraction will be 90°. If the angle of incidence becomes larger still, the light will be totally internally reflected back into the water.

Critical angle

When light is incident from a more optically dense to a less dense medium, it bends away from the normal. As the angle of incidence increases, so does the angle of refraction.

The angle of incidence that produces an angle of refraction of 90° is called the critical angle.

Figure 5.3.19 illustrates this situation.

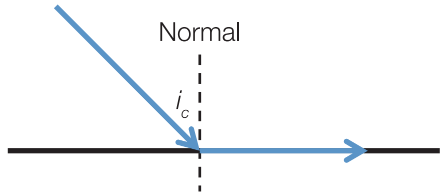


Figure 5.3.19

For a wave travelling from medium 1 into air (n_{air} = 1.0), the critical angle i_c can be calculated as follows:

$$\frac{\sin i_c}{\sin R} = \frac{n_2}{n_1} \quad \therefore \quad \frac{\sin i_c}{\sin 90} = \frac{1}{n_1} \quad \therefore \quad \sin i_c = \frac{1}{n_1}$$

Worked examples

1. Calculate the critical angle for plastic ($n_{plastic}$ = 1.4).

$$\sin i_c = \frac{1}{n_1} \quad \therefore \quad \sin i_c = \frac{1}{1.4} \quad \therefore \quad i_c = \sin^{-1}\left(\frac{1}{1.4}\right) = 46°$$

2. A material has a critical angle of 48.2°. Calculate the refractive index of the material.

$$\sin i_c = \frac{1}{n_1} \quad \therefore \quad \sin 48.2 = \frac{1}{n_1} \quad \therefore \quad n_1 = \frac{1}{\sin 48.2} = 1.34$$

Total internal reflection

When the angle of incidence is greater than the critical angle, total internal reflection occurs. This means that the light is completely reflected back into the incident medium.

Figure 5.3.20 illustrates this situation.

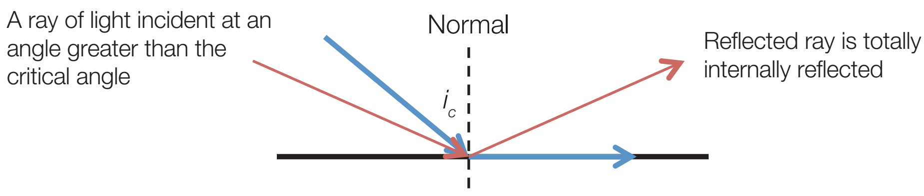


Figure 5.3.20

Applications of total internal reflection

Optical fibres

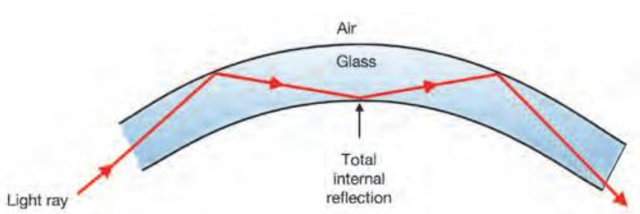


Figure 5.3.21

An optical fibre is a thin strand of glass with a protective coating on the outside. Light or sound waves strike the internal surface at angles greater than the critical angle of the fibre. The waves are internally reflected as shown in in figure 5.3.21. As a consequence the waves bounce along the length of the fibre without loss in intensity. In addition, the waves are completely contained within the fibre. This means that many fibres can be bundled together without the light or sound signals interfering.

Uses include:

- fibroscopes used for internal medical examinations of patients
- communication over large distances
- decorative table lamps
- car instrument panels – many instruments can be lit up from a single globe

NB: The refractive index of the coating must be less than the refractive index of the fibre for total internal reflection to occur.

Activity

Your teacher may demonstrate the transmission of laser light through an optical fibre.

Convex and concave Lenses

Activity

Use a raybox and lenses to investigate the affect that convex and concave lenses have on parallel beams of light.

Convex lenses

Figure 5.3.22 shows parallel beams of light being refracted by a convex lens.

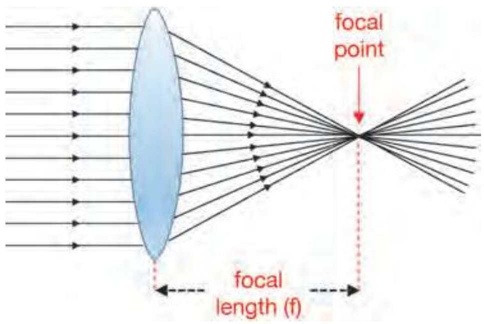


Figure 5.3.22

A **convex** lens refracts light rays so that they focus at a point in front of the lens. This is called the focal point F. The distance between the centre of the lens and the focal point is called the focal length (*f*). Such lenses are referred to as **converging** lenses and their use includes cameras, microscopes and magnifying glasses.

A ray diagram can be used to explain the appearance of the image through the lens. This will depend on the distance between the object and the lens and the focal point of the lens. Figure 5.3.23 is a ray diagram that illustrates the result of placing the object at a distance from the lens that is greater than two focal lengths. The image is inverted, reduced and real.

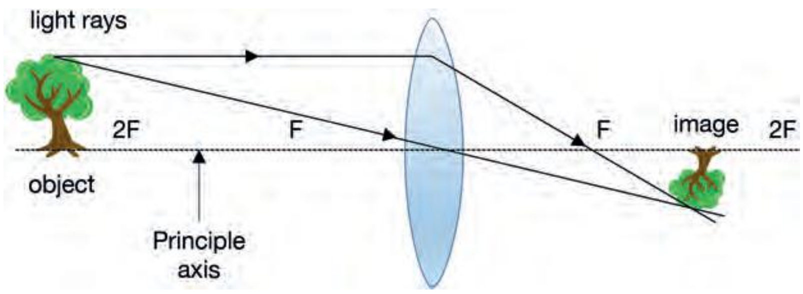


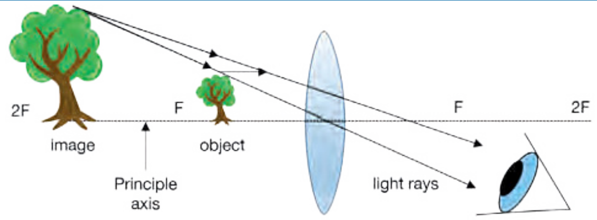
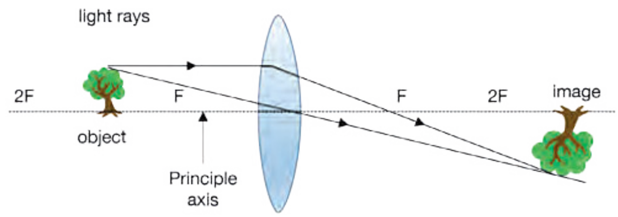
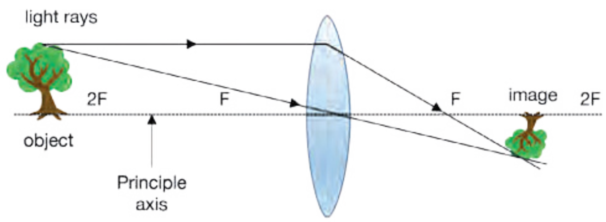
Figure 5.3.23

Helpful online resource

Drawing ray diagrams for convex lenses

http://www.physicsclassroom.com/class/refrn/Lesson-5/Converging-Lenses-Ray-Diagrams

The following table summarises the images formed.

Diagram	Distance (d) between object and focal point	Appearance of image in the mirror	Use
	$0 \leq d < f$	Virtual, upright, enlarged	Magnifying glass
	$d = f$	Same size	photocopier
	$f < d < 2f$	Real, inverted, enlarged	projector
	$d > 2f$	Real, inverted, reduced	camera

Activity

You will notice that the ray diagram for the image produced when the object is placed at a distance from the lens which is equivalent to one focal length is missing.

Draw a ray diagram and confirm that the image will be the same size as the object. Add your ray diagram to the table.

Concave lenses

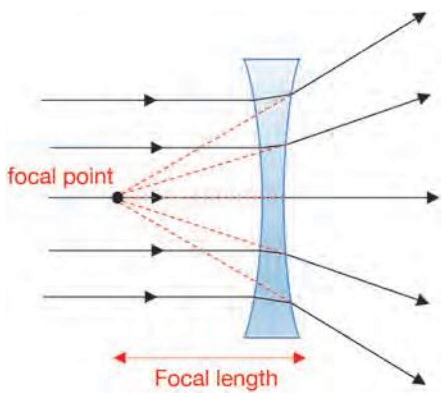


Figure 5.3.24

A **concave** lens refracts light rays so that they spread and appear to focus at a point (called the focal point F) behind the lens. They are referred to as **diverging lenses**. Concave lenses produce an image that is virtual, smaller than the object and upright.

A ray diagram can be used to explain the appearance of the image through the lens. Figure 5.3.25 is a ray diagram that can be used to illustrate that the image formed when the object is placed between one and two focal lengths of the lens will be virtual, upright and smaller than the object.

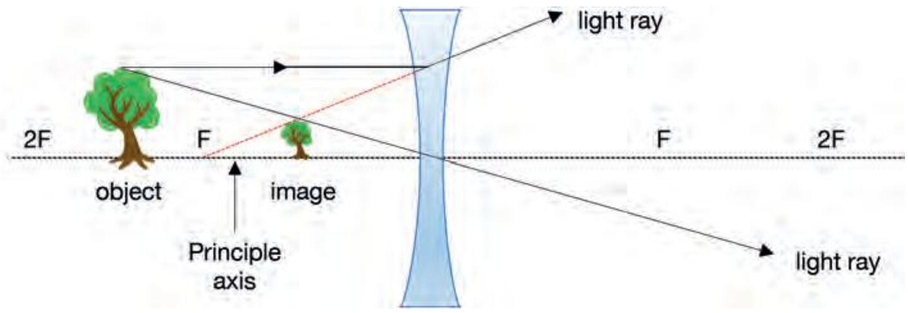


Figure 5.3.25

Helpful online resource

Drawing ray diagrams for concave lenses

http://www.physicsclassroom.com/class/refrn/Lesson-5/Diverging-Lenses-Ray-Diagrams

Uses

Although the uses for concave lens are not as broad as convex lenses, they are useful in correcting near sighted vision, in door peep holes and in flashlights and flood lights to spread the light.

The diffraction of waves

Diffraction is the bending (and hence spreading) of a wave as it passes through an opening or a around an obstacle.

For observable diffraction effects, the wavelength of the waves must be comparable to the slit size.

Figure 5.3.26, figure 5.3.27 and figure 5.3.28 show the diffraction of wavefronts in various situations.

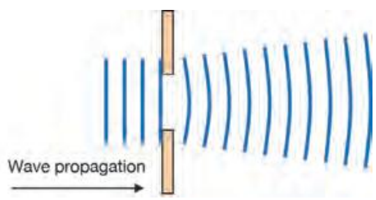


Figure 5.3.26

Slit width much larger than wavelength

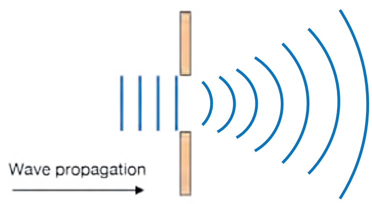


Figure 5.3.27

Slit width about the same size as the wavelength

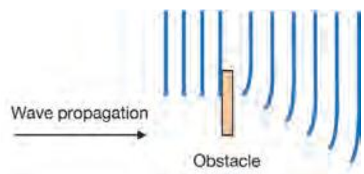


Figure 5.3.28

obstacle

Everyday examples of diffraction

1. You can hear people speaking in another room due to sound waves diffracting around a wall or through a door way.
2. Laser light passed through a single slit produces a single slit diffraction pattern as shown in figure 5.3.29. This consists of a series of bright and dark bands that lose intensity or brightness quickly. The central maxima (bright band) is twice the width of the others.

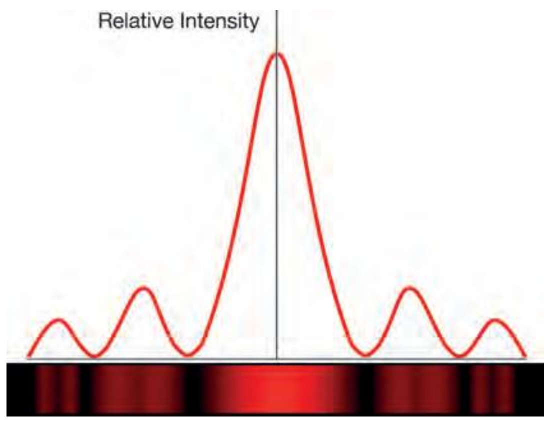


Figure 5.3.29

Polarisation

Plane-polarisation involves the restriction of vibrations to a single plane only.

Shaking a garden hose up and down while the water is flowing produces a vertically plane-polarised water wave as the vibration is in the vertical plane. Shaking the garden hose from side to side produces a horizontally plane-polarised water wave.

A electron vibrating along the length of an antenna will produce an electromagnetic wave (radio or TV wave) which is plane-polarised in the direction of the vibrating charge. If the antenna is vertical, a vertically plane-polarised radio wave is produced (figure 5.3.30). If the antenna is horizontal, a horizontally plane-polarised radio wave is produced. **The plane of polarisation is defined by the plane of the electric field.**

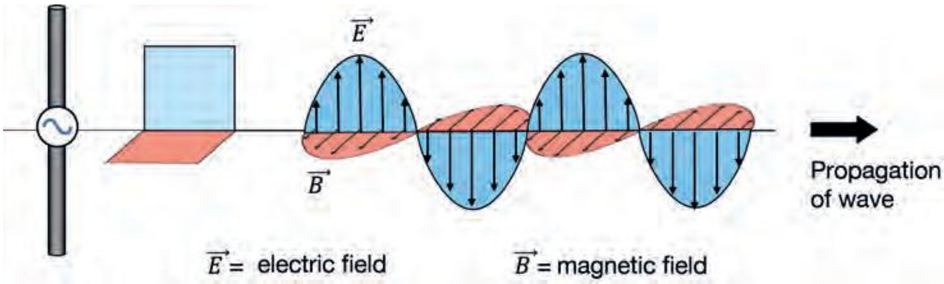


Figure 5.3.30

Most sources of light (e.g. light from the Sun or an incandescent globe) emit unpolarised light waves. This means that waves are produced in randomly oriented planes. Figure 5.3.31 and figure 5.3.32 show a simple way to represent polarised and unpolarised light.

Figure 5.3.31

Representing polarised light

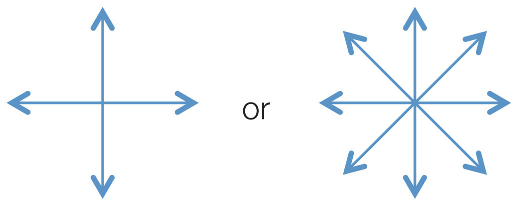


Figure 5.3.32

Representing unpolarised light.

Unpolarised light can be polarised by using a **sheet of polaroid.**

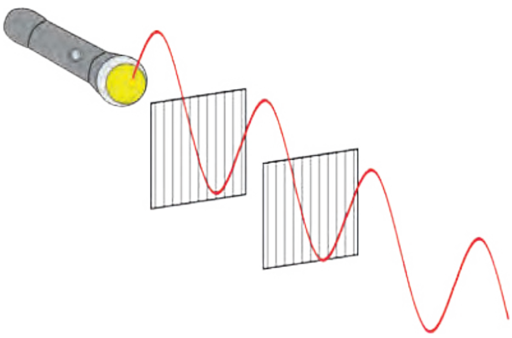


Figure 5.3.33

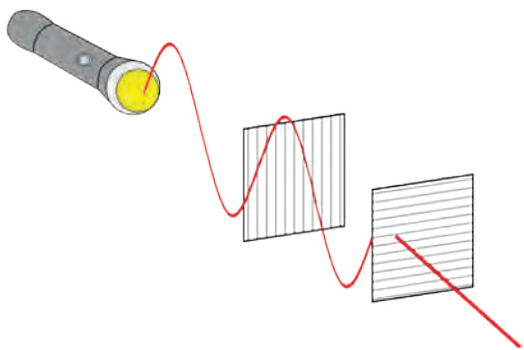


Figure 5.3.33

Figure 5.3.33 shows unpolarised light from a torch passing through two polaroid filters which are orientated so that their polarising planes are parallel. The light is vertically plane polarised by the first filter and proceeds to pass through the second filter. In Figure 5.3.34, the second polaroid filter has been rotated so that its polarising plane is perpendicular to the first filter. The polarised light passing through the first filter is blocked by the second.

Activity

Your teacher will demonstrate the polarisation of light using two polaroid filters.

If one polaroid filter is placed over the other so that the planes of polarisations are parallel, a letter written on a piece of paper can be seen clearly through both filters (figure 5.3.35). If one polaroid filter is then rotated so that the planes of polarisation are perpendicular to one another, the light is blocked and the letter can no longer be seen (figure 5.3.38).

Figure 5.3.35

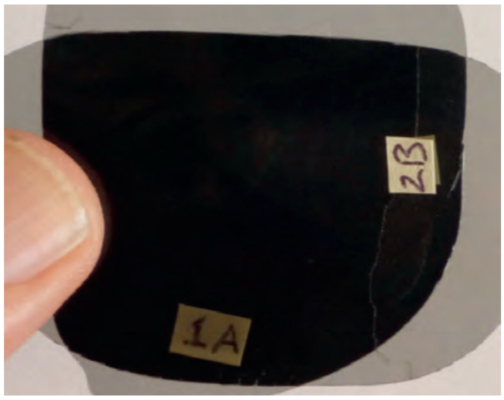


Figure 5.3.36

Science as a human endeavour

The economic and health impacts of ultraviolet radiation exposure.

Everyone is exposed to ultraviolet radiation. The main source of exposure is from the Sun. While the ozone layer absorbs a large proportion of UV light, its depletion means that exposure will increase.

Some of the health concerns include skin cancer, cataract and the potential to reduce a person's resistance to infection. Protection from UV light exposure is therefore important.

It is estimated that are around 200 000 malignant skin cancer or melanoma cases world wide every year (the United Nations Environment Programme). This number is likely to rise. The Cancer Council Australia reported over 2200 skin cancer related deaths in 2013.

Approximately three million people are blinded by cataract produced by the exposure to UV light every year. It costs governments billions of dollars (e.g $3.4 billion in the US) to perform cataract operations every year.

Further ideas for *Science as a human endeavour* investigations

Analyse the interaction between science and technology with advances in:

- optics of camera lenses, telescopes, and binoculars
- optometry (spectacles and corrective laser surgery)
- the uses of optic fibres in medicine and communication
- applications of polarisation (such as 3D glasses, sunglasses)
- the uses of radio waves and microwaves in communication (such as wifi, mobile phones, and space communication)
- heating using microwaves
- the uses of x-rays and gamma rays in diagnostic and therapeutic medicine
- Laser Airborne Depth Sounding (LADS).

5

Exercises

5.1 Wave model

1. Explain the difference between a wave and a pulse.

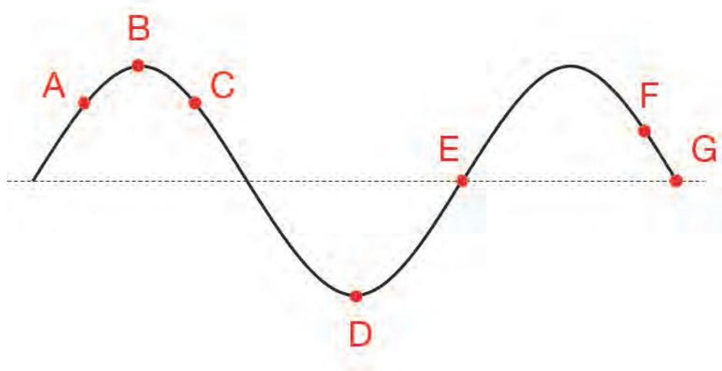
2. Define the following terms as they relate to a wave.
   (a) Amplitude:

   (b) Period:

   (c) Wavelength:

   (d) Wave speed:

3. The diagram below represents a transverse wave.



Several point, A to G marked on the wave.

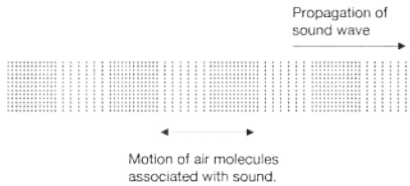
   (a) Consider the definition of two points on a wave that are in phase. Deduce the definition of out of phase.

   (b) State the two points on the wave that are in phase.

   (c) State two points on the wave that are out of phase.

   (d) In terms of wavelength, state the distance between two consecutive points on the wave that are out of phase.

4. (a) Sound is an example of a longitudinal wave. The diagram below represents a sound wave in air.



Explain why sound is sometimes referred to as a pressure wave.

(b) A tuning fork produces a frequency of 440 Hz (A4 note).

(i) What does a frequency of 440 Hz mean about the way the tuning fork vibrates?

(ii) Calculate the period of the waves.

(c) The speed of sound waves in air at sea level and at a temperature of 20.0°C is 343 ms^{-1}. Calculate the wavelength of the sound waves produced by the tuning fork in part (b) under these conditions.

5. A stone is dropped into a pond and after 4.00 s, 49 ripples are observed covering a distance of 1.40 m.

(a) Define the term wavelength and calculate the wavelength of the observed water waves.

(b) Show that water waves have a speed of 0.350 ms^{-1}.

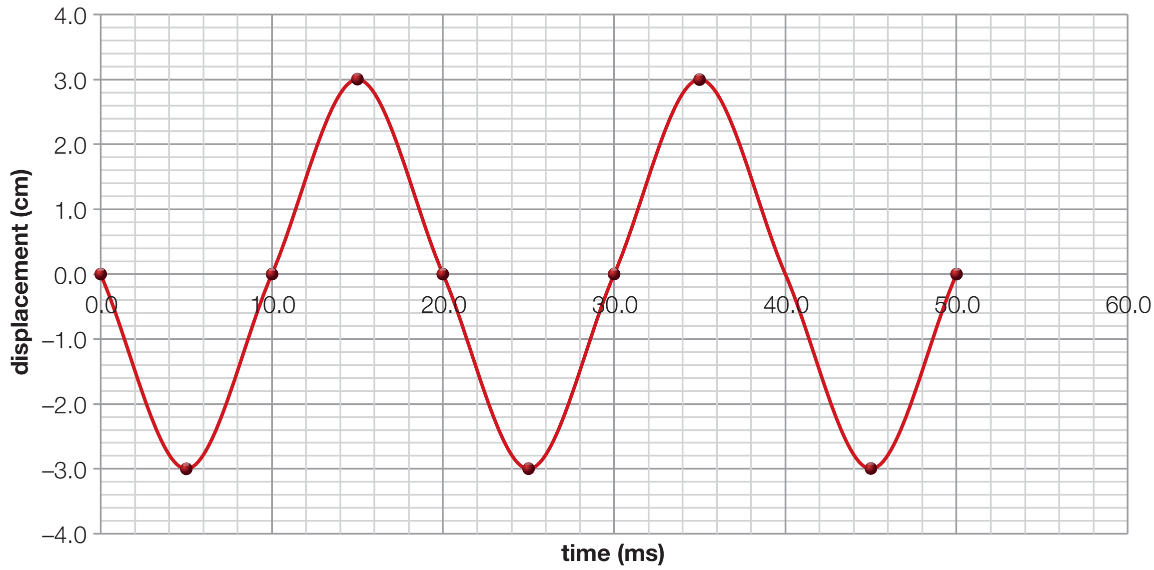
(c) Calculate the frequency of the water waves.

6. A fisherman uses an echo sounder to locate the position of schools of fish. A pulse of ultrasound is emitted and returns to the boat after 0.150 s.

The speed of ultrasound waves in water is 1450 ms^{-1}.

Calculate the depth at which the fish are located.

7. The graph shown below shows how the displacement of a wave varies with time.



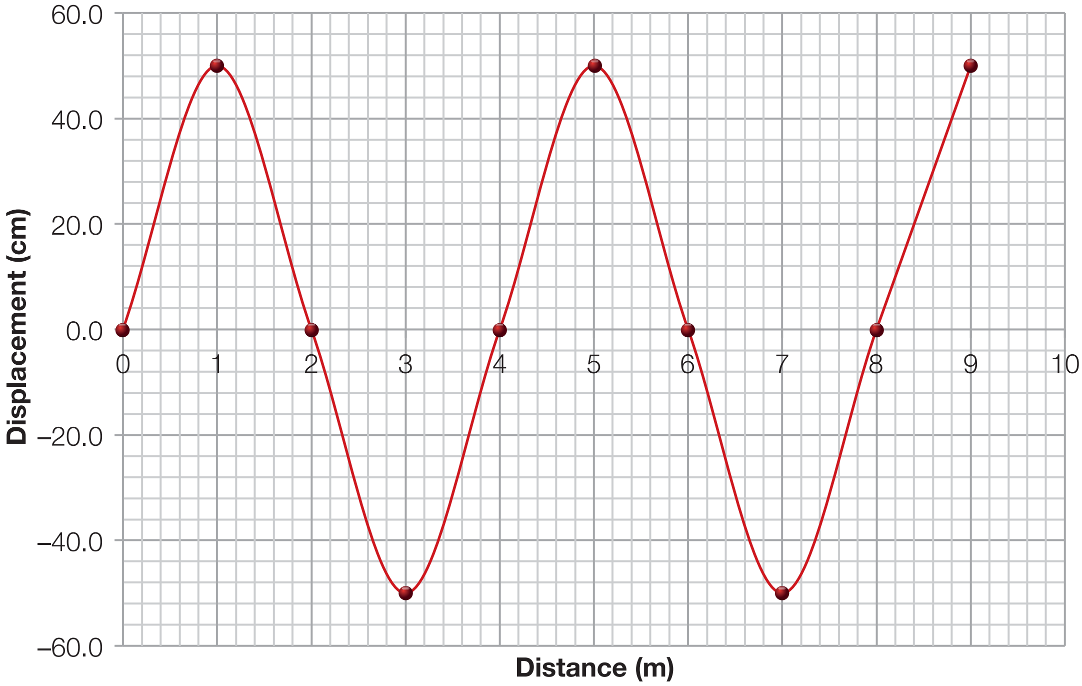
(a) State the amplitude of the wave.

(b) State the period of the wave in seconds.

(c) Calculate the frequency of the wave.

(d) The wave has a wavelength of 30.0 cm. Calculate the speed of the wave.

8. The graph shown below shows how the displacement of a water wave varies with distance. The water wave has a speed of of 3.0 ms^{-1}.



(a) Water waves are transverse. Explain the nature of a transverse wave.

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....

....

(b) State the wavelength of the water wave.

....

(c) State the displacement of a point on the water wave at a distance of 2.5 m.

....

(d) Calculate the frequency of the wave.

....

....

....

9. A young student is seated in a stationary car at a set of traffic lights. A police vehicle approaches the student in the car. She hears the frequency of the siren change.

(a) Describe and explain the change in frequency heard by the student.

....

....

....

....

....

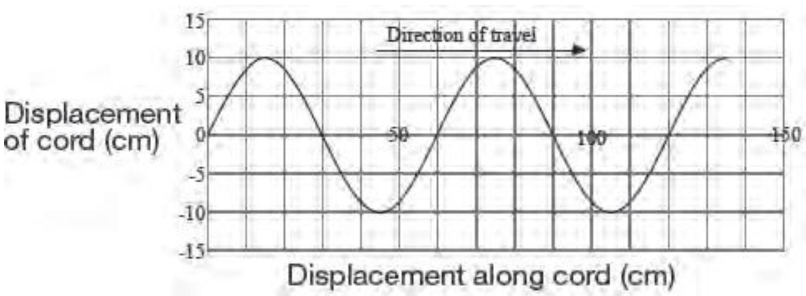
(b) State the name of this phenomenon.

....

10. Consider yourself shaking the garden hose vertically up and down to produce a transverse water wave. Describe and explain the change in the period of the wave when you shake the hose up and down three times faster.

11. The image below shows battle ropes being used as an exercise tool.

The graph shown below represents part of a battle rope along which a wave is travelling.



(a) The wave along the rope is transverse. Explain what is meant by a transverse wave.

(b) State the

(i) amplitude of the rope.

(ii) wavelength of the rope.

(c) The period of the wave is 0.40 s. Calculate the speed of the wave along the rope.

(d) Explain why battle ropes are a good form of exercise.

12. An earthquake causes a tsunami wave. The speed and wavelength of a tsunami depends on the depth of the water. The table below summarises some facts about a tsunami wave for a water depth of 250 m.

Distance travelled (km)	Wavelength (km)	Time to travel distance (minutes)
5.45	52.0	2.00

(a) Calculate the speed of the tsunami wave.

(b) Calculate the frequency of the vibration that created the tsunami.

13. This question requires a longer response.

In answering the question that follows you should:

- *communicate your knowledge clearly and concisely*
- *use physics terms correctly*
- *present information in an organised and logical sequence*
- *include information that is relevant to the question.*

On a stormy night, lightning is accompanied by the sound of thunder. Lightning is always seen before the thunder is heard.

Explain why lightning is always seen before thunder is heard and suggest a method for determining the distance between the source of the lightning and thunder and the observer. You should include a clearly labelled diagram to support your answer.

5

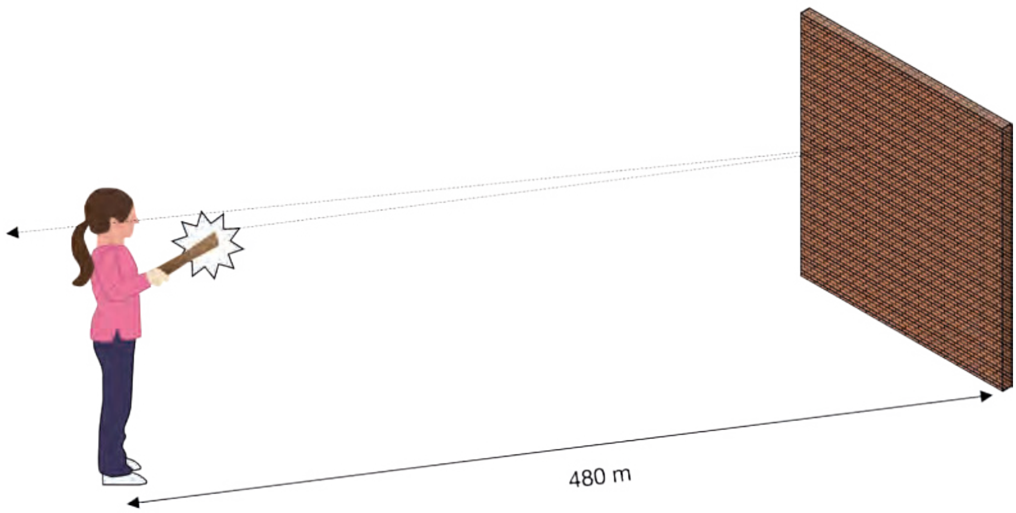
5.2 Mechanical Waves

1. (a) Define the term resonance.

   (b) Consider yourself pushing a child on a swing as shown in the diagram below.

In terms of resonance, explain why there comes a time when very little force needs to be applied in order for the child to continue swinging.

2. A student stands 480m away from a wall.



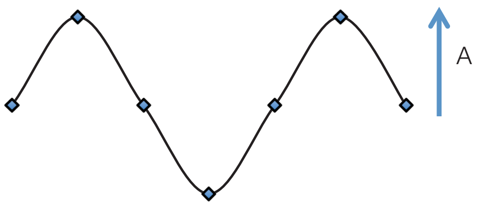
She hits two pieces of wood together and hears an echo a short time later.

   (a) Briefly describe why an echo is heard.

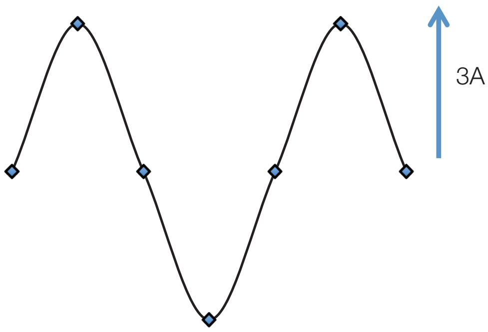
(b) Given the speed of sound is 340 ms^{-1}, calculate the time between the original sound and the sound heard from the echo.

3. (a) State the principle of superposition for waves.

(b) Consider the two waves A and B as shown below. Wave A has an amplitude of A and wave B has an amplitude of 3A. The crest of one wave coincides with the crest of the other (we say that the waves are in phase).



Wave A



Wave B

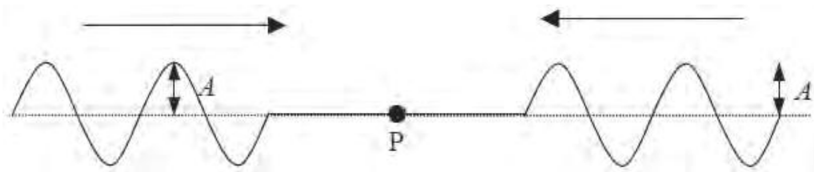
(i) State the amplitude of the wave that results when the two waves meet in phase.

(ii) Name the type of superposition involved.

(iii) State the amplitude of the wave that results if the two waves meet out of phase so that a crest of wave A coincides with a trough of wave B.

(iv) Name this type of superposition.

4. The diagram below shows two identical waves travelling along a string in opposite directions.

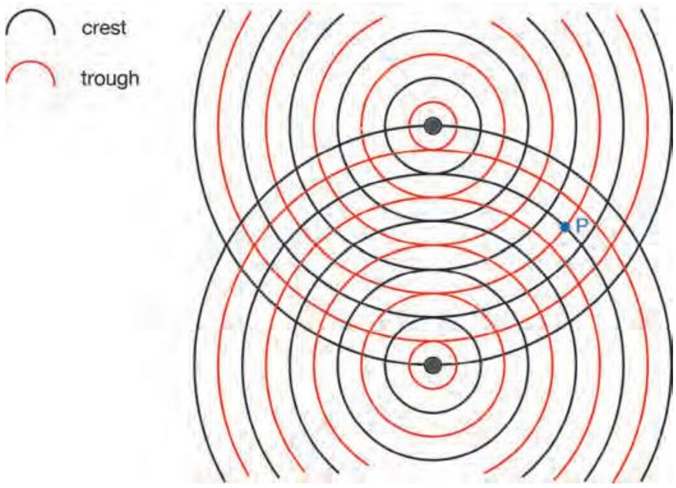


The waves arrive at the point marked P at the same time.

(a) In terms of superposition, explain the resultant amplitude of the wave at P.

(b) Describe the motion of the string at P.

5. The diagram shown below represents two coherent wave sources overlapping.



Consider the point P.

(a) Determine whether constructive or destructive superposition occurs at this point.

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(b) State the path difference at P.

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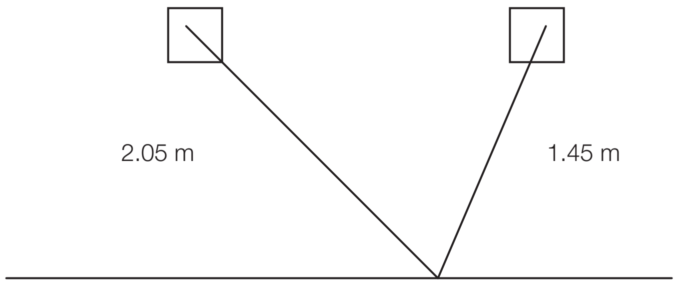
6. Two speakers are placed 1.00 m apart. Both speakers produce sound with the same volume and a frequency of 1700 Hz.



Take the speed of sound to be 340 ms^{-1}.

(a) Calculate the wavelength of the sound waves.

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(b) A student stands at the point P shown on the diagram.

Determine, with reason, the volume of sound at P.

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. ...

7. The diagram below, shows coherent laser light passing through two slits separated by a distance *d*.

An interference pattern is observed on the screen. The centre of the screen is marked on the diagram (C).

(a) Explain why you would expect the intensity (brightness) of the light to be a maximum at C.

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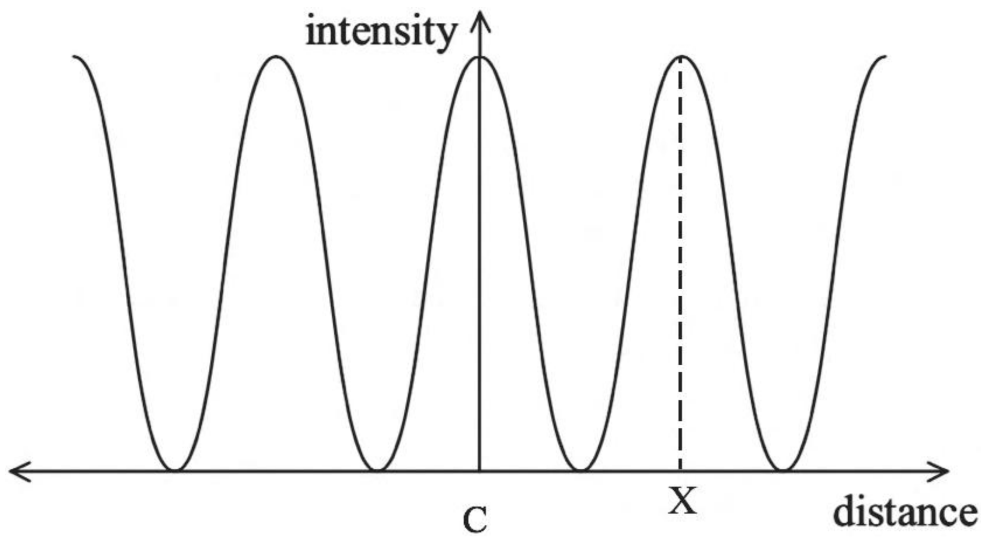
(b) The diagram below represents the observed interference pattern graphically.



(i) Use the graph to help you describe the interference pattern.

. . . .

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. . . .

. . . .

(ii) X is a position on the screen. State the path difference at X.

. . . .

8. (a) Explain how a stationary wave pattern results.

(b) A 2.00 m length of string is stretched and fixed between two supports. A standing wave pattern consisting of three loops forms.

(i) Use the space below to sketch a diagram of a standing wave pattern consisting of three loops.

Label the nodes and antinodes.

(ii) Calculate the wavelength of the standing wave.

9. A 50.0 cm piano string is tensioned such that the speed of the wave produced along the string has a speed of 110 ms^{-1}.

(a) Show that the first harmonic has a frequency of 110 Hz.

(b) Draw the standing wave pattern for the third harmonic.

(c) Calculate the wavelength of the third harmonic.

10. (a) A 45.0 cm violin string produces a first harmonic with a frequency of 512 Hz. Calculate the speed of the wave produced along the string.

(b) Calculate the number of audible harmonics produced by the string.

11. (a) Calculate the length of a flute which produces a first harmonic with a frequency of 200 Hz. Assume the pipe is open at one end only and take the speed of sound to be 340 ms^{-1}.

(b) Sketch and calculate the wavelength of the fifth harmonic.

(c) Explain why the quality of sound produced by a piano string with the same fundamental frequency is better.

12. The third harmonic produced along a particular string has a frequency of 240 Hz and a speed of 150 ms^{-1}.

(a) Calculate the frequency of the fundamental (first harmonic).

(b) Calculate the length of the string.

(c) Determine whether the 180^{th} harmonic is audible.

(d) Show that 250 audible harmonics are produced by the string.

13. The speed of a standing wave along a string is 100 ms^{-1}. The string has a mass of 10.0 g and a length of 40.0 cm. Calculate the tension in the string.

14. A pipe open at one end only produces a first harmonic with a frequency of 450 Hz. Take the speed of sound in air to be 340 ms^{-1}.

(a) Calculate the length of the pipe.

(b) A pipe open at both ends produces the same fundamental frequency.

(i) Use the space below to sketch the standing wave pattern for the fundamental for the pipe open at one end and next to it sketch the standing wave pattern for the fundamental for the pipe open at both ends.

(ii) Compare the length of the pipes.

(c) Compare the number of harmonics produced in each case.

15. When the G string of a tuned guitar is plucked, it produces a frequency of 196 Hz. When the G string is plucked on a second guitar a frequency of 199 Hz is produced.

(a) Explain why beats are produced when the two strings are plucked simultaneously.

(b) State the beat frequency that results.

(c) Explain what this beat frequency means.

5.3 Light

1. Calculate the wavelength of radiowaves transmitted by a radio station that transmits at a frequency of 107.1 MHz.

2. State the following forms of electromagnetic radiation in increasing order of wavelength.

Radiowaves, gamma rays, x-rays, infra-red, visible light

3. Look carefully at the front of the ambulance pictured below.

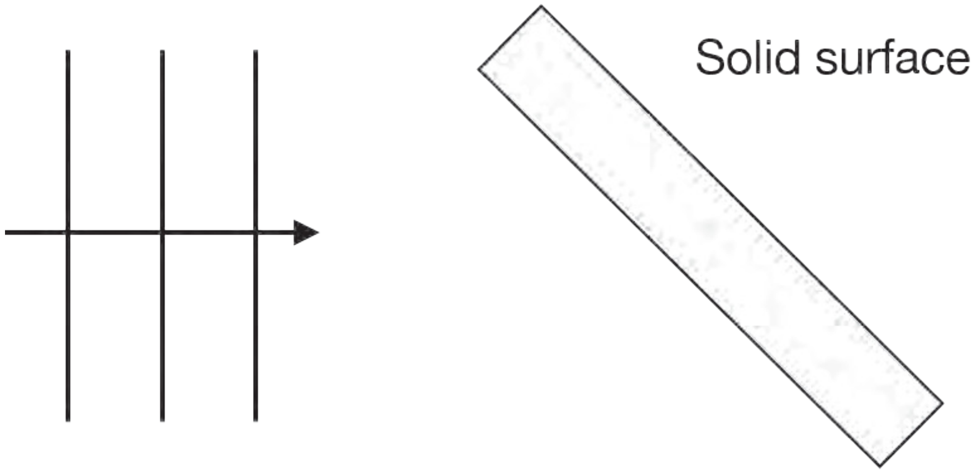
Justify the way the word 'AMBULANCE' appears.

4. Explain why concave mirrors are useful to dentists examining a patient's teeth.

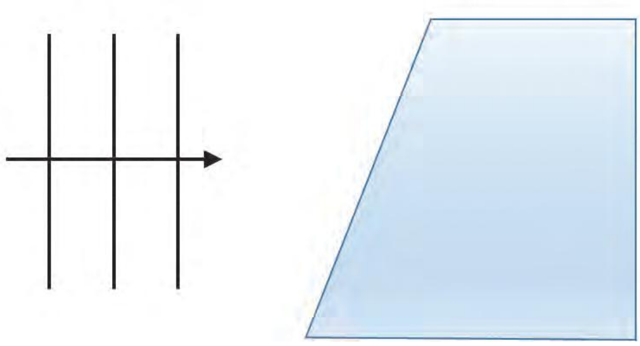
5. Use a diagram to help you explain why a coin at the bottom of a body of water (such as a pond) appears higher in the water than it actually is.

6. Complete each of the diagrams below by adding three wavefronts and a ray for (a) reflection and (b) refraction.

(a)



(b)



7. (a) State Snell's Law in words.

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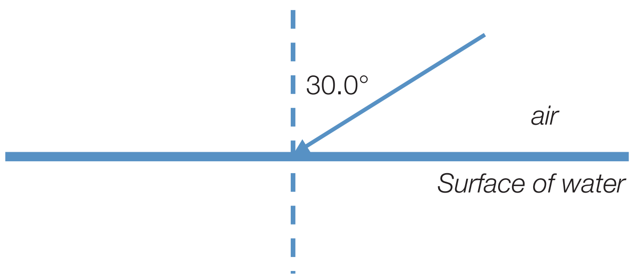
(b) Light with a wavelength of 5.80×10^{-7} m is incident on the surface of water (n = 1.33) as shown in the diagram below.



Calculate the

(i) angle of refraction.

....

....

....

(ii) angle through which the light deviates.

....

(iii) speed of light in the water.

....

....

....

(iv) wavelength of light in the water.

....

....

....

....

8. Light enters a glass prism with a refractive index of 1.5 from air (*n*=1.0).

(a) State the direction you'd expect the light to bend.

....

(b) The angle of refraction is 25°. Calculate the angle of incidence.

....

....

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(c) Calculate the speed of the light in the glass prism.

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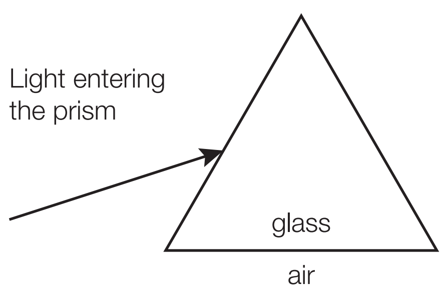
....

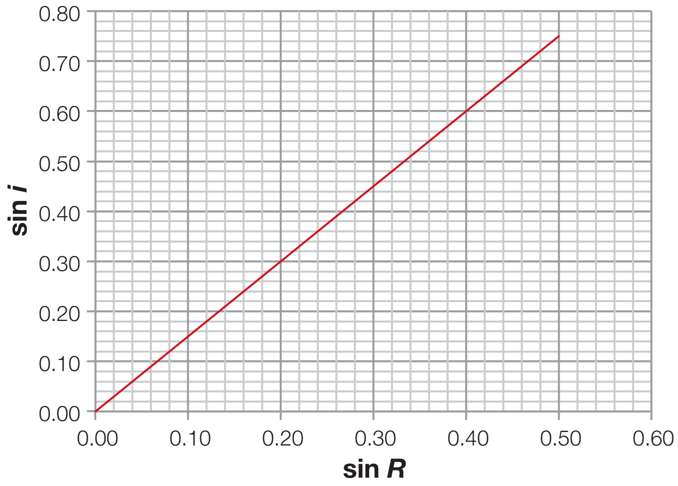
....

9. The diagram below shows a ray of light entering a triangular glass prism.



Complete the diagram by drawing the direction of the ray of light inside the prism and as it exits the prism.

10. A student collects data for light entering a rectangular glass block and plots a graph to confirm Snell's law.



(a) Calculate the gradient of the line.

(b) Write the equation of the line.

(c) Clearly explain why the graph confirms Snell's Law.

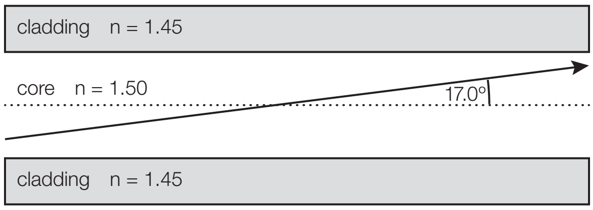
(d) State the refractive index of the glass.

11. (a) Calculate the critical angle for an optical fibre given that the refractive index of the fibre is 1.45.

(b) List the conditions required for total internal reflection to occur.

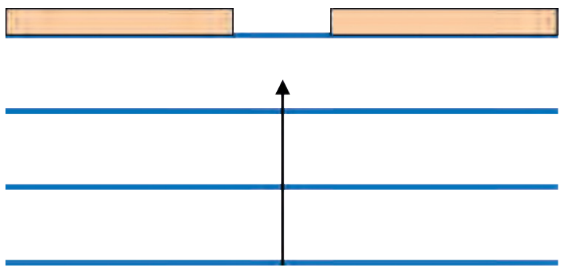
12. The critical angle for a material is 40.0°. Calculate the refractive index of the material.

13. The diagram below shows a section of an optical fibre. The core of the optical fibre is made of a material of refractive index 1.50. The cladding that surrounds the core is made of a material of refractive index 1.45.



Show with reason, that rays of light that enter the core at an angle of 17.0° as shown in the diagram will not be totally internally reflected.

14. Complete the diagram below. Name the wave phenomenon being illustrated.



15. In terms of electric and magnetic fields, describe an electromagnetic wave.

16. (a) What is meant by saying electromagnetic waves are plane polarised?

(b) Explain why radiowaves emitted from a vertical antenna are vertically plane polarised.

Topic 6: Models and radioactivity

6.1 The nucleus

Science understanding

1. The basic structure of an atom comprises a small central nucleus consisting of protons and neutrons (nucleons) surrounded by electrons.
2. Atomic nuclei can be described using their chemical symbol (*X*), mass number (*A*), atomic number (*Z*), and number of neutrons (*N*). A common representation is: ${}^{A}_{Z}X$
   - Describe the structure of an atom, including the relative size and location of the nucleons and electrons.
   - Describe the structure of various nuclei from their symbol and vice versa.
3. Isotopes are atoms of the same element that have different mass numbers.
   - Identify isotopes of an element based on their composition.
   - Explain why isotopes of the same element are chemically identical but have different physical properties.
4. The nucleus is held together by a strong, attractive nuclear force.
   - Describe the properties of the strong nuclear force, including its short range.
   - Describe the balance between the electrostatic force and strong nuclear force in stable nuclei.
   - Use the properties of the electrostatic force and strong nuclear force to explain why some isotopes are unstable.
   - Locate stable and unstable nuclei on an *N versus Z* graph.

The basic structure of the atom

In Topic 2 the basic structure of the atom was introduced. Atoms contain positively-charged protons and negatively-charged electrons. The structure of a typical atom is shown in figure 6.1.1.

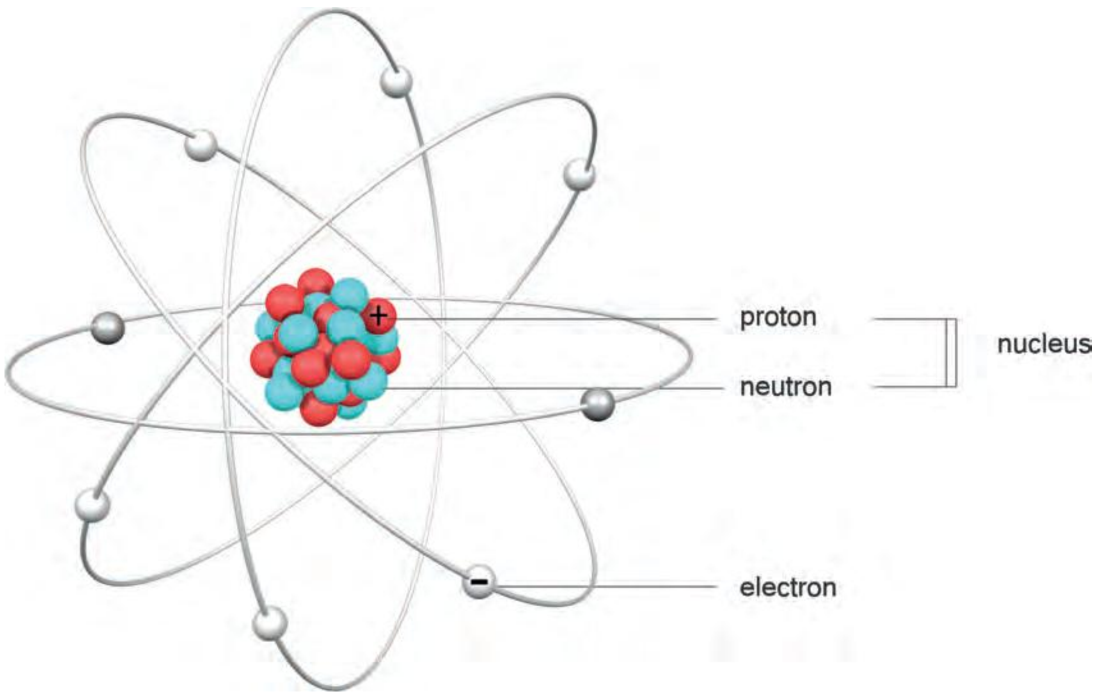


Figure 6.1.1

The nucleus is tiny and dense and located in the centre of the atom. It contains protons and neutral neutrons. The nucleus is positively charged. Electrons circle the nucleus.

The term nucleon can be used to describe either a neutron or a proton.

A neutral atom contains an equal number of protons and electrons.

Nucleons and electrons

The charge, mass, size (diameter) and location of protons, neutrons and electrons are summarized in the table shown below.

Particle	Charge (C)	Size (m)	Mass (kg)	Location in the atom
Proton	$+1.60 \times 10^{-19}$	10^{-15}	1.673×10^{-27}	nucleus
Neutron	0	10^{-15}	1.675×10^{-27}	nucleus
Electron	-1.60×10^{-19}	10^{-18}	9.11×10^{-31}	circle the nucleus in electron clouds

The relative charge, mass and size of protons, neutrons and electrons are summarized in the table shown below.

Particle	Relative charge	Relative mass	Relative size
Proton	+1	1	1
Neutron	0	1	1
Electron	-1	$\frac{1}{1840}$	$\frac{1}{1000}$

Atomic nuclei

Atomic nuclei can represented as: ${}^{A}_{Z}X$ or X^{A}_{Z}

X represents the chemical symbol for the nucleus.

A represents the mass number.

This is the **total number of protons and neutrons** (nucleons) in the nucleus.

Z represents the atomic number.

This is the **number of protons** in the nucleus. It represents the charge of the nucleus.

N represents the number of neutrons in the nucleus.

The **number of neutrons** in the nucleus can be found using: $A - Z$

Worked examples

1. State the number of protons, neutrons and nucleons for a caesium nucleus: ${}^{133}_{55}Cs$

55 protons

133 – 55 = 78 neutrons

133 nucleons

2. Gold (Au) atoms have 79 protons and 118 neutrons.

(a) State the atomic number Z and mass number A for gold.

Z: 79

A: 79 + 118 = 197

(b) State the number of electrons in a neutral atom of gold.

The number of electrons in a neutral atom is the same as the number of protons i.e. 79

Helpful online resource

Use the online interactive to build an atom:

phet.colorado.edu/en/simulation/build-an-atom

Science as a human endeavour

A structure for the atom

Thomson's plum pudding model

In 1904, J J Thomson proposed a model for the atom. He'd discovered the electron almost 10 years earlier and suggested that electrons (approximately equal in number to the atomic charge of the nucleus) were embedded in a positively charged jelly-like substance like plums in a pudding.

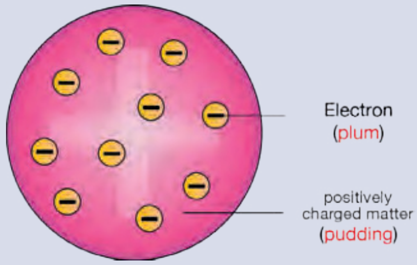


Figure 6.1.2

Science as a human endeavour

Rutherford's alpha particle scattering experiment

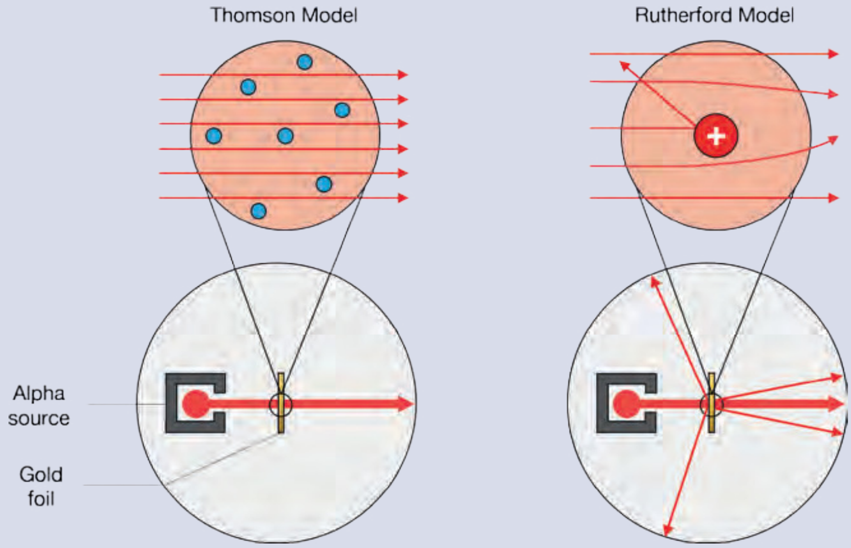


Figure 6.1.2

Ernest Rutherford was a student of J J Thomson. He, like many others, believed that the plum pudding model was a good model. However, in 1907, under Rutherford's guidance, Hans Geiger and one of his students Ernest Marsden performed the 'gold foil' experiment.

Geiger and Marsden fired positively charged alpha particles (or helium nuclei) at very thin gold foil. To do this, alpha particles from a radioactive source (radium) were forced to pass through a hole in a block of lead (alpha particles are blocked by lead). Additional lead plates were used to form a beam.

Any alpha particles that passed through the foil could be detected as a flash of light by a microscope fitted with a zinc sulfide screen. The microscope could rotate so that the number of alpha particles scattered at each angle could be counted over a fixed amount of time. The apparatus was evacuated to ensure that the alpha particles could reach the zinc sulfide screen without being scattered by the air particles.

Most of the alpha particles passed straight through the foil with little or no deflection. The most significant result was that a number of alpha particles were back scattered (approximately 1 in every 10 000). This meant that J J Thomson model for the atom could not be correct. His model would predict that the alpha particles would pass through the gold foil un-deflected.

Rutherford was able to explain the results by suggesting a new model for the atom. The positive charge was concentrated in a tiny sphere at the centre of the atom. The large amount of electrostatic repulsion backscattered the alpha particles as they approached the nucleus. Electrons circled the nucleus and the rest of the atom was empty space. This explained why most of the alpha particles did not deflect through large angles.

Isotopes

Isotopes of an element have the same atomic number but a different mass number.

For instance there are three common isotopes of oxygen: $^{16}_{8}O$ $^{17}_{8}O$ $^{18}_{8}O$

We refer to the isotopes as oxygen-16 (O16), oxygen-17 (O17) and oxygen-18 (O18).

All three isotopes have 8 protons but they have a different number of neutrons.

In a neutral atom, the number of electrons and protons are the same. Isotopes have the same atomic number and therefore the same number of electrons arranged in the same way with in the atom. The chemical properties of an atom are determined by the number of electrons and their arrangement, it therefore follows that isotopes are **chemically identical.** Physical properties such as density and melting and boiling points are determined by the mass number. Since the mass number of isotopes of the same element differ, their **physical properties differ**.

Nuclear force

The electrostatic force between two charges is given by: $F = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$

This repulsive force is very large when the charges are close together. Since the nucleus has a diameter in the order of 10^{-15} m, the electrostatic force of repulsion present is very large.

The nucleus is held together by a strong attractive nuclear force.

The **properties** of the nuclear force are that it is:

- an attractive force (to oppose the Coulomb force)
- very strong (to balance the electrostatic force of repulsion)
- charge independent (the magnitude of the force between two protons, a proton and a neutron or two neutrons is the same)
- a short-range force (only acts over small distances of approximately 10^{-15} m).

The nuclear force decreases very quickly with distance and become close to zero when the nucleons are separated by a distance of about 2.5×10^{-15} m. Figure 6.1.3 shows how the electrostatic and nuclear force acting between two protons varies with distance. At separations greater 2.5×10^{-15} m, the repulsive electrostatic force dominates.

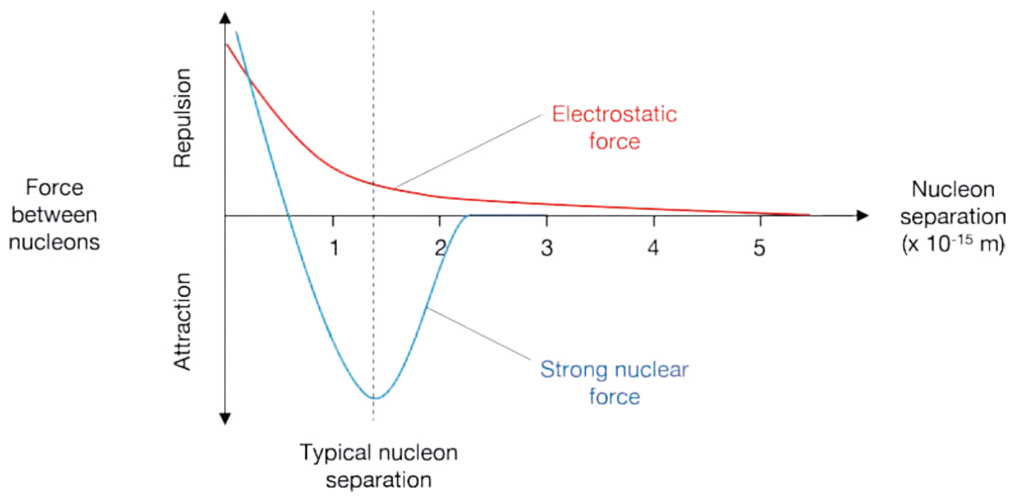


Figure 6.1.3

Larger nuclei contain more protons. The electrostatic force of repulsion is therefore greater. The nucleus becomes unstable because the nuclear force cannot hold the nucleus together against the electrostatic forces of repulsion.

N versus Z graph

Figure 6.1.4 shows the graph that results when neutron number (N) is plotted against proton number (Z). This graph can be used to locate stable and unstable nuclei.

The first twenty or so elements in the periodic table have approximately the same number of protons and neutrons. They are very stable.

As the atomic number increases, the ratio of neutrons to protons increases. Neutrons separate the protons. The strong nuclear force of attraction between nucleons balances the electrostatic force of repulsion.

As the atomic number increases further, the nucleus becomes unstable because the electrostatic force of repulsion increases. For nuclei with atomic number greater than 83 the electrostatic force of repulsion between the protons is too large to be balanced by the strong attractive nuclear force and the nucleus will become unstable. Unstable nuclei decay to become more stable. This process is called radioactive decay and is explored further in subtopic 6.2.

The green curve is referred to as the line of stability. The stable isotopes of elements lie along this line. Unstable nuclei are located above or below this line. Unstable nuclei with too many neutrons lie above this line and unstable nuclei with too many protons lie below this line.

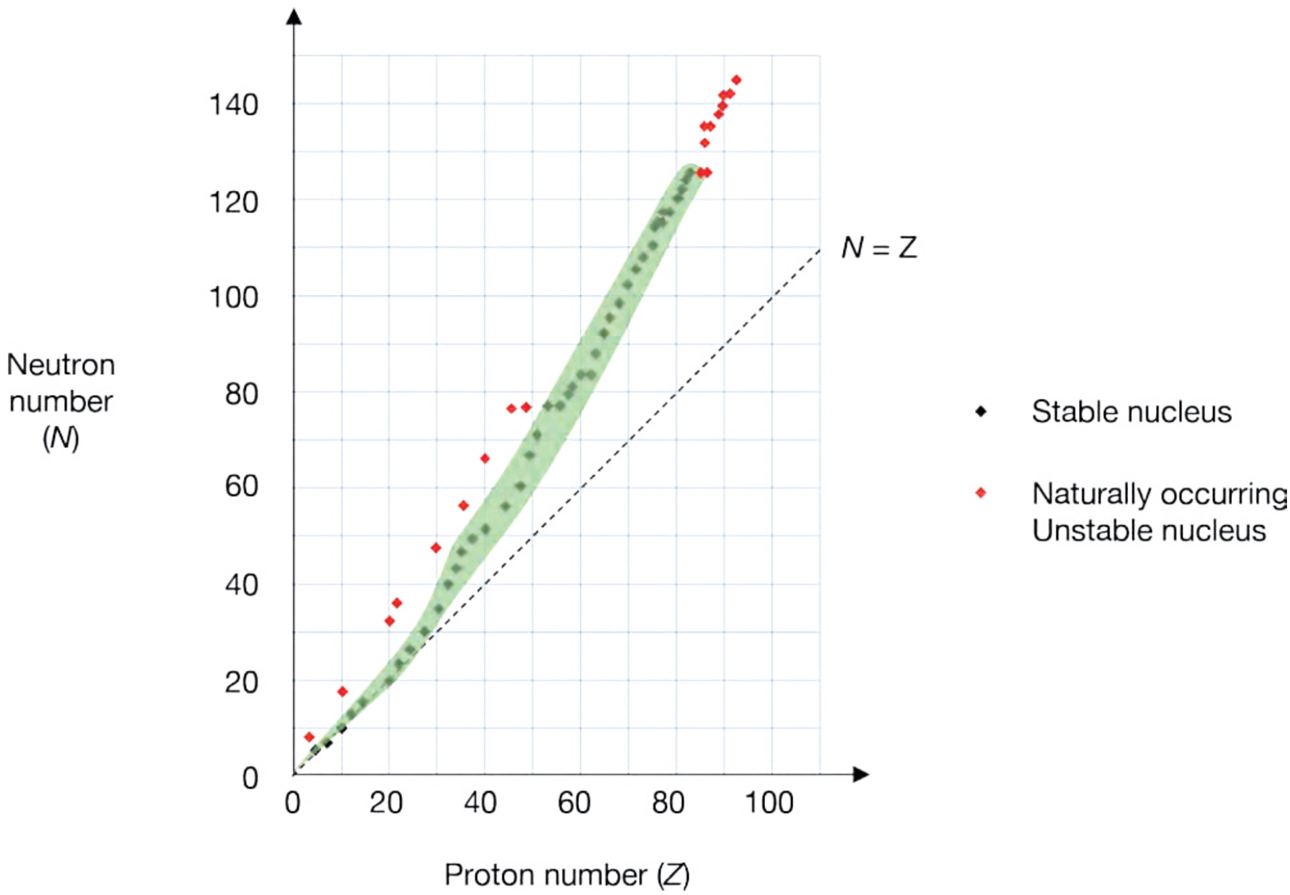


Figure 6.1.4

Science as a human endeavour

Some ideas for student investigations

1. Determine the value of the collaborative work of many scientists in the discovery of the nucleus and modifications made to their models in the light of new information.
2. Research the benefits and limitations of the medical and industrial uses of different isotopes. Discuss monitoring and risk evaluation.
3. Research how the O-18 content of water in ancient ice provides information about climate change and enables scientists to make predictions.

6.2 Radioactive decay

Science understanding

1. Unstable nuclei will undergo radioactive decay in which particles and/or electromagnetic radiation are emitted.
2. In alpha decay, an unstable nucleus emits an alpha particle, ${}^{4}_{2}\alpha$. Alpha decay typically occurs for nuclei with $Z > 83$.
3. The general equation for an alpha decay is given by: ${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$
   - Write equations for the decay of heavy nuclei by alpha decay.
4. In beta minus decay, an unstable nucleus emits an electron (${}^{0}_{-1}e$).
5. Beta minus decay occurs when a nucleus has an excess of neutrons, and involves the decay of a neutron into a proton, electron, and antineutrino. This is shown by the equation: ${}^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$
6. The general equation for beta minus decay of an unstable nucleus is shown by the equation: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}_e$
7. In beta plus decay, an unstable nucleus emits a positron (${}^{0}_{+1}e$).
8. Beta plus decay occurs when a nucleus has an excess of protons, and involves the decay of a proton into a neutron, positron, and neutrino. This is shown by the equation: ${}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{0}_{+1}e + {}^{0}_{0}\nu_e$.
9. The general equation for beta plus decay of an unstable nucleus is given by: ${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + {}^{0}_{0}\nu_e$
   - Describe the structure of unstable nuclei that causes each type of beta decay.
   - Write the equations for the decay of nuclei by beta minus and beta plus decay.
   - Use the conservation of charge to explain the emission of an electron in the decay of a neutron into a proton.
   - Use the conservation of charge to explain the emission of a positron in the decay of a proton into a neutron.
10. In gamma decay, an unstable nucleus emits high-energy gamma rays (γ).
11. Gamma decay occurs when a nucleus is left with excess energy after an alpha or beta decay.
12. The general equation for a gamma decay is given by: ${}^{A}_{Z}X^{*} \rightarrow {}^{A}_{Z}X + n\gamma$ where n is the number of high-energy gamma rays emitted.
    - Write equations for the decay of unstable nuclei involving the emission of gamma rays.
13. The type of decay an unstable nucleus will undergo can be predicted based on the number of protons and neutrons within the nucleus.
    - Use the atomic and mass numbers to predict the type of decay for an unstable nucleus.
    - Use the location on an *N versus Z* graph to predict the type of decay for an unstable nucleus.
14. The particles emitted in radioactive decay have sufficient energy to ionise atoms.
15. The properties of the particles and/or radiation emitted in the different types of radioactive decay result in different penetration of matter.
    - Describe the effects of ionising radiation on living matter.
    - Describe methods of minimising exposure to ionising radiation.
    - Compare and contrast the ionising ability and penetration through matter of alpha, beta, and gamma radiations.

Radioactive decay

When a nucleus is unstable, it will undergo radioactive decay to become more stable. In doing so, the nucleus will emit energy in the form of particles and/or electromagnetic radiation. The structure of unstable nuclei will determine whether alpha, beta and/or gamma decay will occur.

Unstable nuclei will undergo radioactive decay in which particles and/or electromagnetic radiation are emitted.

Alpha decay

Alpha decay typically occurs in large unstable nuclei with an atomic number greater than 83. The nucleus decays by emitting an alpha particle or helium nucleus ($^{4}_{2}He$ or $^{4}_{2}\alpha$).

The general equation for an alpha decay is given by:

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

The **atomic number or charge is conserved** during a nuclear reaction.

The total charge on the left-hand side of the equation is Z, and must be conserved. It follows that the atomic number of the nucleus that results during an alpha decay has decreased by two (Z–2). That is, the nucleus that results has two fewer protons to account for the two protons in the alpha decay (helium nucleus). Mass number (A) is also conserved. The mass number of the nucleus that results has decreased by four (A–4).

The unstable nucleus before the decay has occurred is often referred to as the parent nucleus and the nucleus that results after the decay has occurred is referred to as the daughter nucleus.

Worked examples

1. Complete the equation for the decay of uranium-238 to thorium-234.

   $^{238}_{92}U \longrightarrow {}^{234}_{90}Th + \ldots$

   $^{238}_{92}U \longrightarrow {}^{234}_{90}Th + {}^{4}_{2}\alpha$

2. Americium ($^{241}_{95}Am$) undergoes alpha decay to form neptunium (Np).

   Write an equation for this decay.

   $^{241}_{95}Am \longrightarrow {}^{237}_{93}Np + {}^{4}_{2}\alpha$

Beta minus decay

Beta minus decay occurs when a nucleus has an excess of neutrons, and involves the decay of a neutron into a proton with the emission of an electron or beta minus particle ($^{0}_{-1}e$) and an electron antineutrino ($^{0}_{0}\overline{\nu}$).

The equation for the decay of a neutron into a proton is: $^{1}_{0}n \rightarrow {}^{1}_{1}p + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$

Atomic number or charge is conserved during the decay.

The electric charge of a neutron is zero. The total charge on the left-hand side of the equation is therefore zero. The atomic number of the proton on the right-hand side of the equation is one. It follows that the emission of an electron in the decay of a neutron into a proton balances the charge on both sides of the equation. The emission of the electron antineutrino enables energy and momentum to be conserved during the decay. The explanation of this is not part of this course.

The general equation for beta minus decay of an unstable nucleus is given by: $^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + {}^{0}_{0}\overline{\nu}_e$

6

Worked examples

1. Complete the equation for the beta minus decay of carbon-14 to nitrogen-14.

$^{14}_{6}C \longrightarrow ^{14}_{7}N + \ldots + \ldots$

$^{14}_{6}C \longrightarrow ^{14}_{7}N + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}_e$

2. Strontium ($^{90}_{38}Sr$) undergoes beta minus decay to form yttrium (Y).

Write an equation for this decay.

$^{90}_{38}Sr \longrightarrow ^{90}_{39}Y + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}_e$

Beta plus decay

Beta plus decay occurs when a nucleus has an excess of protons, and involves the decay of a proton into a neutron with the emission of a positron or beta plus particle ($^{0}_{+1}e$) and an electron neutrino ($^{0}_{0}\nu$).

The equation for the conversion of a proton into a neutron is: $^{1}_{1}p \rightarrow ^{1}_{0}n + ^{0}_{+1}e + ^{0}_{0}\nu_e$

Atomic number or charge is conserved during the decay.

The electric charge of a proton is one. The total charge on the left-hand side of the equation is therefore one. The atomic number of the neutron on the right-hand side of the equation is zero. It follows that the emission of a positron in the decay of a proton into a neutron balances the charge on both sides of the equation. The emission of the electron neutrino enables energy and momentum to be conserved during the decay.

The general equation for beta plus decay of an unstable nucleus is shown by the equation: $^{A}_{Z}X \longrightarrow ^{A}_{Z-1}Y + ^{0}_{+1}e + ^{0}_{0}\nu_e$

Worked examples

1. Complete the equation for the beta plus decay of manganese-50 to chromium-50.

$^{50}_{25}Mn \longrightarrow ^{50}_{24}Cr + \ldots + \ldots$

$^{50}_{25}Mn \longrightarrow ^{50}_{24}Cr + ^{0}_{+1}e + ^{0}_{0}\nu_e$

2. Nitrogen-12 ($^{12}_{7}N$) undergoes beta plus decay to form carbon (C).

Write an equation for this decay.

$^{12}_{7}N \longrightarrow ^{12}_{6}C + ^{0}_{+1}e + ^{0}_{0}\nu_e$

Activity

Your teacher may use a cloud chamber to detect alpha and beta decay.

Gamma decay

Gamma decay occurs when a nucleus is left with excess energy after an alpha or beta decay. The unstable nucleus emits high-energy gamma rays.

The general equation for a gamma decay is given by: $^{A}_{Z}X^{*} \rightarrow ^{A}_{Z}X + n\gamma$ where n is the number of high-energy gamma rays emitted.

Gamma rays are a form of electromagnetic radiation. They do not have a charge or a mass and travel at the speed of light (3.00×10^{8} ms^{-1}).

Worked example

When nitrogen-12 ($^{12}_{7}N$) undergoes beta plus decay to form carbon-12 ($^{12}_{6}C$), the daughter nucleus (carbon) is left in an excited state. That is, it is left with excess energy and is unstable. Carbon-12 undergoes gamma decay to become more stable.

Write an equation for this decay.

$^{12}_{6}C^{*} \longrightarrow ^{12}_{6}C + \gamma$

Science as a human endeavour

The emission of the neutrinos in beta decay

The law of conservation of momentum was used to predict the presence of the neutrino and the anti-neutrino in beta plus and beta minus decay respectively.

Originally when beta minus decay occurred, it was just the proton and electron that were detected. When beta decay was analysed it was noted that beta particles were ejected with a range of momenta and kinetic energies. In 1930, Wolfgang Pauli noticed that momentum was not conserved in beta minus decay unless the electron was emitted with maximum kinetic energy and momentum. He proposed that another particle was ejected with the electron to conserve momentum. Beta plus produced a similar result with momentum not being conserved.

In1933, this unknown particle was named the neutrino by Enrico Fermi. It was difficult to detect because it did not have charge or a rest mass and travelled at the speed of light. The neutrino is emitted during beta plus decay and the anti-neutrino during beta minus decay. The first existence of the neutrino was reported in 1956 by Fredrick Reines and Clyde Cowan.

N versus Z graph

The type of decay that an unstable nucleus will undergo can be predicted based on the number of protons and neutrons within the nucleus.

Earlier in the chapter we discussed that nuclei with atomic numbers less than 20 have approximately equal numbers of protons and neutrons and are stable.

Nuclei with excess neutrons undergo beta minus decay and lie above the line of stability as shown on the N versus Z graph in figure 6.2.1. Nuclei with excess protons undergo beta plus decay and lie below the line of stability as shown on the N versus Z graph in figure 6.2.1. Nuclei with atomic numbers greater than 83 undergo alpha decay.

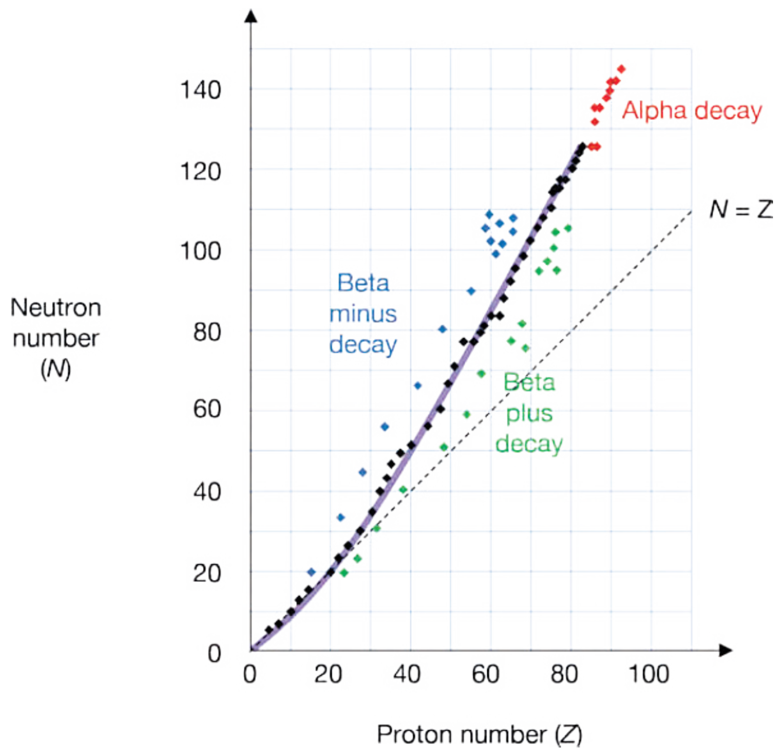


Figure 6.2.1

Effect of ionising radiation on living matter

The particles emitted in radioactive decay have sufficient energy to ionise atoms. This means that they can remove electrons from the atom.

The energy possessed by ionising radiation can break chemical bonds in living matter, and this can kill the cells. It can also change genetic material in cells (cause DNA mutations) that are passed on to subsequent cell divisions. This may ultimately result in the formation of a cancerous tumour.

Minimising exposure to ionising radiation

Exposure to ionising radiation can be minimised by:

1. Increasing the distance from the ionising source – ionising radiation becomes less intense as the distance from the source increases.
2. Limiting exposure time – e.g. breaks in work schedules for miners and other workers exposed to ionising radiation.
3. Shielding – the penetration of radiation is reduced if it is passed through lead, concrete or water. Workers exposed to ionising radiation are often asked to use lead-lined gloves and aprons, and rooms are often lined with lead or made out of thick concrete. Radioactive materials are often stored in lead-lined containers.

Penetration

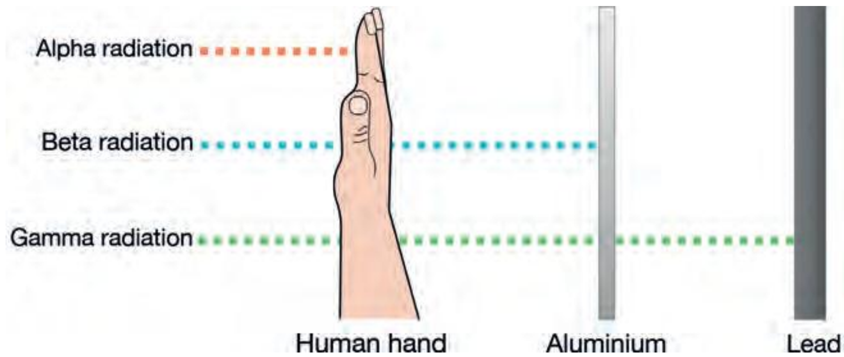


Figure 6.2.2

Alpha particles have a high ionising ability because they carry a double positive charge. This means that they can easily remove electrons from atoms when they pass through matter. However this means that they lose kinetic energy very quickly and their penetration power is low. Alpha decay is easily stopped by thin sheets of cardboard and does not penetrate human flesh deeply.

Beta decay has a single charge so it does not ionise matter as easily as alpha decay. However, beta decay has a higher penetrating power than alpha decay. Beta decay is stopped by thin sheets of metal foil.

Gamma decay is not charged, which means that its ionising ability is very low. However, it has a high penetrating power. Gamma decay can easily penetrate human flesh and thin metal foils. Gamma decay is stopped by several centimetres of lead or thick concrete.

Helpful online resources

1. Use the Australian Government ARPANSA website:
   www.arpansa.gov.au/radiationpro tection/basics/radioactivity.cfm
2. Simulate alpha decay:
   phet.colorado.edu/en/simulation/alpha-decay
3. Simulate beta decay:
   phet.colorado.edu/en/simulation/beta-decay

Science as a human endeavour

Some ideas for student investigations:

1. Explore examples of the collaborative work that has led to the discovery of radioactive elements and discuss the subsequent development of a range of applications.
2. Explore the benefits and unexpected consequences of using alpha decay in, for example, quantum tunnelling (in a scanning tunnelling microscope) or in smoke alarms.
3. Evaluate the benefits and risks of the use of beta decay in industry and medicine.
4. Explore industrial, scientific and medical uses of gamma emitters such as Tc-99 and assess the risks and their management.
5. Discuss the protection for workers handling radioactive materials.

6.3 Radioactive half-life

Science understanding

1. The number of radioactive nuclei in a sample of a given isotope decreases exponentially with time.
2. Half-life is the time required for half of the radioactive nuclei in a sample to decay.
3. The half-life of radioactive nuclei is independent of both the physical state and the chemical state of the material.
4. The activity of a radioactive substance is the number of radioactive nuclei that decay per unit time.
   - Relate the activity of a sample to the number of radioactive nuclei present, and hence explain how it decreases exponentially with time.
   - Use data to estimate the half-life of radioactive nuclei.
   - Use data to estimate the activity or number of radioactive nuclei of a sample at different times.
   - Estimate the age of a sample based on the relative activity or the relative amounts of radioactive nuclei or their decay products.
5. The range of products of nuclear decay and their long half-lives mean that nuclear waste must be stored for long periods
   - Explain the requirements for the safe storage of nuclear waste.

Half-life

The number of radioactive nuclei in a sample of a given isotope decreases exponentially with time. Figure 6.3.1 shows how the number of radioactive nuclei decreases with time.

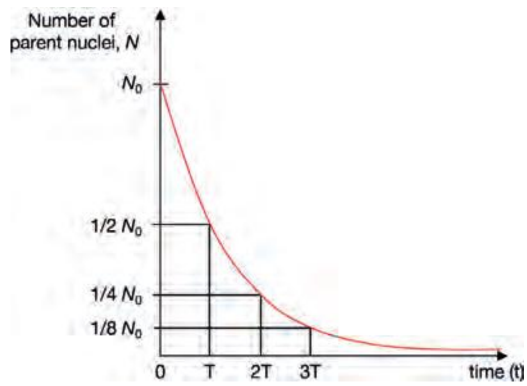


Figure 6.3.1

The time taken for half of the original number of nuclei to decay is called the **half-life**.

The half-life of a radioactive sample does not depend on the initial number of nuclei or mass nor the temperature. Radioactivity is a **random process**. There is no way of telling when an individual nucleus will decay but the average number of radioactive nuclei will halve in one half-life. This means that the **half-life of radioactive nuclei is independent of both the physical state and the chemical state of the material**.

6

Activity

The activity of a radioactive sample is the number of radioactive nuclei that decay per unit time.

Activity is measured in Becquerel (*Bq*) and 1 *Bq* is equivalent to one decay per second.

The activity is proportional to the number of radioactive nuclei present and will also decreases exponentially with time.

The half-life for the activity is the same as the half-life of the radioactive nucleus.

Worked examples

1. The number of nuclei in a radioactive sample decreases from 6.0 million to 1.5 million in exactly 28 minutes.

   Determine the half-life of the radioactive sample.

   2 half-lives have passed in 28 minutes. The half-life is therefore 14 minutes.

2. The mass of a radioactive sample has decreased to $\frac{1}{8}$ of its original mass in 12 days.

   (a) Determine the half-life of the radioactive sample.

   Three half-lives have passed for the mass to reduce to one eighth.

   Three half-lives in 12 days means that the half-life is 4 days.

   (b) Determine the fraction of radioactive nuclei that have decayed after 8 days.

   8 days corresponds to 2 half-lives.

   $\frac{1}{4}$ of the nuclei remain. This means that $\frac{3}{4}$ have decayed.

3. (a) The activity of a radioactive isotope is 80 Bq. Calculate the number of decays that occur at this rate in one minute.

   $80 \times 60 = 4800$

   (b) If the half-life of the sample is 1 day, determine its activity after 4 days.

   Four half-lives have passed after 4.0 days.

   This means that the activity is reduced to $\frac{1}{16}$.

   Activity $= \frac{80}{16} = 5\ Bq$

Carbon dating

Carbon-14 is created in the upper atmosphere when neutrons collide with nitrogen atoms. Carbon-14 undergoes beta minus decay to form nitrogen-14.

$$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$$

All living things take in carbon from the air. Once the living organism dies, the level of carbon-14 decreases as it decays but the level of the stable isotope carbon-12 does not change. By examining the fraction of carbon-14 remaining in an organism and using its half-life of 5730 years, the age of a sample can be determined. The age is calculated by multiplying the number of half-lives that have passed by 5730.

For example if the level of carbon-14 in a sample is $\frac{1}{8}$th that of a living organism then 3 half-lives have passed. The age of the organism is *3 × 5730 = 17 190 years.*

Uranium-lead dating

Older formations such as rocks and meteorites can be dated using Uranium-lead dating. Uranium-238 decays to lead-206 in a series of steps. This is shown in Figure 6.3.2. Each step of the decay process has its own half-life. The first step from uranium-238 to thorium-234 is by far the longest (a half-life of 4.5×10^9 years). It can be considered the half-life of the whole decay series.

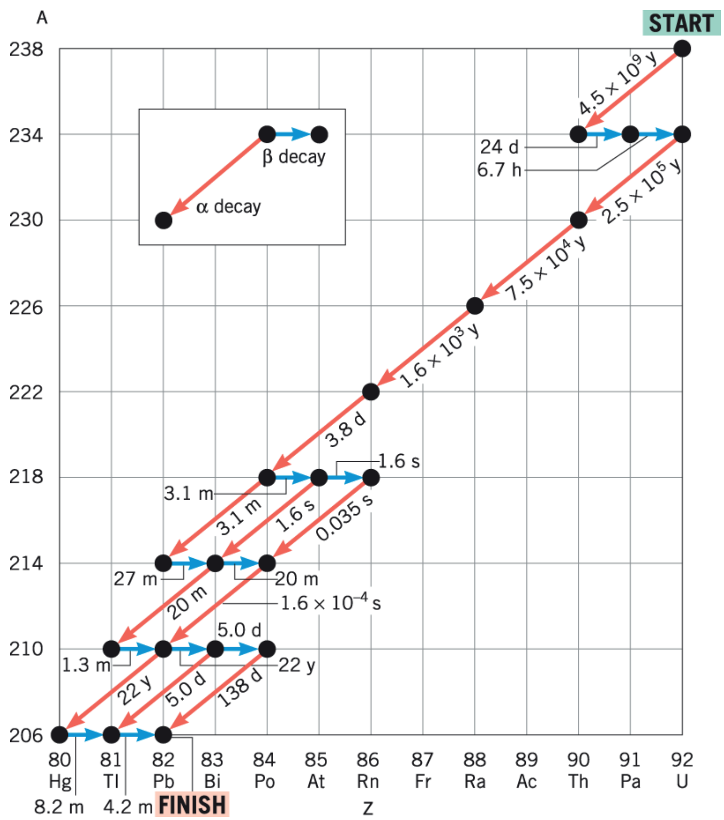


Figure 6.3.2

It is assumed that the original number of lead-206 atoms in a sample is zero. With time, the number of lead-206 atoms increases and the number of uranium-238 atoms decreases. The ratio of uranium to lead atoms can be used to determine the number of half-lives that have passed. For instance, a sample that is 4.5×10^9 years old will have an equal number of uranium-238 and lead-206 atoms. The ratio of uranium-238 has halved. A sample twice as old, that is 9.0×10^9 years old, will have three lead-206 atoms for every uranium-238 atom. That is, the ratio of uranium-238 has quartered and two half-lives have passed. The age of the sample is calculated by multiplying the number of half-lives by 4.5×10^9 years.

In a similar way to uranium-238, uranium-235 decays to lead 207 in a series of steps. The same principles can be used to date samples containing this isotope. The difference is that the half-life used for this decay series is 7.0×10^8 years.

Storing radioactive waste

The range of products of nuclear decay, some with long half-lives mean that nuclear waste must be stored for long periods. Short-lived radioactive waste (e.g. medical waste) is often stored on site in lead-lined containers. Some low-level and medium-level radioactive waste is buried in shallow pits beneath the Earth's surface. High-level waste created from the generation of electricity is generally stored in steel-lined concrete pools filled with water, in steel and concrete airtight containers (see figure 6.3.3) or buried deep below the Earth's surface (figure 6.3.4).

6

Figure 6.3.3

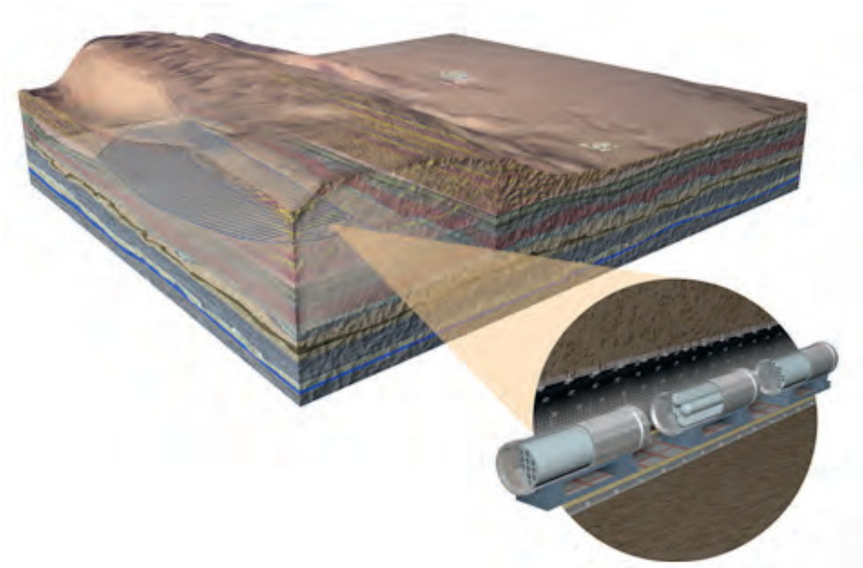


Figure 6.3.4

Helpful online resources

1. Investigate radioactive dating using:
   phet.colorado.edu/en/simulation/radioactive-dating-game

2. Investigate radiocarbon dating using:
   www.pbs.org/wgbh/nova/tech/radiocarbon-dating.html

Science inquiry practical

Some ideas for student investigations

1. Use the Geiger counter to detect radioactive emissions from different radioactive sources and plot a decay graph. Determine the half-life from the decay graph.
2. Simulate radioactive decay using dice.

Science as a human endeavour

Some ideas for student investigations:

1. Explore the benefits and limitations of radioactive dating, including:
   - carbon dating to determine age of various artefacts and remains.
   - uranium-to-lead ratio to determine age of rocks, comets.
2. Research the issues associated with storing radioactive waste generated by the nuclear power and medical industries.

6.4 Induced nuclear reactions

Science understanding

1. Nuclear fission can be induced in some heavy nuclei by the capture of a neutron.
2. The nucleus splits into two nuclei and several neutrons.
3. The total mass of the reactants in a fission reaction is greater than that of the products, releasing energy given by $E = \Delta mc^2$, where Δm is the mass of the reactants minus the mass of the products.
   - Calculate the energy released per fission reaction, given the relevant masses (in kg).
4. On average, more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will induce further fissions, resulting in a chain reaction.
   - Relate the starting, normal operation, and stopping of a nuclear reactor to the nature of the chain reaction.
5. The neutrons emitted as a result of nuclear fission have high speeds.
6. ^{235}U undergoes fission with slow neutrons. Hence to induce fission in these nuclei the neutrons must be slowed down.
7. Many neutrons are absorbed by surrounding nuclei, or escape and cause no further fissions.
   - Explain why neutrons have to be slowed down in order to produce fission in ^{235}U.
8. Enrichment increases the proportion of ^{235}U in uranium fuel
   - Describe how enrichment enables a chain reaction to proceed.
   - Use a diagram of a reactor to locate and discuss the function of the principal components of a water-moderated fission power reactor.
9. Energy released during nuclear fission reactions can be harnessed for use in power generation.
   - Explain the use of nuclear fission in power production.
   - Describe some of the risks associated with the use of nuclear energy for power production.
10. Nuclear fusion is the process in which two nuclei combine into a single nucleus.
    - Explain why high temperatures are needed for nuclear fusion to occur.
11. The energy absorbed or released is given by $E = \Delta mc^2$, where Δm is the difference in mass between the reactants and the products.
    - Calculate the energy released per fusion reaction, given the relevant masses (in kg).

Nuclear fission

Nuclear fission is the splitting of a heavy unstable nucleus into smaller more stable fragments.

Spontaneous fission occurs in extremely unstable nuclei (Z>83). However, nuclear fission can be induced in some heavy nuclei by the capture of a low-energy neutron. The nucleus splits into two nuclei and several neutrons. Gamma decay is also released during fission. Fission releases a large amount of energy.

Example

The products of fission are not unique. The nuclei that result and the number of neutrons released can vary. The equation below represents one possible fission reaction.

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \gamma$$

Why does fission occur?

When a neutron comes to within 10^{-15} m of the uranium nucleus, it is absorbed due to the short-range nuclear attractive force. The nucleus becomes elongated and vibrates. The short-range nuclear-attractive force can no longer overcome the long-range electrostatic-repulsive force between the protons in the nucleus. The nucleus becomes unstable and splits. This process is illustrated in figure 6.4.1.

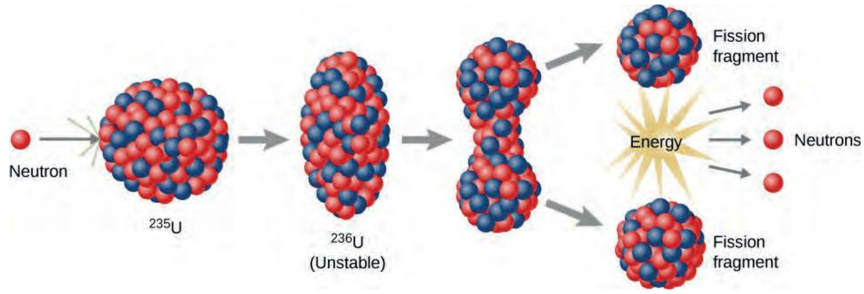


Figure 6.4.1

Explanation of the energy released

The total mass of the reactants in a fission reaction is greater than that of the products. The difference in mass is converted into energy and released. The amount of energy released is given by $E = \Delta mc^2$, where Δm is the mass of the reactants minus the mass of the products.

The energy that is released is in the form of the kinetic energy of the products and the energy of the gamma ray photons.

Worked example

1. Calculate the energy released when $^{235}_{92}U$ undergoes induced fission with a neutron to form $^{141}_{56}Ba$ and $^{92}_{36}Kr$.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \gamma$$

$m\,^{235}_{92}U = 3.9017 \times 10^{-25}\ kg \quad m\,^{141}_{56}Ba = 2.28922 \times 10^{-25}\ kg \quad m\,^{92}_{36}Kr = 1.57534 \times 10^{-25}\ kg$

Mass of products:

$m_{Ba} + m_{Kr} + 3m_{neutrons} = 2.28922 \times 10^{-25} + 1.57534 \times 10^{-25} + 3 \times 1.675 \times 10^{-27} = 3.915 \times 10^{-25}$ kg

Mass of reactants:

$m_U + m_{neutron} = 3.90170 \times 10^{-25} + 1.675 \times 10^{-27} = 3.918 \times 10^{-25}$ kg

$\Delta m = m_{reactants} - m_{products} = 3.918 \times 10^{-25} - 3.915 \times 10^{-25} = 3.000 \times 10^{-28}$ kg

$E = \Delta mc^2 = 3.000 \times 10^{-28} \times (3 \times 10^8)^2 = 2.700 \times 10^{-11}$ J

Chain reaction

On average, more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will be absorbed by other uranium nuclei that will undergo induced fission. The result is a chain reaction.

Figure 6.4.2 shows three neutrons released during a fission reaction colliding with three other U-235 nuclei in a chain reaction.

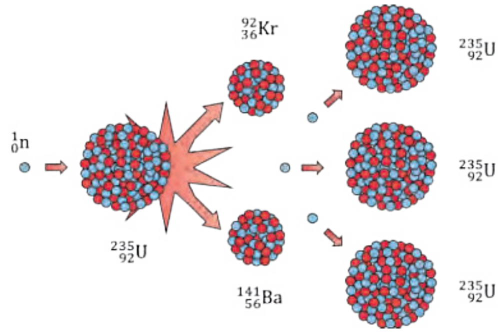


Figure 6.4.2

Helpful online resource

Demonstrate the chain reaction using a simulation.

www.phet.colorado.edu/en/simulation/nuclear-fission

Moderators

The neutrons emitted as a result of nuclear fission have high speeds, corresponding to a kinetic energy of between 1 and 2 MeV. Fast-moving neutrons tend to collide and bounce from the nucleus whereas slow-moving neutrons can move close to the nucleus (within 10^{-15}m) giving the strong nuclear attractive force a greater chance to act so that the neutron can be absorbed.

Neutrons are slowed down as a result of collisions with a moderator.

A moderator such as graphite or heavy water has particles of a similar size to neutrons (i.e. they have a low mass). When neutrons collide with the atoms of a moderator, the neutrons lose a significant amount of kinetic energy. Within a few collisions, they have slowed down to a speed that allows them to be captured by a uranium nucleus.

Many neutrons are absorbed by surrounding nuclei, or escape and cause no further fissions. The moderator does not readily absorb neutrons; this helps ensure that there are enough neutrons for a chain reaction to occur.

Enrichment

Enrichment increases the proportion of U-235 in uranium fuel.

The isotope U-238 does not readily undergo induced fission. The isotope U-235 does, but it constitutes less than one per cent of all uranium reserves. Enrichment increases the fraction of U-235 in a sample and ensures that there are enough uranium nuclei to undergo induced fission so that a chain reaction can take place.

Nuclear reactors

Figure 6.4.3 shows a typical water-moderated fission reactor used to generate electricity for domestic and commercial use.

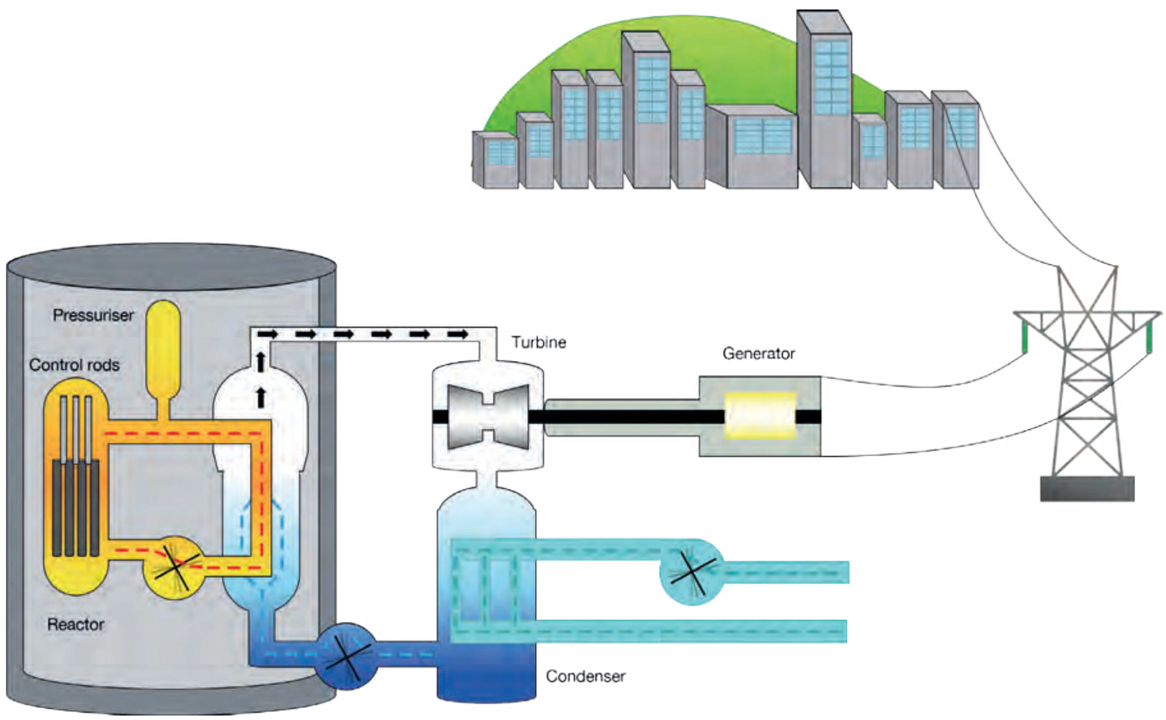


Figure 6.4.3

The components of a water-moderated fission reactor

Component	Description
Core or reactor vessel	The vessel in which the fission chain reaction occurs.
Fuel rods	Long, thin metal rods filled with uranium oxide.
Moderator	Slows neutrons down so that they are more likely to be captured. Water is held under high pressure. This enables the liquid in the core (primary coolant) to reach temperatures of around 320ºC without boiling.
Heat exchanger	Hot liquid from the core (primary coolant) enters the heat exchanger and transfers heat energy to a separate supply of unpressurised water (secondary coolant) heating it to boiling point and producing steam. The cooled primary coolant returns to the core after being condensed and is heated again while the steam turns the blades of a turbine which in turn rotates the generator to produce electricity.
Control rods	Long thin tubes filled with neutron-absorbing elements such as boron, silver or cadmium. The rods are lowered and raised from within the core. This is done to control the number of neutrons involved in the chain reaction.
Safety rods	Safety rods absorb a large amount of neutrons quickly. If they are dropped into the core the reaction can be stopped very quickly. The safety rods are in addition to the control rods and are not shown in figure 6.4.3.
Shielding	The reactor is built with shielding around it. The shielding usually consists of a thick concrete structure but may also be made from lead or steel to contain the high level of radioactivity present.

Helpful online resource

Use a nuclear power plant simulator to gain an understanding of how the fission process is controlled.

https://esa21.kennesaw.edu/activities/nukeenergy/nuke.htm

Operating a reactor

Energy released during nuclear fission reactions can be harnessed for use in power generation.

The principal components of a water-moderated fission power reactor enable the energy released to be harnessed to produce electricity. As indicated in the table describing each component, the fission reactions occur in the core or reactor vessel. These reactions heat water held under high pressure (primary coolant). The heated primary coolant moves through the heat exchange and transfers heat to a separate supply of unpressurised water (secondary coolant). The secondary coolant is heated and boils to produce steam. The steam turns the blades of a turbine which in turn rotate the generator to produce electricity.

The starting, normal operation and stopping of a nuclear reactor

To start the reactor, a start-up neutron source is used. A start-up neutron source is any source that emits neutrons. Radioisotopes that undergo spontaneous fission are commonly used as a start-up neutron source. They are placed in evenly spaced positions within the reactor vessel. During start-up, the control rods are raised out of the core to promote fission reactions.

Once a fission reactor approaches its steady-state operation, the control rods are lowered into the core to control the number of neutrons. A nuclear reactor can maintain a constant power output if on average only one neutron from each fission reaction goes on to cause a further fission reaction.

When the power output of the reactor needs to be increased the control rods are raised out of the core. The average number of neutrons from each fission that go on to cause further induced fission will increase. As the power output increases, the control rods are lowered. Neutrons are absorbed so that on average only one neutron from each fission reaction goes on to cause further fission reactions. As the fuel becomes depleted, control rods are gradually raised. When the power output needs to be decreased, control rods are reinserted so that the average number of neutrons that can go on to cause further fission reactions falls below one. This slows the chain reaction.

When the reactor needs to be stopped (e.g. to empty the core and insert new fuel rods or in the case of an emergency), the control rods and safety rods are used to quickly absorb neutrons and stop the fission reactions.

Advantages and risks associated with the use of nuclear energy

Fission reactors have the major advantage in that they provide a large amount of energy and do not produce greenhouse gases like fossil-fuel power stations. Unfortunately there are risks associated with the use of nuclear energy for power supply. These include the risks associated with

- transporting and storing the high-level radioactive waste products.
- maintaining a controlled chain reaction.
- the reactor sites becoming and remaining radioactive for many years.
- accidents (e.g. Chernobyl, Ukraine, and Fukushima, Japan)

Science as a human endeavour

Ideas for student research

1. Assess the economic, social and environmental impacts of the Manhattan Project.
2. Investigate the way in which science informs public debate and is in turn influenced by public debate over the use of nuclear weapons.
3. Analyse the economic and social benefits and the consequences of enrichment of isotopes of uranium from the ore.
4. Explore the innovations which use neutron beams from nuclear reactors to produce radioisotopes for use in medicine and industry.
5. Explore the beneficial or unexpected consequences of nuclear power and assess its monitoring, assessment, and risk.
6. Explore public debate about nuclear power. Discuss some of the advantages and disadvantages of nuclear fission over fossil-fuel power stations.

Nuclear fusion

Nuclear fusion is the process in which two nuclei combine into a single nucleus.

Example

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{4}_{2}He$$

Fusion requires the colliding nuclei to possess a large amount of kinetic energy in order to overcome the large electrostatic repulsive forces between the positive nuclei. It follows that high temperatures (close to those found in the Sun) are needed for nuclear fusion to occur. Sustainable fusion reactions have not yet been achieved on Earth.

6

Explanation of the energy released

Just as with fission, the total mass of the reactants in a fusion reaction is greater than that of the products. The difference in mass is converted into energy and released. The amount of energy released is given by $E = \Delta mc^2$, where Δm is the mass of the reactants minus the mass of the products. This energy is released in the form of the kinetic energy of the products.

The Sun and other stars

Fusion is the main energy conversion process in the Sun and other stars. The Sun contains a high proportion of hydrogen at high density. Through a series of steps, hydrogen (including its isotopes) undergo fusion and are converted to helium. Each step releases a large amount of energy.

The high density and pressure in the Sun enable the high rate of particle collisions needed to maintain the Sun's temperature (about 20 million degrees Celsius). This high temperature gives the nuclei the kinetic energy they need to overcome the large electrostatic repulsive forces between the positive nuclei so that they can fuse.

A reaction pathway thought to occur in the Sun is given below:

$$ {}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{1}H + {}^{0}_{1}e + {}^{0}_{0}\nu $$

$$ {}^{1}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He $$

$$ {}^{3}_{2}He + {}^{3}_{2}He \rightarrow {}^{4}_{2}He + {}^{1}_{1}H + {}^{1}_{1}H $$

The two protons produced at the end of the series can start the reaction pathway again.

Science as a human endeavour

Ideas for student research

1. Compare the availability of fuel for fission and fusion reactions.
2. Examine the reasons it is not currently possible to use fusion for electricity generation.
3. Compare the processes needed to safely control fission and fusion reactions.
4. Research attempts by scientists to produce sustainable fusion and predict possible outcomes.
5. Research the birth and life cycle of stars and the detection of gravitational waves created by colliding black holes and assess the available evidence.
6. Identify the conditions in the interiors of the Sun and other stars that allow nuclear fusion to take place, and hence how nuclear fusion is their main energy conversion process. Envisage the ways this may be harnessed.
7. Discuss the advantages and disadvantages of nuclear fusion over nuclear fission as a future source of power.

Exercises

6.1 The nucleus

1. Define the following terms:
   (a) atomic number

   (b) mass number

   (c) nucleon

2. Complete the following table.

Nucleus	Protons	Neutrons	Nucleons
${}^{23}_{11}Na$			
${}^{222}_{86}Rn$			
${}^{137}_{56}Ba$			

3. (a) Describe J J Thomson's 'plumb pudding' model for the atom.

   (b) For Rutherford's 'gold foil' experiment, describe the
      (i) procedure

      (ii) results

      (iii) new model for the atom that resulted.

4. (a) Define the term 'isotope of an element'.

(b) Carbon has three main isotopes. They are listed below.

$^{12}_{6}C$ $^{13}_{6}C$ $^{14}_{6}C$

(i) Describe how each isotope differs from the others.

(ii) Explain why the three isotopes of carbon are chemically identical.

5. (a) Explain how the nucleus is held together despite there being a large amount of electrostatic repulsion between the protons in the nucleus.

(b) Describe how neutrons in the nucleus help stabilise the nucleus.

6.2 Radioactive decay

1. Describe the structure of nuclei that undergo each type of decay.

(a) alpha decay

(b) beta minus decay

(c) beta plus decay

(d) gamma decay

2. Determine the value of the unknown mass and atomic numbers in each of the following nuclear decays.

(a) ${}^{A}_{Z}Ra \rightarrow {}^{222}_{86}Rn + \alpha$ A = ... Z = ...

(b) ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{A}_{Z}Q$ A = ... Z = ...

(c) ${}^{137}_{56}Ba^{*} \longrightarrow {}^{A}_{Z}Ba + \gamma$ A = ... Z = ...

(d) ${}^{A}_{Z}Mg \longrightarrow {}^{23}_{11}Na + {}^{0}_{+1}e + {}^{0}_{0}\nu$ A = ... Z = ...

(e) ${}^{A}_{99}Ac \rightarrow {}^{221}_{Z}Fr + \alpha$ A = ... Z = ...

(f) ${}^{152}_{Z}Dy^{*} \longrightarrow {}^{A}_{66}Dy + \gamma$ A = ... Z = ...

(g) ${}^{231}_{91}Pa \rightarrow {}^{A}_{Z}Ac + \alpha$ A = ... Z = ...

(h) ${}^{11}_{Z}C \longrightarrow {}^{A}_{5}B + {}^{0}_{+1}e + {}^{0}_{0}\nu$ A = ... Z = ...

3. Write the equation for the following decays.

(a) ${}^{61}_{30}Zn$ decaying to *Cu* by beta minus decay.

. . ..

(b) ${}^{144}_{60}Nd$ decaying to *Ce* by alpha decay.

. . ..

(c) ${}^{40}_{18}Ar$ undergoing gamma decay.

. . ..

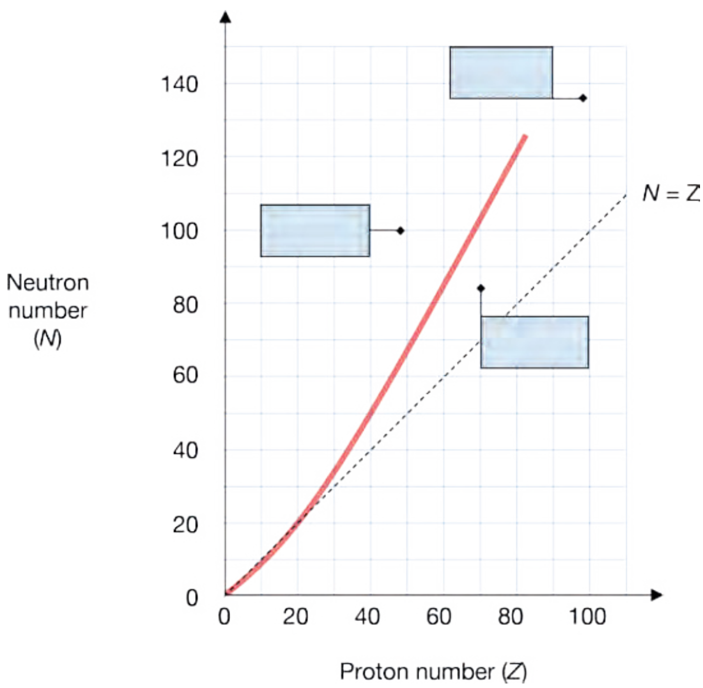
4. U^{234}_{92} undergoes four alpha decays and one beta minus decay. Determine the atomic and mass number of the resulting nucleus.

. . ..

. . ..

. . ..

5. Label the regions of the N versus Z graph shown below by filling in the boxes with the most likely type of decay.



6. Describe the effect that ionising radiation can have on living matter.

. ...

. ...

. ...

. ...

7. (a) Compare the ionising ability of alpha decay and beta minus decay.

. ...

. ...

. ...

(b) Compare the penetration of alpha decay and beta minus decay.

. ...

. ...

. ...

8. The photograph below shows a smoke detector fitted to the ceiling of a room. Smoke detectors use Americium-241. Americium is a source of alpha decay. Smoke detectors are designed to detect fire.

(a) In terms of exposure to radioactivity, explain why you don't have to be worried about having smoke detectors in your home.

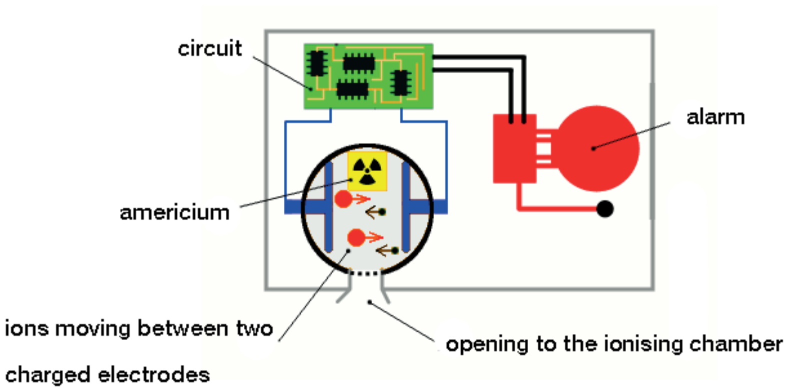
. ...

. ...

. ...

. ...

(b) The diagram below shows the internal structure of a smoke detector



The ionising chamber contains the americium. The alpha decay released by americium ionises air particles in the chamber. The ions that result move between two charged electrodes to produce a current.

Use the diagram of the internal structure of a smoke detector to deduce how the smoke detector works to detect a fire.

9. The photograph shows a sprouting potato. Potatoes are sometimes exposed to beta or gamma decay in order to delay sprouting.

A worker in this industry shields himself from the radioactive decay with a thick sheet of steel. Comment as to whether this shielding is sufficient to protect the worker.

10. State three ways to minimise exposure to ionising radiation.

11. Uranium undergoes several alpha and beta decays to form lead.

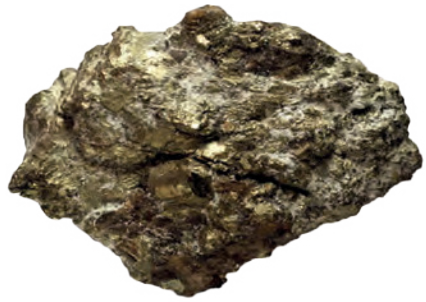
$$U_{92}^{238} \longrightarrow Pb_{82}^{206}$$

Determine the number of alpha and beta particles produced. Justify your answer.

12. This question requires a longer response.

In answering the question that follows you should:

- *communicate your knowledge clearly and concisely*
- *use physics terms correctly*
- *present information in an organised and logical sequence*
- *include information that is relevant to the question.*



Uranium ore is shown in the photograph. Uranium ore emits alpha and gamma decay but will also emits beta decay as part of its decay series.

Unstable nuclei such as those found in uranium ore will decay emitting particles and/or energy to become more stable. Describe the characteristics of nuclei that undergo alpha, beta and gamma decay and describe the nature of the emitted particle(s) in each case.

6.3 Radioactive half-life

1. (a) Define the term 'half-life'.

....

....

....

(b) A radioactive isotope has a half-life of 14 minutes. A sample of this isotope initially consists of 32×10^{10} nuclei.

(i) Use the space below to sketch a graph that illustrates how the number of nuclei varies over 70 minutes.

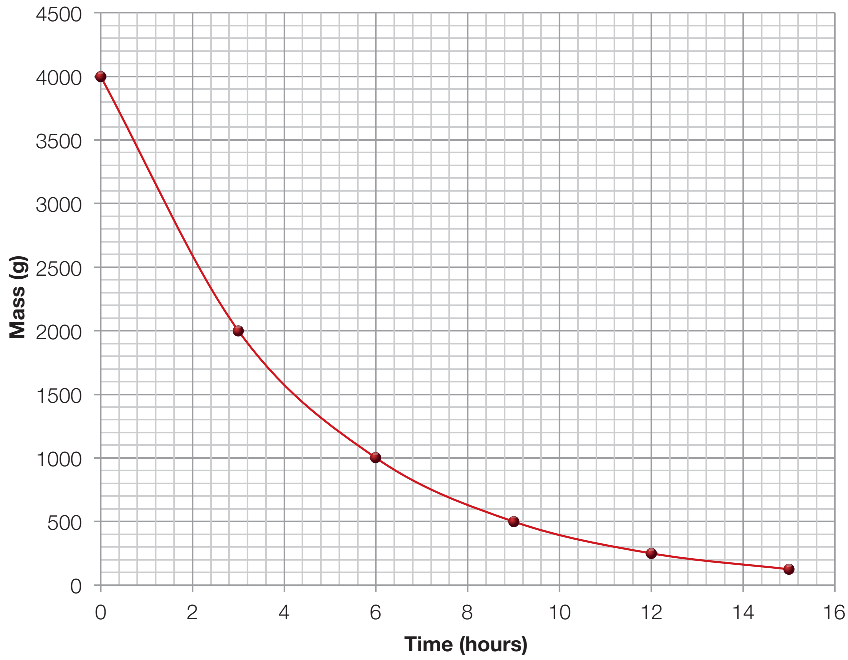
(ii) State the number of half-lives that have passed after 56 minutes.

....

(iii) State the number of nuclei that remain after 56 minutes.

....

2. A graph showing how the mass of a radioactive isotope varies over time is pictured below.



(a) State the half-life of this radioactive isotope.

(b) Use the graph to determine the mass of isotope that has decayed after 8 hours.

(c) Describe and explain how the shape of the graph would change, if at all, when the activity of the radioactive isotope is plotted against time.

3. The half-life of Zn-71 is 2.4 minutes.

Consider a 100.0 g sample of this isotope. Calculate the mass remaining after 7.2 minutes has elapsed.

4. The initial activity of the isotope Pd-100 is measured to be 400 Bq. Pd-100 has a half-life of 3.6 days.

(a) State, with reason, the time it would take for the activity decrease to 100 Bq.

(b) Calculate the activity of Pd-100 after 18 days.

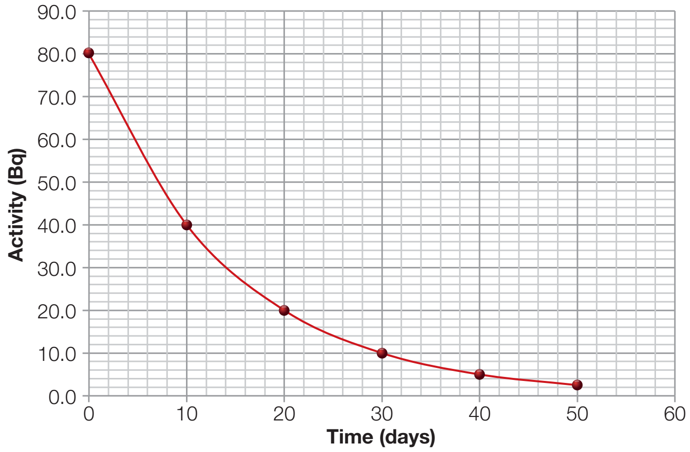
5. A sample of technetium 99 is injected into a cancer patient. Technetium has a half life of 6.0 hours. The initial activity of the sample is 240 Bq.

Determine the activity of the sample after a period of

(a) 12 hours

(b) one day.

6. Consider the graph below. It represents the activity of a radioactive isotope.



(a) State the half-life of the radioactive sample.

(b) Sketch a new line on the graph above that illustrates how the activity would change if the half-life was half the value stated in (a).

(c) State the effect that doubling the temperature of the isotope would have on its half-life.

(d) Calculate the time it would it take for $\frac{3}{4}$ of the original isotope to decay.

7. The half-life of carbon-14 is 5730 years. Determine the age of a sample if the ratio of carbon-14 to carbon-12 isotope is 12.5% of the origin ratio.

8. (a) In terms of its effect on living matter, explain why it is important to store radioactive waste carefully.

(b) Outline the main methods for storing radioactive waste.

6.4 Induced nuclear reactions

1. (a) Explain what is meant by the term 'induced fission'.

(b) Explain why energy is released during a fission reaction.

2. The energy released during a fission reaction can be calculated using the equation $E = \Delta mc^2$.

Describe the meaning of each term in the equation.

3. The following equation shows a possible fission reaction for U 235.

$$n_0^1 + U_{92}^{235} \rightarrow Rb_{37}^{A} + Cs_{Z}^{143} + 3n_0^1$$

(a) State the values of A and Z.

A:........................

Z:........................

(b) The products of the reaction are radioactive.

Predict the type of decay that results. Explain your answer.

(c) Write an equation for the decay of Rb_{37}^{A}.

(Assume the chemical symbol for the resulting nucleus to be Y)

(d) Calculate the energy released in this fission reaction.

The following data may be useful.

$m^{235}_{92}U = 3.9017 \times 10^{-25}\ kg \quad mRb^{A}_{37} = 1.41962 \times 10^{-25}\ kg \quad mCs^{143}_{Z} = 2.20756 \times 10^{-25}\ kg$

4. (a) Explain why a chain reaction occurs during the induced fission of U-235.

(b) Explain how enrichment enables a chain reaction to proceed.

5. Briefly describe and explain the role of each of the following in a in a water-moderated fission power reactor:

(a) the moderator

(b) the heat exchanger.

6. (a) Define the term ‘nuclear fusion’.

(b) Explain the need for high temperatures for a fusion reaction to proceed.

7. Calculate the energy released for the fusion reaction below.

$$H_1^2 + H_1^2 \rightarrow He_2^4$$

$$m_1^2H = 3.3445 \times 10^{-27}\,kg$$

$$m_2^4H = 6.645 \times 10^{-27}\text{ kg}$$

Solutions

Topic 1: Linear motion and forces

1.1 Motion under Constant Acceleration

Speed

1. (a) $v = \frac{s}{t} = \frac{5000}{15 \times 60} = 5.6\ ms^{-1} = 20\ kmh^{-1}$

   (b) Average speed is a calculation of the total distance travelled divided by the total time taken. It does not take changes in motion into account. For example it is not known whether the cyclist slows down or turns a corner.

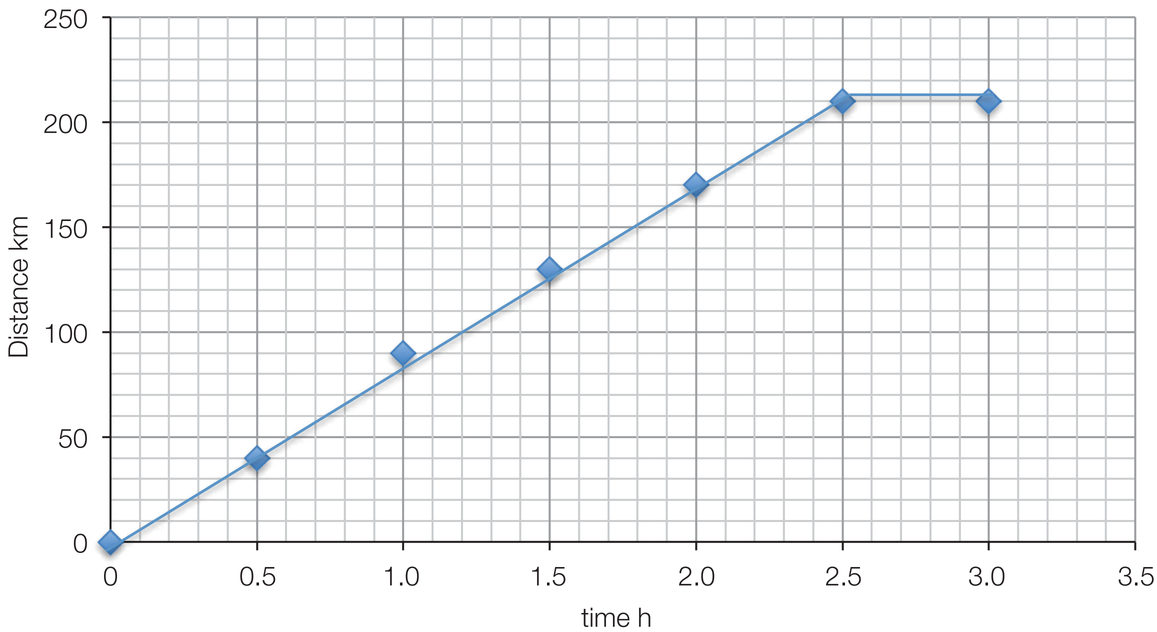
2. (a) $s = vt = 60 \times \frac{8}{60} = 8.0\ km$

   (b) $v = \frac{s}{t}\ \therefore\ t = \frac{s}{v} = \frac{1250}{60} = 20.8\ h$

3. $v = \frac{s}{t}$ $\quad v = \frac{2\pi r}{t} = \frac{2\pi \times (16000 \times 10^3 + 6.4 \times 10^6)}{7.4 \times 60 \times 60} = 5.3 \times 10^3\ ms^{-1}$

4. $s = vt = 3 \times 10^8 \times (4.2 \times 365.25 \times 24 \times 60 \times 60) = 3.98 \times 10^{16}\ m = 3.98 \times 10^{13}$ km

5. (a) and (b)



   (c) The motion is constant for the first 2.5 h i.e. t = 0 to 2.5 h.

   This is illustrated by the straight line of best fit through the origin.

   The car remains stationary for the final half an hour of its motion.

   (d) $gradient = speed = \frac{rise}{run} = \frac{210}{2.5} = 84\ kmh^{-1}(2sf)$

   (e) $84\ kmh^{-1} \div 3.6 = 23\ ms^{-1}$

6. (a) The distance between successive images is the same. The ball therefore travels the same distance per unit time (constant speed).

   (b) $v = \frac{s}{t} = \frac{0.36}{0.18 \times 4} = 5.00\ ms^{-1}$

S

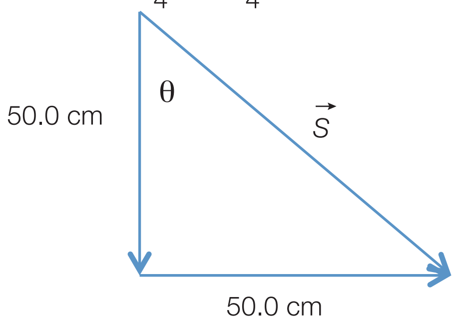
Displacement and velocity

1. (a) Any motion in a straight line. For example, if you walk down your driveway in a straight line, the distance that you travel and your displacement will have the same magnitude.

   (b) If you walk a given distance but your displacement is zero e.g. walking in a circular path, your speed (distance per unit time) will not be zero but your velocity (displacement per unit time) will be zero.

2. (a) distance $= \frac{2\pi r}{4} = \frac{2\pi(0.5)}{4} = 0.785\ cm$

   (b)



$\vec{s} = \sqrt{50^2 + 50^2} = 70.7\ cm$

$\theta = Tan^{-1}(\frac{50}{50}) = 45°$

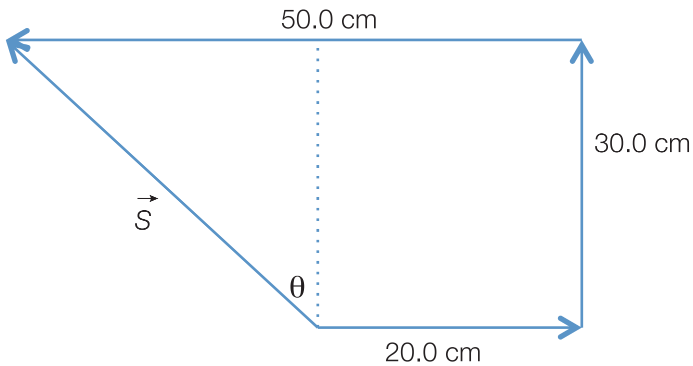
The displacement of the mouse is 70.7 cm 45.0° anticlockwise from the vertical as shown in the vector diagram.

   (c) $\vec{v} = \frac{\vec{s}}{t} = \frac{0.707}{3} = 0.236\ ms^{-1}$

i.e. 0.236 ms^{-1} 45.0° anticlockwise from the vertical as shown in the vector diagram.

3. (a) 100 cm

   (b)



$\vec{s} = \sqrt{30^2 + 30^2} = 42.4\ cm$

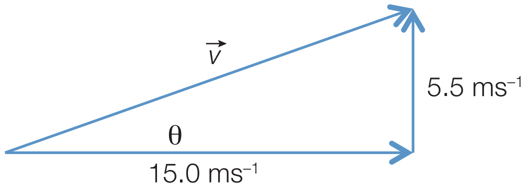
$\theta = Tan^{-1}(\frac{30}{30}) = 45°$

The displacement of the ant is 42.4 cm N45°W

   (c) $v = \frac{s}{t} = \frac{1}{45} = 0.0222\ ms^{-1}$

   (d) $\vec{v} = \frac{\vec{s}}{t} = \frac{0.424}{45} = 9.42 \times 10^{-3}\ ms^{-1}\ N45°W$

4. (a)



$\vec{v} = \sqrt{15^2 + 5.5^2} = 16\ ms^{-1}$

$\theta = Tan^{-1}(\frac{5.5}{15}) = 20°$

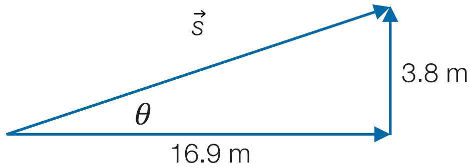
The velocity of the plane is 16 ms^{-1} E20°N

(b) $\vec{s} = \vec{v}t$ = 16 × (2 × 60) = 1900m E20°N

(c) $s = vt$ = 5.5 × (2 × 60) = 660m (North)

5. (a) The final displacement of the student is smaller than the total distance travelled through the corridors. The average velocity (displacement per unit time) will be smaller than the speed (distance per unit time).

(b) $\vec{s}$ 16.9 → +3.8 ↑



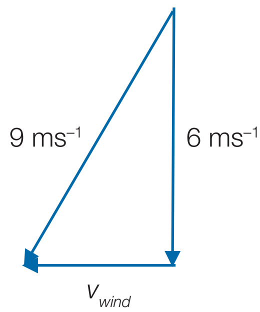
$\vec{s} = \sqrt{16.9^2 + 3.8^2} = 17.3\ m$

Tan$\theta = \frac{3.8}{16.9}$ ∴ θ = 12.7°

$\vec{v} = \frac{\vec{s}}{t} = \frac{17.3}{72}$ = 0.240 ms^{-1} $E12.7°\ N$

6. $\vec{v}$ = 6 ↓ + v_{wind} ← = 9

$v_{wind} = \sqrt{9^2 - 6^2}$ = 6.71 ms^{-1}



Acceleration

1. $a = \frac{v_f - v_i}{\Delta t} = \frac{\frac{460}{3.6} - 0}{12} = 10.6\ ms^{-2}$

2. $a = \frac{v_f - v_i}{\Delta t} = \frac{0 - 10}{0.22} = -45.5\ ms^{-2}$

3. $a = \frac{v_f - v_i}{\Delta t}$ $v_i = v_f - at = 20 - (-3) \times 8 = 44\ ms^{-1}$

4. $\Delta v = v_f - v_i = 400\uparrow - 400\downarrow \rightarrow = 400\uparrow + 400\uparrow = 800\ ms^{-1}\uparrow$

$a = \frac{\Delta v}{\Delta t} = \frac{800}{0.01} = 80000\ ms^{-2}\uparrow$ (90° away from the wall)

5. (a) 0 ms^{-1}

(b) 9.80 ms^{-2}

(c) $a = \frac{v_f - v_i}{\Delta t}$ ∴ $\Delta t = \frac{v_f - v_i}{a} = \frac{0 - 25}{-9.8} = 2.55\ s$

Graphing Motion

1. (a) speed
   (b) acceleration
   (c) distance
   (d) velocity
   (e) acceleration
   (f) displacement

2. (a) The remote controlled car travels with constant speed for 4.0 s travelling a distance of 5.0 m. The remote controlled car then travels with a different (lower) constant speed for 7.0 s travelling a further 7.0 m. The remote controlled car then remains at rest for the final 4.0 s of its motion.

(b) 12.0 m

(c) $v = \frac{s}{t} = \frac{12}{15} = 0.8\ ms^{-1}$

(d) $gradient = speed = \frac{7}{7} = 1.0\ ms^{-1}$

S

3. (a) 5.0 s

(b) $gradient = velocity = \frac{-60}{4} = -15\ ms^{-1}$

i.e. 15 ms^{-1} in a negative direction.

(c) The object is stationary for the first 5.0 s. It then travels with a constant velocity of 15 ms^{-1} in a negative direction.

4. (a) The object accelerates at a constant rate from rest for 2 s reaching a speed of 10 ms^{-1}. The object then travels with a constant speed for 1 s before accelerating at a constant rate for 4 s and reaching a speed of 20 ms^{-1}. The object then travels with a constant speed for 3 s before it decelerates at a constant rate for the final 3 s of its motion and comes to rest.

(b) The gradient of the line represents the acceleration. The greatest gradient and hence acceleration is $\frac{-20}{3} = -6.7\ ms^{-2}$ during the time interval 10 s to 13 s.

(c) $Area\ under\ the\ graph$ = distance = $\frac{10\times2}{2} + 10\times1 + \frac{10\times4}{2} + 10\times4 + 20\times3 + \frac{20\times3}{2} = 170\ m$

5. (a) The object travels with a constant velocity of 10 ms^{-1} for 20 s. The object then decelerates at a constant rate, comes to rest momentarily and turns around to accelerate at a constant rate in the opposite direction. After 25 s the object has reached a velocity of 10 ms^{-1} in the negative direction. The object then decelerates at a constant rate for 5 s, momentarily comes to rest, turns and then accelerates in its original direction of motion for 30 s.

(b) (i) 0 ms^{-2}

(ii) $gradient = acceleration = \frac{-20}{5} = -4\ ms^{-2}$

(iii) $gradient = acceleration = \frac{30}{35} = 0.86\ ms^{-2}$

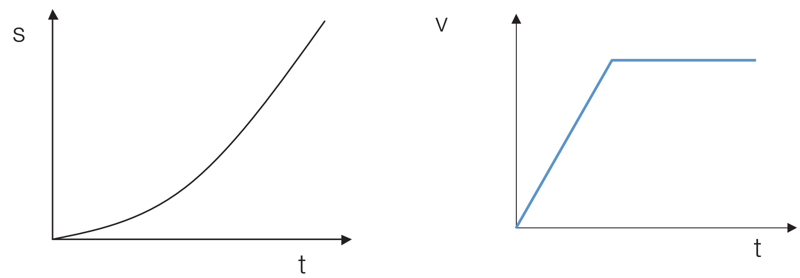
(c) $Area\ under\ the\ graph = distance = 10\times20 + \frac{10\times2}{2} + \frac{10\times3}{2} = 225\ m$

(d) The displacement of the object after 25 s is smaller than the distance travelled.

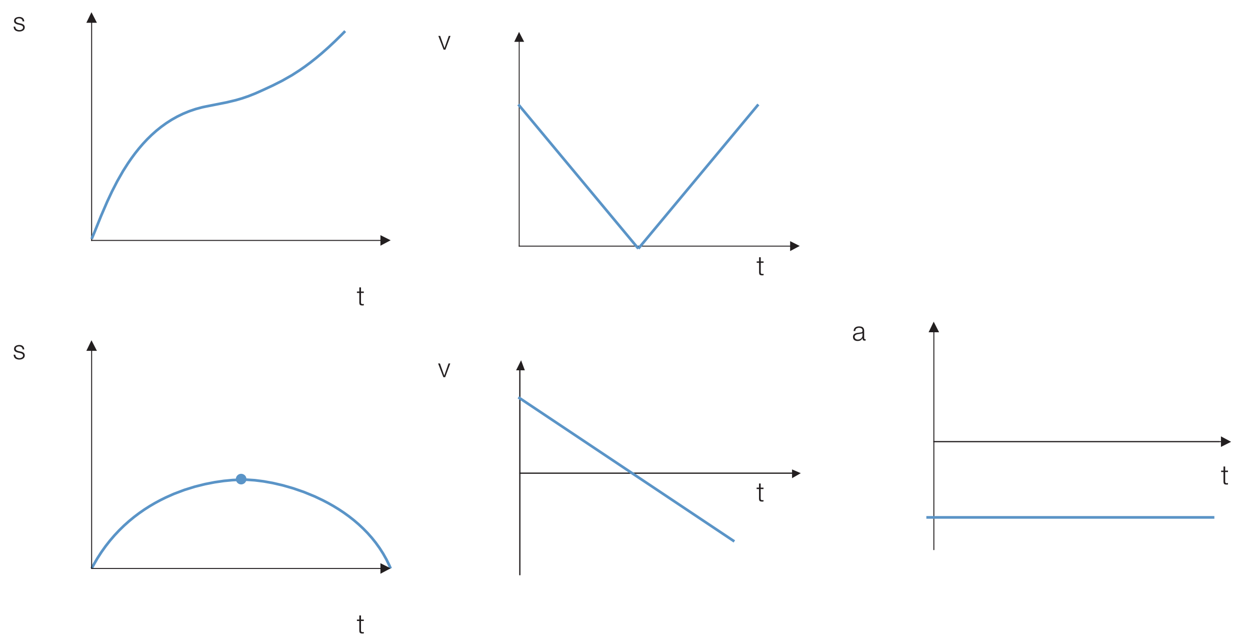
The displacement is given by the difference in area above and below the time axis.

$displacement = 10\times20 + \frac{10\times2}{2} - \frac{10\times3}{2} = 195\ m$

6.



7.



Equations of motion for constant acceleration

1. (a) 100 kmh^{-1}= 27.8 ms^{-1}

$$a = \frac{v - v_0}{t} = \frac{27.8 - 0}{7.2} = 3.86\ ms^{-2}$$

(b) $s = v_0 t + \frac{1}{2}at^2 = 0 + 0.5 \times 3.86 \times (7.2)^2 = 100\ m$

(c) $s = v_0 t + \frac{1}{2}at^2 \quad t = \sqrt{\frac{2s}{a}} = \sqrt{\frac{2 \times 200}{3.86}} = 10.2\ s$

(d) $v = \frac{s}{t} = \frac{100}{7.2} = 13.9\ ms^{-1}$

2. (a) $s = v_0 t + \frac{1}{2}at^2 = 0 + 0.5 \times 9.8 \times (0.75)^2 = 2.8\ m$

(b) $v^2 = v_0^2 + 2as$

$v = \sqrt{2as} = \sqrt{2 \times 9.8 \times 2.8} = 7.4\ ms^{-1}$

(c) $v^2 = v_0^2 + 2as$

$v = \sqrt{2as} = \sqrt{2 \times 9.8 \times 1.4} = 5.2\ ms^{-1}$

3. (a) $v = v_0 + at$

$$t = \frac{v - v_0}{a} = \frac{0 - 25}{-9.8} = 2.55\ s$$

(b) Motion is symmetrical so the time taken to return to the person's hand is twice the time to reach maximum height.

2.55 × 2 = 5.10s

(c) $v^2 = v_0^2 + 2as$

$$s = \frac{v^2 - v_0^2}{2a} = \frac{0^2 - 25^2}{2 \times -9.8} = 31.9\ m$$

(d) The ball is falling from maximum height for a time of 3.55 – 2.55 =1.00 s

$v = v_0 + at = 0 + 9.8 \times 1 = 9.80\ ms^{-1}$ *downwards*

or

$v = v_0 + at = 25 - 9.8 \times 3.55 = -9.79\ ms^{-1}$ *i.e.* 9.79 ms^{-1} *downwards*

(NB: Rounding off has caused a slight discrepancy in the final value depending on the method used)

4. (a) 72.0 kmh^{-1} = 20.0 ms^{-1}

$s = vt = 20 \times 0.13 = 2.60\ m$

(b) $v^2 = v_0^2 + 2as$

$$s = \frac{v^2 - v_0^2}{2a} = \frac{0^2 - 20^2}{2 \times -6} = 33.3\ m$$

(c) Total stopping distance = 2.6 + 33.3 = 35.9 m

The car hits the cat.

(d) Time taken for the car to decelerate and stop

$v = v_0 + at$

$$t = \frac{v - v_0}{a} = \frac{0 - 20}{-6} = 3.33\ s$$

Total stopping time = 0.13 + 3.33 = 3.46 s

5. (a) $v^2 = v_0^2 + 2as \therefore s = \frac{v^2 - v_0^2}{2a} = \frac{5^2 - 0}{2 \times -9.8} = 1.28\ m$

(b) $v^2 = v_0^2 + 2as \therefore a = \frac{v^2 - v_0^2}{2s} = \frac{0 - 5^2}{2 \times 0.012} = -1.04 \times 10^3\ ms^{-2}$

6. (a) $v^2 = v_0^2 + 2as = 0 + 2 \times 9.8 \times 1.56 \therefore v = 5.53\ ms^{-1}$

(b) $s = v_0 t + \frac{1}{2}at^2 \therefore t = \sqrt{\frac{2s}{a}} = \sqrt{\frac{2 \times 1.56}{9.8}} = 0.564\ s$

S

7. (a) $60.0\ kmh^{-1} = 16.7\ ms^{-1}$

$v^2 = v_0^2 + 2as \therefore a = \frac{v^2 - v_0^2}{2s} = \frac{0-16.7^2}{2\times12.9} = -10.8\ ms^{-2}$

(b) $v = v_0 + at \therefore t\ \frac{v - v_0}{a} = \frac{0-16.7}{-10.8} = 1.55\ s$

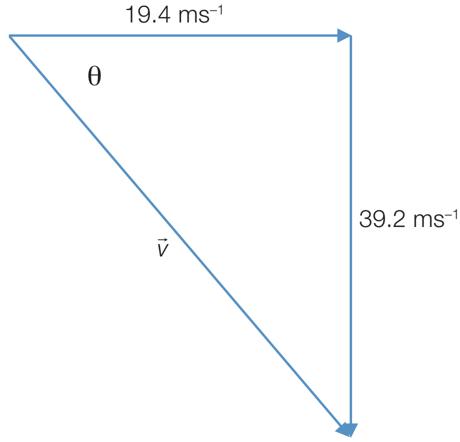
Projectile Motion

1. (a) $s = v_o t + \frac{1}{2}at^2 = \frac{1}{2}\times 9.8\times 4^2 = 78.4\ m$

(b) $v_H = 70/3.6 = 19.4\ ms^{-1}$

$s_H = v_H t = 19.4 \times 4 = 77.6\ m$

(c) $v_H = 70/3.6 = 19.4\ ms^{-1}$



$v_v = v_o + at \qquad v_o = 0$

$= 9.8 \times 4$

$= 39.2\ ms^{-1} \downarrow$

$v = \sqrt{39.2^2 + 19.4^2} = 43.7\ ms^{-1}$

$\tan\theta = \frac{O}{A} = \frac{39.2}{19.4} \Rightarrow \theta = 63.7°$

$\vec{v} = 43.7\ ms^{-1}$ $63.7°$ *below the horizontal*

(d) $v_H = \frac{S_H}{t} = \frac{100}{4} = 25\ ms^{-1} = 90\ kmh^{-1}$

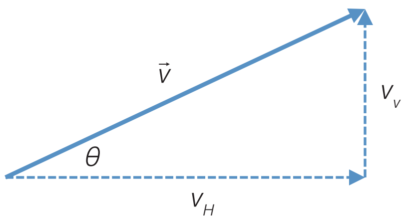
The girl can throw the ball with a maximum speed of 70 kmh^{-1}. Achieving 90 kmh^{-1} or more would be too hard. She shouldn't bother entering the competition.

(e) By launching the projectile at an angle it rises higher in the air.

It therefore spends a greater amount of time in the air.

Since range is given by $s_H = v_H t$ then a greater time in the air results in a greater range or horizontal distance despite the horizontal velocity decreasing slightly if the ball is still thrown at a speed of 70 kmh^{-1}.

2. (a)



$v_H = v\cos\theta = 30\cos30 = 26.0\ ms^{-1} \rightarrow$

$v_v = v\sin\theta = 30\sin30 = 15.0\ ms^{-1} \uparrow$

(b) Time taken to reach maximum height:

$v = v_o + at$ $v = 0$ *max height*

$0 = 15 - 9.8\ t$

$t = \frac{15}{9.8} = 1.53\ s$

total time $= 2 \times 1.53 = 3.06\ s$

(c) $v^2 = v_o^2 + 2as \qquad v = 0$ *max height*

$0 = 15^2 - 2 \times 9.8\ s$

$s = \frac{15^2}{2\times 9.8} = 11.5\ m$

(d) $s_H = v_H t = 26 \times 3.06 = 79.6\ m$

(e) $a = 9.80\ ms^{-2} \downarrow$

(f) $v = 30\ ms^{-1}$ 30° *below the horizontal*

3. (a) $v_H = v\cos\theta = 10\cos 45 = 7.07\ ms^{-1}\ \rightarrow$

$v_v = v\sin\theta = 10\sin 45 = 7.07\ ms^{-1}\ \uparrow$

(b) $v^2 = v_o^2 + 2as \qquad v = 0$ *max height*

$0 = 7.07^2 - 2 \times 9.8s$

$s = \dfrac{7.07^2}{2 \times 9.8} = 2.55\ m$

Total height $= 2.55 + 2 = 4.55\ m$

(c) Time to maximum height:

$v = v_o + at$ $v = 0$ *max height*

$0 = 7.07 + 9.8\ t$

$t = \dfrac{7.07}{9.8} = 0.721\ s$

time to fall $4.55\ m$

$s = v_o t + \dfrac{1}{2}at^2$

$4.55 = \dfrac{1}{2} \times 9.8 \times t^2 \quad \therefore \quad t = 0.964\ s$

Total time = 0.721 + 0.964 = 1.69 s

(d) $s_H = v_H t = 7.07 \times 1.69 = 11.9$ m

(e) 7.07 ms^{-1} horizontally in the direction that the shot put was thrown

(f) $v_H = 7.07\ ms^{-1}\ \rightarrow$

$v_v = v_o + at \qquad v_o = 0$

$= 7.07 - 9.8 \times 1$

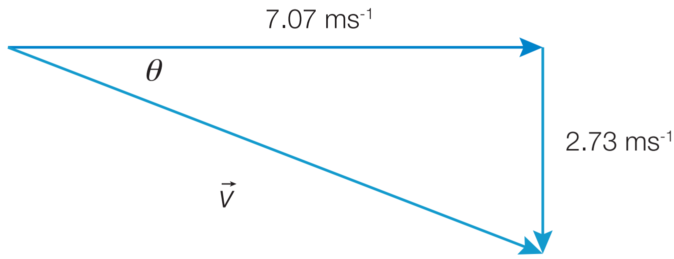
$= -2.73\ ms^{-1}$

ie $2.73\ ms^{-1}\ \downarrow$

$v = \sqrt{7.07^2 + 2.73^2} = 7.58\ ms^{-1}$

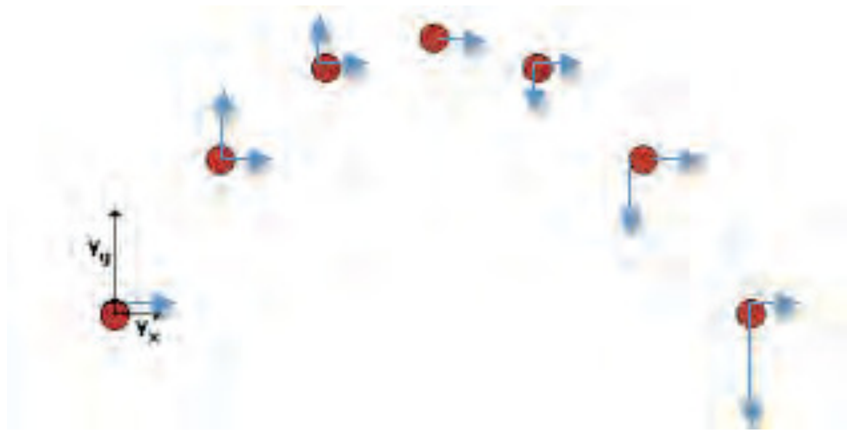
$\tan\theta = \dfrac{O}{A} = \dfrac{2.73}{7.07} \Rightarrow \theta = 21.1°$

$\vec{v} = 7.58\ ms^{-1}$ 21.1° *below the horizontal*



(g) A path (no longer parabolic) with a smaller height and range.

4.



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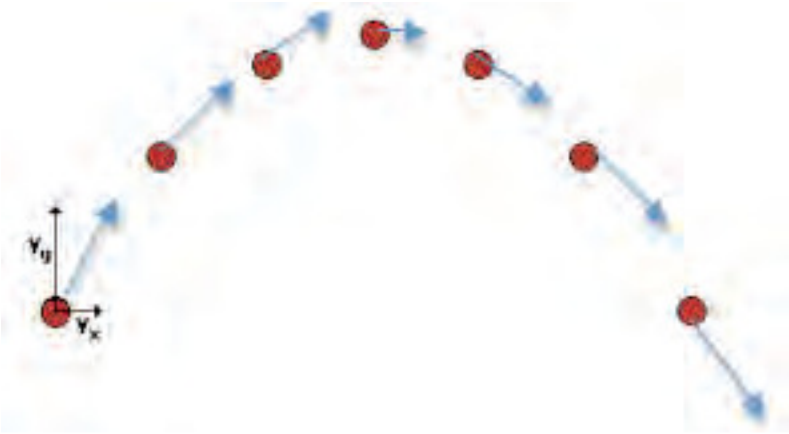
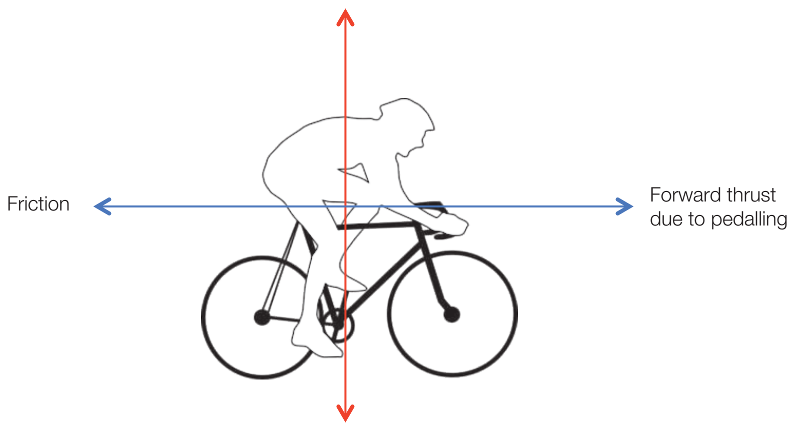
5.



6.

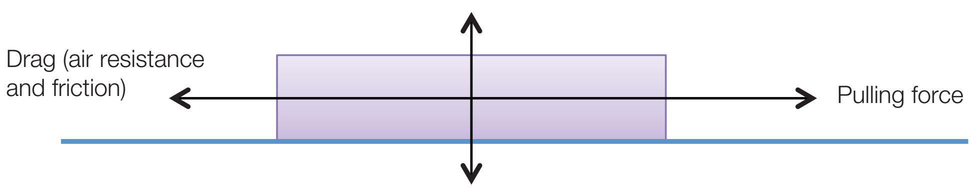
1.2 Forces

1. (a)



(b) 135 N in a forward direction.

2.



3. (a) $a = \frac{F}{m} = \frac{20 \times 10^3}{12 \times 10^3} = 1.67\ ms^{-2}$

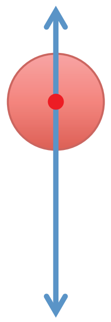
(b) $v = v_o + at$

$0 = 25 - 1.67\ t$

$t = \frac{25}{1.67} = 14.97 = 15.0\text{s (3 sf)}$

(c) $s = v_o t + \frac{1}{2}at^2 = 25 \times 15 + \frac{1}{2} \times -1.67 \times 15^2 = 187\ m$

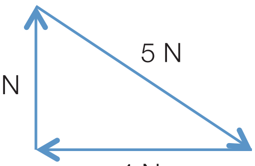
4. (a)



(b) $F = mg - drag = 0.2 \times 9.8 - 0.15 = 1.81N$

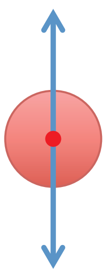
(c) $a = \frac{F}{m} = \frac{1.81}{0.2} = 9.05\ ms^{-2}$ downwards

5. The resultant force is zero. This means that the ice skater does not accelerate.



6. The swimmer pushes against the water as they take a stroke. This action exerts an ***action force*** on the water. According to Newton's Third Law, the water applies an equal and opposite ***reaction force*** on the swimmer. It is this reaction force that propels the swimmer forward.

7.



According to Newton's First Law, the forces acting on the parachutist must be balanced because they are falling with a terminal or constant speed. This means that the upward drag forces are equal in magnitude to the downward gravitational force or weight of the parachutist.

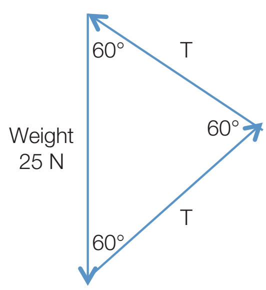
$Drag = mg = 110 \times 9.8 = 1078\ N = 1100\ N$ *(2sf)*

8. (a) $W = mg = 2.5 \times 9.8 = 24.5 = 25\ N$

(b) The resultant force on the picture frame is zero.

The vector sum of the three forces adds to zero as shown in the vector triangle.

Since the vector triangle is equilateral, the tension force is 25 N.



9. (a) $F = ma = 1120 \times 10.8 = 1.21 \times 10^4\ N$

(b) Newton's Second Law states that the acceleration of an object is directly proportional to the force applied providing the mass is constant. This means that the acceleration varies by the same factor as the force. If half the braking force is applied to a model with the same mass, you'd expect the acceleration to halve.

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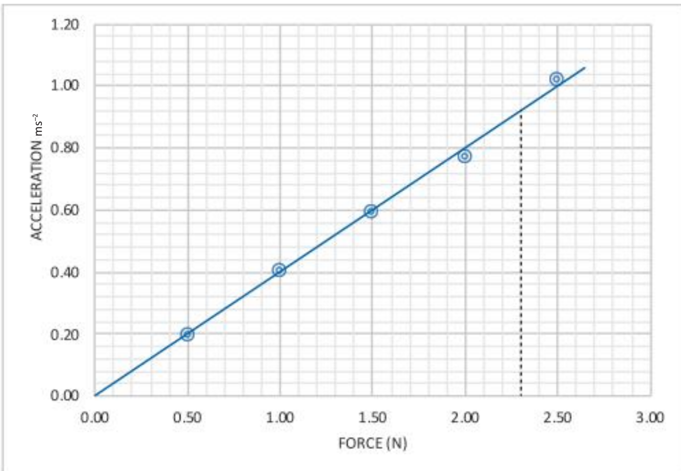
10. (a) Force
    (b) 1.14
    (c) 0.406
    (d) (i)



(ii) A straight line of best fit passes through the origin. This indicates that acceleration is directly proportional to force (for a constant mass). Newton's Second Law has been verified by the results of the experiment.

(iii) $gradient = \frac{0.92}{2.3} = 0.400\ ms^{-2}\ N^{-1}$

(iv) Comparing y = mx to $a = \frac{F}{m}$, the gradient = $\frac{1}{mass}$

Mass of system = $\frac{1}{gradient} = \frac{1}{0.400}$ = 2.50 kg

Mass of the trolley = 2.50 – 0.25 = 2.25 kg

The mass of the trolley is 2.30 kg. The experimental value is very close to the known value i.e. very accurate

(v) Friction opposes the motion of the trolley. The time taken for the trolley to move 0.500 m would be greater, reducing the acceleration.

(vi) The students could have used an air track. This would reduce the friction experienced by the motion trolley.

(e) The equipment is set up in a similar way. The distance between the light gates is measured. Two 50.0 g masses are attached to the trolley using a piece of string. The two 50.0 g masses are suspended over the side of the bench. The suspended masses are released and the time taken for the motion trolley to accelerate from rest across the distance between the light gates is recorded. The distance between the light gates is changed and once again measured. The time taken for the motion trolley to move across this new distance is recorded when the same two suspended masses are released over the side of the bench. This ensures that the force on the motion trolley is constant. This process of changing the distance between the light gates and recording the time taken for the motion trolley to accelerate across the measured distance is repeated so that at least five results for distance are recorded. The procedure is repeated two more times so that three values of time are recorded for each distance. The average time for each distance is calculated. A graph of time against distance is plotted.

Weight and Mass

1. (a) $W = mg = 54 \times 9.8 = 529\ N$
   (b) 54.0 kg
   (c) $W = mg = 54 \times 1.67 = 90.2\ N$
2. $W = mg = 3 \times 0.82 \times 9.8 = 24$ N upwards
3. $W = mg$

   $g = \frac{W}{m} = \frac{296}{80} = 3.70\ Nkg^{-1}$

   The planet is Mercury.
4. The gravitational acceleration on the Moon is approximately six times smaller than the gravitational acceleration on Earth. This means that the gravitational force (weight) pulling objects to the ground is approximately six times smaller. This means a person can jump approximately six times higher than they can on Earth.

Topic 2: Electric circuits

2.1 Potential Difference and Electric Current

1.

Sign of one charge	Sign of second charge	Description of force between the charges
positive	positive	repulsion
positive	negative	attraction
negative	negative	repulsion

2. The greater the electronegativity of a material the greater its tendency to hold on to its electrons.

   When brass is rubbed with wool, the wool will lose electrons and the brass will gain them. The brass will acquire a negative charge.

   When glass is rubbed with wool, the glass will lose electrons and the wool will gain them. The glass will acquire a positive charge.

3. When you polish a car you rub it. The body of the car becomes charged. It therefore attracts nearby dust particles in the air because they become charged by induction. Charges within the dust particles rearrange so that the side of the dust particles closest to the car have an opposite charge to the car. The dust particles are then attracted to the car.

4. Plastic is a good insulator. This will prevent the charges that are transferred from the Van de Graaff generator to your body from passing straight in to the earth and allow the charges to accumulate on your body.

5. Charge the electroscope negative by touching the cap with a negatively charged rod (ebonite rubbed with fur). The needle will deflect to indicate that the electroscope is charged. If the balloon is negatively charged the needle of the electroscope will deflect further when the balloon is brought close to the electroscope.

6. The stream of water would bend towards the charged rod. Charges in the molecules of water rearrange so that the negative charges are closest to the positive rod. The water is attracted to the rod because the force of attraction between unlike charges is greater than the force of repulsion between like charges.

7. (a) A material is a conductor if it allows charge to flow freely or redistribute itself evenly over the whole surface.

   A material is an insulator if it does not allow charge to flow freely. Any charge that is introduced to the surface of a solid insulator is confined to a localised area. This is because electrons are held tightly and are not free to move throughout the material. Electrons can accumulate on the surface but cannot redistribute themselves.

   (b) Copper is a conductor. Any charges introduced to the surface while rubbing it will flow through the copper to your hand. The charge will be earthed.

8. When the Van de Graff generator is switched on, charge accumulates on the dome. Metals are good conductors of charge so the pie plates acquire the same charge as the dome by contact. Like charges repel. The pie plates will experience a force of repulsion from each other as well as the dome.

   The top plate is the first to lift off the dome because it is repelled from the dome as well as the pie plate beneath it. The pie plate is light which means that the electric force and is large enough to overcome its weight (*w=mg*).

   The same principle applies to the other plates that remain on the dome. The pie plates lift off the dome one plate at a time. The pie plate at the top is the first to lift off the dome, followed by the others beneath it.

Electric force

1. $\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2} = \frac{9\times10^9\times6.5\times10^{-3}\times7.5\times10^{-3}}{0.35^2} = 3.6\times10^6 N$ *attraction*

2. (a) $\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2} = \frac{9\times10^9\times40\times10^{-9}\times25\times10^{-9}}{1.5^2} = 4.00\times10^{-6} N$ *repulsion*

   (b) 

   (c) (i) $F \alpha q_1$ *for* q_2, r *constant*

   If one charge is tripled the force will be three times larger. Reversing the sign does not affect the magnitude of the force but instead it becomes an attractive force.

   (ii) $F \alpha \frac{1}{r^2}$ *for* q_1, q_2 *constant*

   If the distance is halved, the force becomes four times larger.

   (iii) The effect would be that the force becomes $3 \times 4 = 12$ times larger.

3. $F=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}=\frac{9\times10^9 q_1q_2}{r^2}$

$r=\sqrt{\frac{9\times10^9 q_1q_2}{F}}=\sqrt{\frac{9\times10^9\times5\times10^{-6}\times3\times10^{-6}}{0.5}}=0.52\ m$

4. Force due to Q_A: $\vec{F}_A=\frac{1}{4\pi\varepsilon_0}\frac{Q_AQ_C}{r_A^2}=\frac{9\times10^9\times3\times10^{-6}\times9\times10^{-6}}{0.75^2}=0.432\ N\ \rightarrow$

Force due to Q_B: $\vec{F}B=\frac{1}{4\pi\varepsilon_0}\frac{Q_BQ_C}{r_B^2}=\frac{9\times10^9\times5\times10^{-6}\times9\times10^{-6}}{0.55^2}=1.34\ N\ \leftarrow$

$\vec{F}=\vec{F}_A+\vec{F}_B=0.432\rightarrow+1.34\leftarrow=0.908N\leftarrow$

5. (a) $F=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}=\frac{9\times10^9 q_1q_2}{r^2}$

$q_2=\frac{Fr^2}{9\times10^9 q_1}=\frac{4\times10^4\times2^2}{9\times10^9\times5\times10^{-3}}=3.6\times10^{-3}\ C$

(b) The force is 16 times larger.

Using $F\alpha\frac{1}{r^2}$ *for* q_1,q_2 *constant*

The distance has been reduced 4 times i.e. the new distance is 50 cm

6. Force due to 0.75 C charge: $\vec{F}_1=\frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r_1^2}=\frac{9\times10^9\times0.75\times0.6}{1^2}=4.05\times10^9\ N\ \rightarrow$

Force due to 0.85 C charge: $\vec{F}_2=\frac{1}{4\pi\varepsilon_0}\frac{q_2q_3}{r_2^2}=\frac{9\times10^9\times0.85\times0.6}{2^2}=1.15\times10^9\ N\ \leftarrow$

$\vec{F}=\vec{F}_1+\vec{F}_2=4.05\times10^9\rightarrow+1.15\times10^9\leftarrow=2.90\times10^9 N\rightarrow$

Potential difference

1. $\Delta V=\frac{E_p}{q}=\frac{5\times10^{-17}}{3.2\times10^{-19}}=160\ V$

2. (a) $E_p=q\Delta V=1.6\times10^{-19}\times6000=9.6\times10^{-16}J$

(b) The kinetic energy gained is 9.6×10^{-16} J (using the law of conservation of energy).

3. $E_p=q\Delta V=1.6\times10^{-19}\times30000=4.80\times10^{-15}J$

2.4 Current

1. Electric current is defined as the charge flowing past a point in a conductor per second or the rate of flow of charge.

2. (a) $I=\frac{q}{t}=\frac{8}{30}=0.267A$

(b) Number of electrons $=\frac{total\ charge}{e}=\frac{8}{1.6\times10^{-19}}=5.00\times10^{19}$

3. Charge flowing: $q=It=0.5\times60=30.0C$

Number of electrons $=\frac{total\ charge}{e}=\frac{30}{1.6\times10^{-19}}=1.88\times10^{20}$

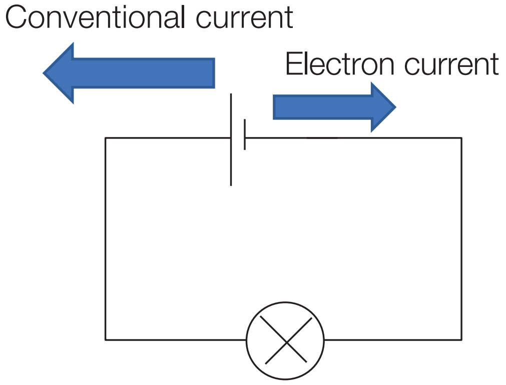
4. Number of electrons $=\frac{total\ charge}{e}$ $\therefore$ *total charge* = Number of electrons $\times\ e$

$q=3\times10^{19}\times1.6\times10^{-19}=4.8\ C$

$I=\frac{q}{t}=\frac{4.8}{10}=0.480\ A$

5. (a) Conventional current refers to the direction that positive charges flow through a circuit. Electron current refers to the direction that electrons flow through a circuit i.e. in the opposite direction to conventional current.

   (b)



2.2 Resistance

1. $R = \frac{V}{I} = \frac{8}{0.15} = 53\Omega$

2. (a) The electrical resistance of a component is defined as the ratio of the potential difference applied across the component to the current flowing in the component.

   (b) Charge carriers (electrons) flowing through a conductor collide with each other and the positive ions in the metal. The electrons transfer kinetic energy to the vibrating positive ions. The ions vibrate faster. This means that the conductor heats up.

   Since resistance is an indication of how hard it is for charge to flow through a conductor. The higher the resistance the harder it is for the charge to flow and the greater the heat that results.

3. $R = \frac{V}{I} \quad \therefore \quad V = IR = 1.5 \times 10 = 15\ V$

4. (a) Conductors that obey Ohm's law ($I \alpha V$) are said to be ohmic conductors. Their resistance remains constant.

   (b) Ohm's law states that the current is directly proportional to potential difference providing the temperature of the conductor remains constant. If the temperature of a conductor increases so too does the resistance. The conductor does not obey Ohm's law and cannot be ohmic.

5. $R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{240}{50} = 4.8\ A$

6. (a) The student would expect a straight line through the origin.

   (b) The gradient represents $\frac{1}{R}$.

   (c) AV^{-1}

   (d) The resistance of the resistor is given by $\frac{1}{gradient}$.

7. (a) The current is directly proportional to potential difference.

   (b) $gradient = \frac{rise}{run} = \frac{0.3}{10} = 0.030\ AV^{-1}$

   (c) $gradient = \frac{1}{R} \quad \therefore \quad R = \frac{1}{gradient} = \frac{1}{0.03} = 33\ \Omega$ (2 sf)

   (d) If the resistance increases the gradient decreases. A straight line through the origin should be drawn that is less steep than the original.

8. (a) The potential difference V for the particular value of current is read from the graph. The ratio V/I gives the value of resistance.

   (b) Resistance is not constant. The filament therefore does not behave like an ohmic conductor i.e. does not obey Ohm's Law ($V \alpha I$).

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Resistance and resistivity

1. $R = \frac{\rho L}{A} = \frac{1.8 \times 10^{-8} \times 0.25}{4.5 \times 10^{-6}} = 1.0 \times 10^{-3}\ \Omega$
2. (a) Resistivity of a material is the resistance of a 1 m length of the wire with an area of cross-section of 1 m^2.

   (b) $R = \frac{\rho L}{A} \quad \therefore \quad \rho = \frac{RA}{L} = \frac{1.3 \times 10^{-3} \times 2 \times 10^{-6}}{1.5} = 1.7 \times 10^{-9}\ \Omega\ m$
3. (a) $R = \frac{\rho L}{A}$ where $A = \pi r^2$

   $R = \frac{\rho L}{A} = \frac{1.7 \times 10^{-8} \times 1}{\pi (1.5 \times 10^{-3})^2} = 2.41 \times 10^{-3}\ \Omega$

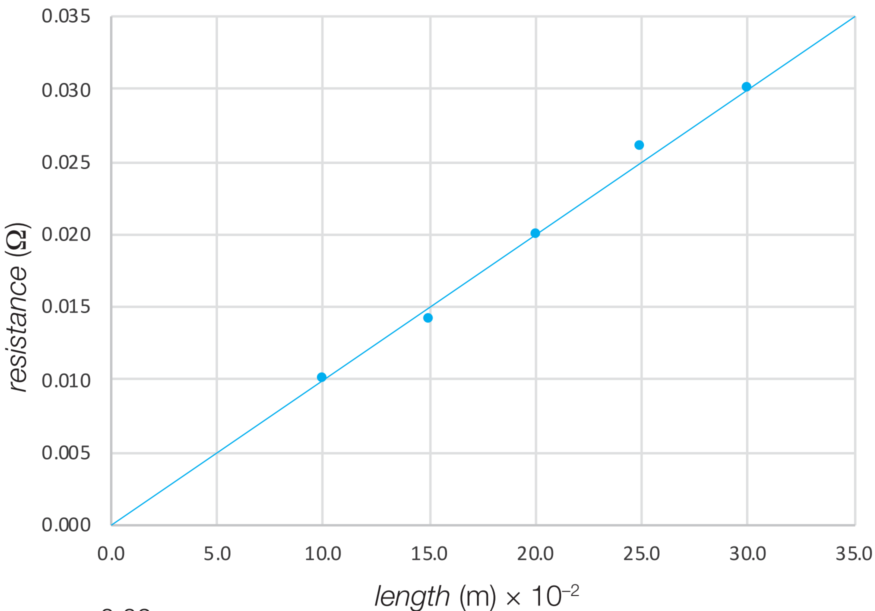
   (b) $R = \frac{\rho L}{A} \quad \therefore \quad L = \frac{RA}{\rho} = \frac{1 \times \pi (1.5 \times 10^{-3})^2}{1.7 \times 10^{-8}} = 416\ m$
4. The student will need to plot a graph of resistance against the inverse of area of cross-section.

   A straight line of best fit through the origin should result.
5. (a) $R \alpha L$ a piece of wire that is three times longer would have three times the resistance.

   R = 7.25 × 3 = 21.8 Ω

   (b) Since $R \alpha \frac{1}{A}$ *and* $A = \pi r^2$ then if the radius is doubled, the area of cross-section is four times larger. This makes the resistance four times smaller.

   $R = \frac{7.25}{4} = 1.81\ \Omega$
6. (a) Resistance
7. (b)



   (a) (i) gradient = $\frac{0.02}{20 \times 10^{-2}} = 0.10\ \Omega m^{-1}$

   (ii) $R = 0.10\ l$

   (i) Comparing $R = \frac{\rho L}{A}$ to $R = 0.10\ l$ the gradient = $\frac{\rho}{A}$

   ρ = gradient × A = 0.1 × 1 × 10^{-5} = 1.0 × 10^{-6} Ω*m*

   (b) The students could repeat the measurement of resistance for each length of wire several times (say three) and average the value.
8. If there is a power surge and too much current flows through a circuit, a fuse or circuit breaker stops the current from flowing.

   Once the problem is addressed or the current returns to safe levels, current can flow through the circuit as normal. In the case of a fuse, it will need to be replaced.

   This will prevent overheating and the risk of fire.

2.3 Circuit Analysis

1. (a) $R_t = 10 + 30 + 60 = 100\ \Omega$

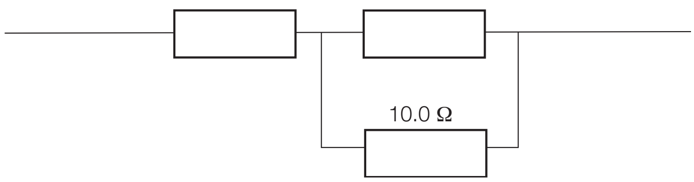
   (b) parallel branch $\frac{1}{R_{||}} = \frac{1}{10} + \frac{1}{40}$ $\therefore$ $R_{||} = 8.0\ \Omega$

   $R_t = 5 + 8 + 50 = 63\ \Omega$

   (c) small parallel branch $\frac{1}{R_{1||}} = \frac{1}{20} + \frac{1}{60}$ $\therefore$ $R_{1||} = 15.0\ \Omega$

   Top branch = 5 + 15 = 20.0 Ω

   $\frac{1}{R_t} = \frac{1}{20} + \frac{1}{120}$ $\therefore$ $R_t = 17.1\ \Omega = 17\ \Omega$ (2sf)

2. 

   $\frac{1}{R_{||}} = \frac{1}{8} + \frac{1}{10}$ $\therefore$ $R_{||} = 4.44\ \Omega$

   $R_t = 9 + 4.44 = 13.4\ \Omega$

3. (a) Ammeter

   (b) Voltmeter

   (c) $R = \frac{V}{I}$ $\therefore$ $I = \frac{V}{R} = \frac{6}{10} = 0.600\ A$

   (d) $q = It = 0.6 \times 60 = 36\ C$

   Number of electrons = $\frac{total\ charge}{e} = \frac{36}{1.6 \times 10^{-19}} = 2.25 \times 10^{20}$

4. (a) An ammeter is connected to the positive terminal of the power supply.

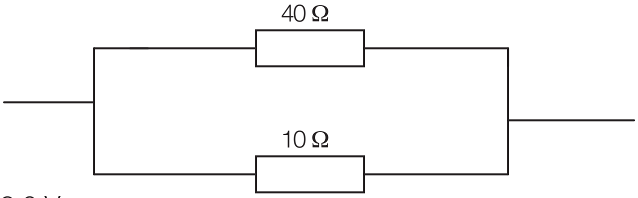
   A 10 Ω resistor followed by a 30 Ω resistor are connected to the ammeter in series and back to the negative terminal of the power supply. A voltmeter is connected in parallel to the 30 Ω resistor.

(b) 40.0 Ω

(c) $R = \frac{V}{I}$ $\therefore$ $I = \frac{V}{R} = \frac{4.5}{40} = 0.113\ A$

(d) $R = \frac{V}{I}$ $\therefore$ $V = IR = 0.113 \times 30 = 3.39\ V$

5. (a)



   (b) 8.0 V

   (c) $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

   $\frac{1}{R} = \frac{1}{40} + \frac{1}{10}$

   $R = 8.0\ \Omega$

   (d) $R = \frac{V}{I}$ $\therefore$ $I = \frac{V}{R} = \frac{8}{8} = 1.0\ A$

   (e) 8.0 V

   (f) Resistance is now 10 Ω

   $R = \frac{V}{I}$ $\therefore$ $I = \frac{V}{R} = \frac{8}{10} = 0.80\ A$

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6. (a)

parallel branch: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

$\frac{1}{R} = \frac{1}{20} + \frac{1}{25}$

$R = 11.1\ \Omega$

Total resistance: 11.1 + 30 = 41.1 Ω

(b) $R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{10}{41.1} = 0.243\ A$

(c) potential difference across the 30.0 Ω resistor

$R = \frac{V}{I} \quad \therefore \quad V = IR = 0.243 \times 30 = 7.29\ V$

potential difference across the 25.0 Ω resistor = 10 – 7.29 = 2.71 V

(d) $R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{2.71}{20} = 0.136\ A$

7. (a)

parallel branch: $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$

$\frac{1}{R} = \frac{1}{4} + \frac{1}{5}$

$R = 2.2\ \Omega$

Total resistance: 2.2 + 5 + 2 = 9.2 Ω

(b) $R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{12}{9.2} = 1.3\ A$

(c) $R = \frac{V}{I} \quad \therefore \quad V = IR = 1.3 \times 5 = 6.5\ V$

(d) potential difference across the 2.0 Ω resistor

$R = \frac{V}{I} \quad \therefore \quad V = IR = 1.3 \times 2 = 2.6\ V$

potential difference across the 4.0 Ω resistor = 12 – 2.6 – 6.5 = 2.9 V

(e) $R = \frac{V}{I} \quad \therefore \quad I = \frac{V}{R} = \frac{2.9}{4} = 0.73\ A$

8. Let R be the resistance of each light globe

total resistance $R_t = \frac{V}{I} = \frac{4.5}{0.5} = 9\ \Omega$

But $\frac{1}{R_t} = \frac{1}{R} + \frac{1}{R} = \frac{2}{R} \therefore R_t = \frac{R}{2} \therefore$ R = 2 × 9 = 18 Ω

2.4 Electrical Power

1. $P = VI = 50 \times 1.2 = 60\ W$
2. $P = \frac{V^2}{R} = \frac{550^2}{150} = 2.0 \times 10^3 W = 2.0\ KW$
3. (a) $P = \frac{\Delta E}{t} \quad \therefore \quad \Delta E = Pt = 2400 \times 95 = 2.28 \times 10^5\ J$

   (b) $0.3 \times 2.28 \times 10^5 = 6.84 \times 10^4$ J
4. *Cost = P(kilowatts) × number hours × cost per kilowatt = 2.2 × 5 × 18 = 198 cents*

   i.e. \$1.98 = \$2.00
5. (a) $P = I^2 R = 2^2 \times 450 = 1800 W$

   (b) $P = \frac{\Delta E}{t} \quad \therefore \quad \Delta E = Pt = 1800 \times (3 \times 60) = 3.2 \times 10^5 J$

   (c) *Cost = P(kilowatts) × number hours × cost per kilowatt =*

   $= 1.8 \times \frac{3}{60} \times 20 = 1.8$ *cents*

   (d) Useful energy = $3.2 \times 10^5 - 1.0 \times 10^5 = 2.2 \times 10^5$ J

   $efficiency = \frac{useful\ energy}{total\ energy} = \frac{2.2 \times 10^5}{3.2 \times 10^5} = 0.69$

   i.e. an efficiency of 69%
6. (a) $q = It = 35 \times 10^{-3} \times 20 \times 10^{-6} = 7.0 \times 10^{-7}\ C$

   (b) $R = \frac{V}{I} = \frac{6}{35 \times 10^{-3}} = 170\ \Omega$

   (c) $P = VI = 6 \times 35 \times 10^{-3} = 0.21\ W$

   (d) Number of electrons $= \frac{total\ charge}{e} = \frac{7 \times 10^{-7}}{1.6 \times 10^{-19}} = 4.4 \times 10^{12}$
7. (a) $P = VI = 10 \times 0.5 = 5.0\ W$

   (b) $P = VI = 6 \times 0.5 = 3.0\ W$

   (c) $efficiency = \frac{useful\ power\ output}{power\ output} = \frac{3}{5} = 0.6$

   i.e. an efficiency of 60%

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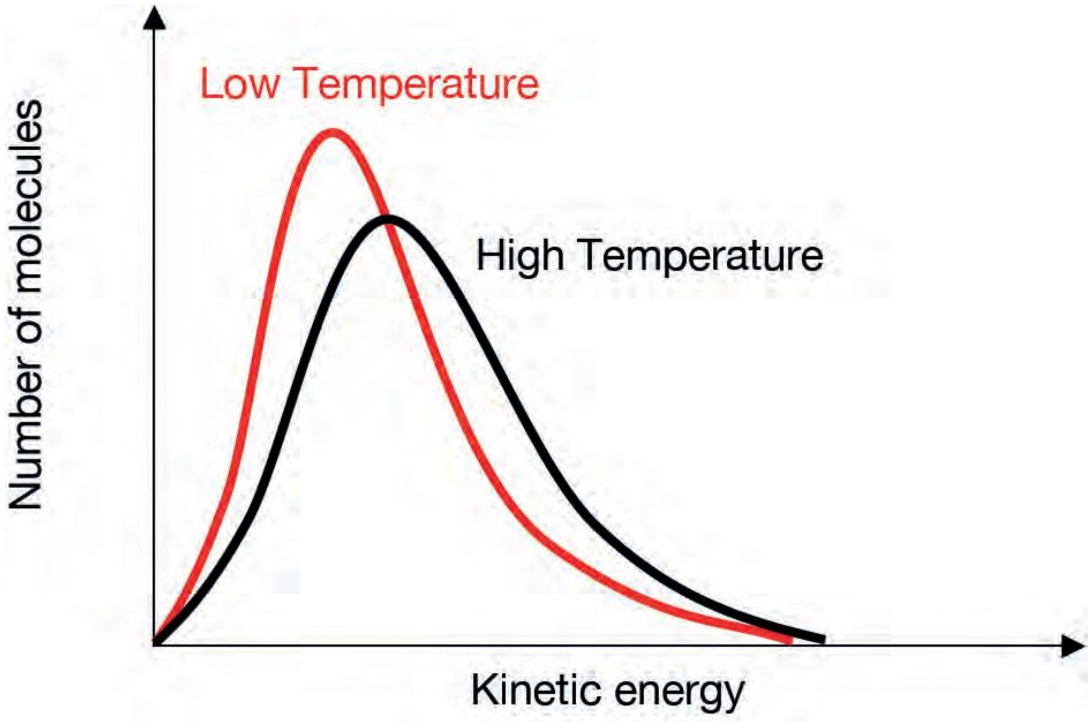
Topic 3: Heat

3.1 Heat and temperature

1. Thermal energy is made up of the combined potential energy and kinetic energy due to the vibration of the particles within an object.

   Heat is the thermal energy that is absorbed, released or transferred between objects.

2. (a) and (b)



3. Thermal energy is defined as the combined potential energy and kinetic energy due to the vibration of the particles within an object. The greater the temperature of an object, the greater the average kinetic energy of the particles making up the object. By definition the thermal energy increases.

4. (a) 86°F

   (b) 313 K

   (c) –223°C

   (d) 37.8°C

5. (a) Absolute zero (0 K) is defined as the temperature at which particle motion almost stops.

   (b) 0 K or –273°C

6. Temperature is defined as a measure of the average kinetic energy of the particles in a substance. Heat flows from a region of high temperature to a region of low temperature. Temperature therefore determines the direction of thermal energy transfer (or heat flow).

7. Heat stops flowing when two objects are at the same temperature or in thermal equilibrium.

8. Conduction is the transfer of thermal energy from a region of high temperature to a region of low temperature by particle collision and without a transfer of matter. When the heat bag is in contact with your body, heat flows from the heat bag to your body because your body is at a lower temperature. The heat bag loses thermal energy and its temperature decreases.

9. A jumper is usually made of a material that acts as a good insulator (e.g. wool). This helps slow the heat transfer from your body at a higher temperature to the surrounding cooler air. In addition, the jumper traps a layer of air between your body and the jumper. Air is a good insulator. The combined effect is that the jumper keeps you warm.

10. Metal is a good conductor of heat and allows the transfer of thermal energy to occur readily. Since the tea is hot, the temperature of the spoon increases until it is in thermal equilibrium with the tea. This is too hot to place in your mouth unless the tea cools down.

11. (a) The flame heats the air close to the flame and creates a convection current in the oven. The air repeatedly passes over the flame and is heated. Heating by convection stops when the oven reaches the desired temperature.

(b) Heat flows from a region of high temperature to a region of low temperature. When the oven door is opened, thermal energy flows from the hot oven to the cooler surrounding air. The statement should be that hot air leaves the oven if it is opened.

12. (a) conduction

(b) radiation

(c) Plastic is a good insulator of heat and does not allow the transfer of thermal energy to occur readily. Metal is a good conductor of heat and allows the transfer of thermal energy to occur readily. The contents of the flask would lose thermal energy and cool down faster if a metal screw-top were used.

(d) Firstly the silvered walls reflect heat back to the contents of the flask. The vacuum between the double walls prevents heat flowing from the hot contents to the cooler outside air by conduction and convection. The combined effect is that the contents of the flask remain hot for extended periods of time.

13. (a) conduction

(b) When the water in the kettle is heated by the heating element, the water near the bottom of the kettle becomes less dense and starts to rise. As it rises, it displaces the cooler more dense water near the top of the kettle. This water sinks to the bottom, is heated, and the process repeats. A convection current forms and the water continues to heat up.

(c) The plastic casing is in contact with the water. As the water gets hotter, it transfers thermal energy to the inside of the kettle casing. The plastic particles vibrate faster and, in turn, vibrate their slower neighbouring particles. The neighbouring particles vibrate faster and, in turn, vibrate their neighbours. The process continues and thermal energy is transferred through the plastic casing. An increase in the average kinetic energy of the particles means that the temperature of the plastic casing will increase.

14. Solids expand when heated. This makes the cork too tight to remove from the bottle when it heats up. When the bottle cools, so does the cork. The cork contracts and is easier to remove.

15. When heated, the particles of a solid vibrate faster over a greater distance. The particles take up more space and the object expands. Similarly, the particles of a liquid move around each other faster and take up more space. Liquids expand more than solids because the forces between the particles are weaker. When heated, the particles of a liquid move further apart.

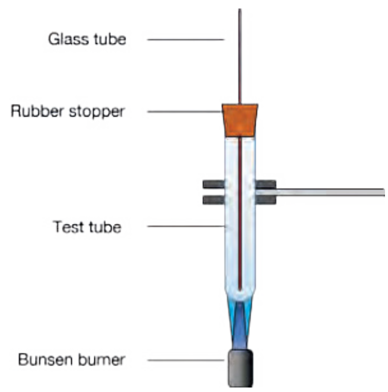
16. *Step 1:* Trap some water in a glass tube that fits firmly into a single-holed rubber stopper.

Step 2: Slide the tube through the hole in the rubber stopper.

Step 3: Seal an empty test tube with the rubber stopper.

Step 4: Heat the test tube using a Bunsen burner for a short time.

Step 5: The water that is trapped in the tube will move further up the tube. This indicates that the air/gas inside the test tube has expanded.



17. Solutions may vary. The following is a suggested solution to the question.

With the heating element at the base of the cooker, the contents would be heated via convection currents. The liquid near the base would heat up, become less dense and rise. The rising liquid displaces cooler liquid at the top of the contents. The cooler liquid is pushed to the base of the cooker where it is heated and the process repeats. In a short amount of time, the entire liquid content is heated. In addition, the liquid heats any solid contents of the cooker through conduction.

A heating element at the top of the cooker would not be as efficient as one placed at the base. When the cooker is filled with food and liquid, there would be a layer of air at the top of the cooker above the contents so that the lid can shut. Air is a good insulator and the transfer of heat to the contents would take longer if the cooker were designed with the heating element at the top. In addition, it would take much longer for convection currents to start flowing through the liquid contents. For these reasons, a heating element at the top of the cooker would be inefficient and is better placed at the base of the cooker.

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3.2 Specific heat capacity

1. The specific heat capacity is defined as the thermal energy needed to raise the temperature of one kilogram of a substance by one Kelvin/°C.

2. $Q = mc\Delta T \quad Q \propto \Delta T \quad m, c$ constant

   The thermal energy absorbed is directly proportional to the change in temperature experienced by the lead. Four times the thermal energy is absorbed, which means that four times the temperature change will occur. The temperature increases by $60 \times 4 = 240$ K.

3. (a) $Q = mc\Delta T = 0.5 \times 4180 \times (80) = 1.67 \times 10^5$ J

   (b) $Q_{released\ by\ heater} = Q_{absorbed\ by\ water}$

   $Pt = 1.67 \times 10^5$

   $P = \frac{1.67 \times 10^5}{t} = \frac{1.67 \times 10^5}{(60+15)} = 2.23 \times 10^3$ s

4. $Q = -mc\Delta T = -mc(T_f - T_i)$

   $T_f = -\frac{Q}{mc} + T_i = \frac{-1.23 \times 10^3}{0.075 \times 450} + 130 = 94$ °C

5. $Q_{released\ by\ hot\ water} = Q_{absorbed\ by\ cooler\ water}$

   $-m_H c_H \Delta T_H = m_c c_c \Delta T_c \qquad \Delta T = T_{final} - T_{initial}$

   $-m_H c_H (T_{final} - T_{H initial}) = m_c c_c (T_{final} - T_{H initial})$

   $-1.2 \times 4180 \times (T_{final} - 365) = 1.5 \times 4180 \times (T_{final} - 323)$

   $-1.2 \times (T_{final} - 365) = 1.5 \times (T_{final} - 323)$

   $-1.2\ T_{final} + 438 = 1.5\ T_{final} - 484.5$

   $-2.7\ T_{final} = -922.5$

   $T_{final} = 342$ K

6. (a) $Q_{released\ by\ lead} = Q_{absorbed\ by\ water}$

   $-m_L c_L \Delta T_L = m_w c_w \Delta T_w \qquad \Delta T = T_{final} - T_{initial}$

   $-m_L c_L (T_{final} - T_{H initial}) = m_w c_w (T_{final} - T_{H initial})$

   $-0.2 \times 130 \times (26 - 700) = 0.25 \times 4180 \times (26 - T_i)$

   $17524 = 1045 \times (26 - T_i)$

   $17524 = 27170 - 1045 T_i$

   $-9646 = -1045 T_i$

   $T_{initial} = 9.2$°C

   (b) That no thermal energy is transferred to the surroundings, e.g. to the air as the lead is transferred to the water or to the container in which the water is held.

7. (a) $Q_{released\ by\ metal X} = Q_{gained\ by\ water} + Q_{gained\ by\ calorimeter}$

   $-m_X c_X \Delta T_X = m_w c_w \Delta T_w + m_c c_c \Delta T_c \qquad \Delta T = T_{final} - T_{initial}$

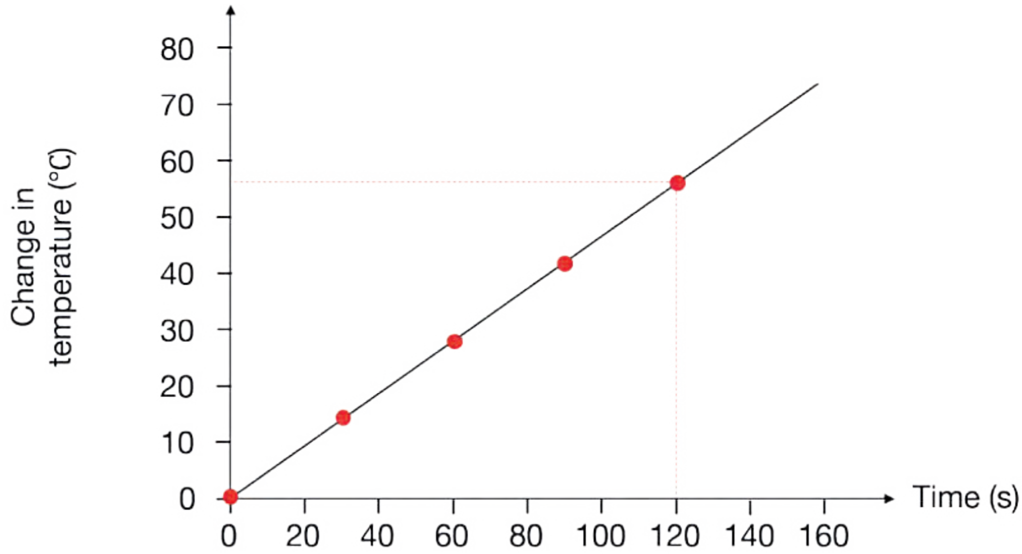
   $c_x = \frac{m_w c_w \Delta T_w + m_c c_c \Delta T_c}{-m_x \Delta T_x} = \frac{0.1 \times 4180 \times (19-15) + 0.1 \times 385 \times (19-15)}{-0.05 \times (19-100)} = 451\ J\ kg^{-1}\ °C$

   (b) The specific heat capacity of metal X is 451 J kg^{-1} °C. This means that one kilogram of the metal will absorb 451 J of thermal energy in raising its temperature by one degree Celsius or one Kelvin.

8. (a) Heating time

(b) The change in temperature of the water.

(c)



(d) $gradient = \frac{rise}{run} = \frac{57}{120} = 0.475 = 0.48\,°C\,s^{-1}$

(e) The change in temperature experienced by the water is directly proportional to the heating time.

$$\Delta T = 0.48t$$

(f) $Q_{released\ by\ heater} = Q_{gained\ by\ water}$

$\therefore \quad Pt = m_w c_w \Delta T_w \qquad \therefore \quad \Delta T_w = \frac{Pt}{m_w c_w}$

When compared to the equation of a straight line through the origin $y = mx$, the $gradient = \frac{P}{m_w c_w}$

It therefore follows that $c = \frac{P}{m_w \times gradient} = \frac{200}{0.1 \times 0.48} = 4167 = 4200\ J\,Kg^{-1}\,°C\ (2sf)$

(g) From the diagram, it can be seen that the potential difference and current can be measured using the voltmeter and ammeter respectively. The formula $P = VI$ gives the power rating of the heating element.

(h) Some thermal energy is absorbed by the cover. This is a random error.

(i) The measurements recorded for the change in temperature of the water should be repeated several times and averaged for each heating time.

(j) The plotted points lie on or very close to the line of best fit, i.e. there is very little scatter in the plotted points.

9. (a) $Pt = mc\Delta T$

$t = \frac{mc\Delta T}{P} = \frac{1.25 \times 4180 \times 79}{1.8 \times 10^3} = 229\ s = 3.82\ minutes$

(b) Saucepans come in various sizes. If a small saucepan is heated on a large heating element, part of the element will not be covered by the saucepan. The heat energy released by the heating element cannot be used to heat the contents of the saucepan and is 'lost' or wasted in heating the surrounding air. In terms of saving energy, it is best to choose an element that is closer to the size of the saucepan being heated.

10. (a) Copper is a good conductor of heat and readily allows heat energy to flow from the source (target) to the cooling fins.

(b) radiation

(c) Black materials readily emit radiation. Having spaces between the fins increases the surface area of the cooling fins. More heat can be transferred from the cooling fins to the surrounding air.

(d) The heat energy drawn away from the target in 0.1 s = 9.35×10^3 J

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3.3 Change of state

1. The latent heat of fusion of a substance is defined as the thermal energy needed to change one kilogram of a substance from solid state to liquid state without a change in temperature. The latent heat of vaporisation of a substance is defined as the thermal energy needed to change one kilogram of a substance from liquid state to gaseous state without a change in temperature.
2. $Q = mL = 5 \times 3.34 \times 10^5 = 1.7 \times 10^6\ J$
3. $Q = Q_{melt\ the\ ice} + Q_{raise\ temp\ to\ 100} + Q_{vaporise}$

   $Q = mL_f + mc\Delta T + mL_v$

   $Q = 0.2 \times 3.34 \times 10^5 + 0.2 \times 4180 \times (100) + 0.2 \times 2.26 \times 10^6$

   $Q = 6.02 \times 10^5\ J$
4. (a) $Q = Q_{raise\ temp\ to\ 100} + Q_{vaporise\ half}$

   $$Pt = mc\Delta T + \frac{m}{2}L_v$$

   $$P = \frac{mc\Delta T + \frac{m}{2}L_v}{t}$$

   $$P = \frac{0.5 \times 4180 \times (100 - 22) + 0.25 \times 2.26 \times 10^6}{(3 \times 60)}$$

   $$P = 4.0 \times 10^3\ W$$

   (b) This power rating means that the kettle uses 4.0×10^3 J of electrical energy every second.
5. Since the water is boiling, the temperature will remain constant at 100°C. The pasta won't cook any faster.
6. $Q = Q_{melt\ the\ ice} + Q_{raise\ temp\ to\ 37}$

   $Q = mL_f + mc\Delta T$

   $Q = 0.08 \times 3.34 \times 10^5 + 0.08 \times 4180 \times (37)$

   $Q = 3.91 \times 10^4\ J$
7. The water will evaporate from the towel. The towel loses thermal energy and cools down. Thermal energy then flows from your body at higher temperature to the cooler towel. Your body loses thermal energy and you cool down.
8. (a) Thermal energy needed to raise the temperature of the ball bearing to 100°C

   $Q = mc\Delta T = 0.3 \times 450 \times (80) = 10800\ J$

   Mass of ice that melts

   $$Q = mL_v \qquad m = \frac{Q}{L_v} = \frac{10800}{3.34 \times 10^5} = 3.23 \times 10^{-2}\ kg = 32.3\ g$$

   (b) The assumption is that all of the thermal energy absorbed by the ball bearing is transferred to the ice.
9. Thermal energy needed to raise the temperature to 100°C

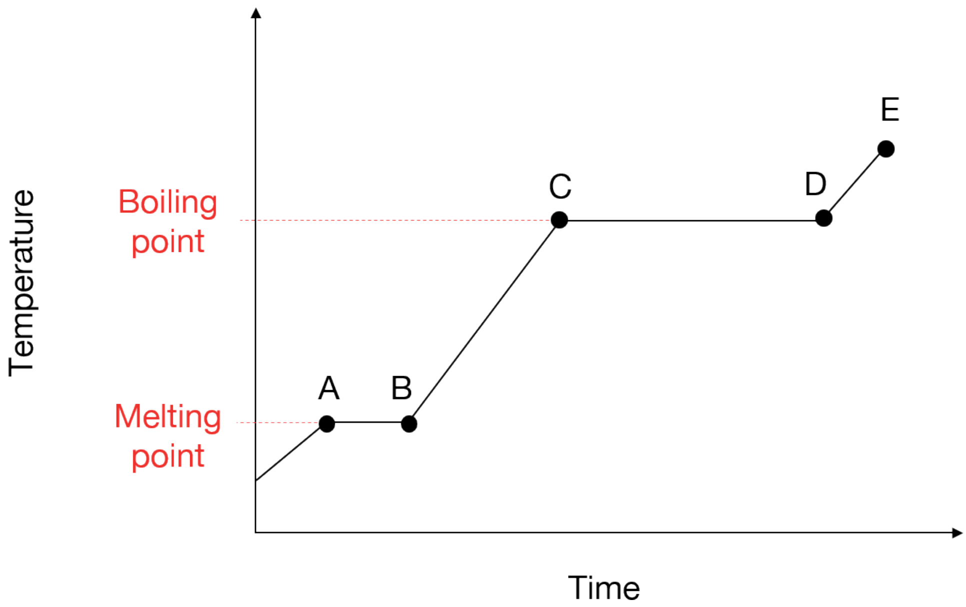
   $E_H = mc\Delta T = 2 \times 4180 \times (100 - 70) = 2.51 \times 10^5\ J$

   Energy available to vaporise the water to steam

   $Q = 2.00 \times 10^6 - 2.51 \times 10^5 = 1.749 \times 10^6\ J$

   $$Q = mL_v \quad \therefore \quad mass\ of\ steam \quad m = \frac{Q}{L_v} = \frac{1.749 \times 10^6}{2.26 \times 10^6} = 0.774\ kg$$

10.



(a) (i) BC

(ii) DE

(b) (i) AB

(ii) CD

(c) See graph

(d) See graph

(e) While a change of state is taking place, the temperature of the substance remains constant because the thermal energy being supplied is used to break chemical bonds between the particles.

This thermal energy is used to increase the distance between the particles without changing the kinetic energy of the particles so that the change of state can occur.

11. Boiling involves a substance changing from a liquid to a gas. It takes place at a temperature that is characteristic to a substance and occurs throughout the liquid.

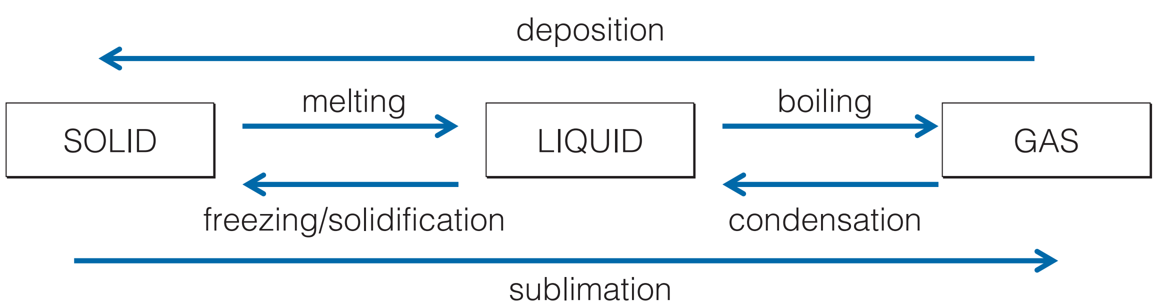
Evaporation is the term used when a substance changes from a liquid to a gas at a temperature below boiling point and occurs at the surface of the liquid and at all temperatures.

12. Boiling water contains the thermal energy that was absorbed to bring the water to the boil $Q = mc\Delta T$.

To get steam, additional heat energy must be absorbed for a change of state to occur i.e. $Q = mL$.

Steam contains more energy than boiling water. Since energy has the ability to cause change, a burn from steam is more severe than a burn from boiling water.

13.



14. (a) $Q_{removed} = Q_{cool\ water\ to\ zero} + Q_{freeze\ water} + Q_{reduce\ temperature\ of\ ice}$

$Q_{removed} = mc_w\Delta T_w + mL + mc_i\Delta T_i$

$Q_{removed} = 0.48 \times 4200 \times 22 + 0.48 \times 3.3 \times 10^5 + 0.48 \times 2200 \times 5$

$Q_{removed} = 2.1 \times 10^5\ J$

(b) Water expands when it is frozen and the plastic contracts when it is cooled. This causes the plastic bottle to deform.

Topic 4: Energy and momentum

4.1 Energy

1. (a) Work done is defined as the product of the displacement created by a force and the component of force parallel to the displacement.

   (b) W = Fs =15 × 2 = 30.0 J

   (c) 30.0 J

2. W = Fs = mas = 3000 × 1.57 × 1000 = 4.71 × 10^6 J

3. (a) W = Fscosθ = 220 × 300 × cos40 = 5.1 × 10^4 J

   (b) Reducing the angle at which the suitcase is being pulled increases the component of force parallel to the displacement. This increases the work done.

4. $W = Fs \ \therefore\ s = \frac{W}{F} = \frac{7.2 \times 10^3}{480} = 15\ m$

5. (a) The energy possessed by moving charges that make up an electrical current.

   (b) The energy possessed by vibrating air or matter molecules.

   (c) The energy possessed by the electronic structure of atoms and molecules. It is the energy associated with foods and fuels.

6. (a) Electrical energy ⟶ sound energy

   (b) Electrical energy ⟶ heat energy

   (c) Chemical potential energy ⟶ gravitational potential energy

   (d) Elastic potential energy ⟶ kinetic energy

7. As the person jumps off the springboard, elastic potential energy is converted into kinetic energy. As the person rises in the air, kinetic energy is converted into gravitational potential energy. At maximum height, all of the kinetic energy originally possessed by the diver is completely converted into gravitational potential energy. As the diver falls towards the water, gravitational potential energy is converted into kinetic energy.

8. (a) Kinetic energy is the energy possessed by a moving object.

   (b) Mass and speed.

   (c) The kinetic energy possessed by an object is directly proportional to its mass. This means that if the mass doubles so does the kinetic energy of the object. If the mass becomes five times smaller, so does the kinetic energy of the object i.e. the kinetic energy changes by the same factor as the mass.

   The kinetic energy possessed by an object is directly proportional to the square of its speed. This means that if the speed doubles, the kinetic energy of the object becomes four times larger. If the speed becomes five times smaller, the kinetic energy of the object becomes 25 times smaller.

9. $E_k = \frac{1}{2}mv^2 = \frac{1}{2}(3.9 \times 10^5)(\frac{950}{3.6})^2 = 1.36 \times 10^{10}\ J$

10. 40 kmh^{-1} = 11 ms^{-1}.

    $E_k = \frac{1}{2}mv^2 = \frac{1}{2}(1 \times 10^3)(11)^2 = 6 \times 10^4\ J\ (1sf)$

11. $E_k = \frac{1}{2}mv^2 \ \therefore\ v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 5.8 \times 10^2}{60}} = 4.40\ ms^{-1}$

12. (a) Gravitational potential energy is the energy possessed by an object due to its height in a gravitational field.

    (b) $E_P = mgh = 75 \times 9.8 \times 233 = 1.71 \times 10^5\ J$

    (c) The gravitational acceleration on the Moon is approximately six times smaller than the gravitational acceleration on Earth. This means that the gravitational potential energy of the bungee jumper would be approximately six times smaller.

13. $E_p = mgh \ \therefore\ h = \frac{E_p}{mg} = \frac{5.8 \times 10^2}{10 \times 9.8} = 5.92\ m$

14. (a) $E_k = \frac{1}{2}mv^2 = \frac{1}{2} \times (0.25)(160)^2 = 3200\ J$

(b) The work done in stopping the arrow is equivalent to the kinetic energy of the arrow.

$W = Fs \ \therefore\ F = \frac{W}{s} = \frac{3200}{0.08} = 4.0 \times 10^4\ N$

i.e. 4.0×10^3 N in the opposite direction that the arrow was initially travelling.

(c) Using Newton's Third Law, the force that the arrow exerts on the tree is equal and opposite to the force that the tree exerts on the arrow.

4.0×10^3 N in the direction that the arrow was originally travelling.

15. (a) $E_{k_{bottom}} = E_{p\ top}$ *Law of conservation of energy*

$\frac{1}{2}mv^2 = mgh$

$v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 36} = 26.6\ ms^{-1}$

(b) When the pot plant is released it possesses gravitational potential energy. As it falls, the gravitational potential energy is converted into kinetic energy. Once the pot plant reaches the ground, all of the gravitational potential energy it originally possessed is completely converted into kinetic energy.

(c) The kinetic energy of the plant pot on impact with the ground is transformed in to heat, sound and energy to deform/smash the pot. The pot is not elastic so the kinetic energy cannot be returned to pot as elastic energy which would enable it to bounce.

16. (a) $W = Fs = 285 \times 3.5 = 1000\ J$

(b) The work done is equivalent to the kinetic energy gained.

$E_k = \frac{1}{2}mv^2 = mgh \ \therefore\ v = \sqrt{\frac{2E_k}{m}} = \sqrt{\frac{2 \times 1000}{12}} = 12.9\ ms^{-1}$

17. (a) As the ball is thrown it possesses kinetic energy. As it rises, the kinetic energy is converted into gravitational potential energy. The higher the ball rises, the more kinetic energy is converted into gravitational potential energy. Once it reaches maximum height, all of the kinetic energy originally possessed by the ball is completely converted into gravitational potential energy.

(b) $E_{k_{when\ thrown}} = E_{p_{top\ of\ flight}}$

$\frac{1}{2}mv^2 = mgh$

$h = \frac{v^2}{2g} = \frac{20^2}{2 \times 9.8} = 20.4\ m$

18. (a) Using the law of conservation of energy

$E_{kA} = E_{pB}$

$\frac{1}{2}mv^2 = mgh$

$v = \sqrt{2gh} = \sqrt{2 \times 9.8 \times 0.06} = 1.08\ ms^{-1}$

(b) $0\ ms^{-1}$

Using the law of conservation of energy, as the ball swings up, the kinetic energy at A is completely converted back into gravitational potential energy at C.

19. (a) Total energy at the Start: $E_p + E_k = mgh_{start} + \frac{1}{2}mv_{start}^2$

It follows that $mgh_{start} + \frac{1}{2}mv_{start}^2 = \frac{1}{2}mv_A^2$

Therefore $gh_{start} + \frac{1}{2}v_{start}^2 = \frac{1}{2}v_A^2 \ \therefore\ v_A = \sqrt{2(gh_{start} + \frac{1}{2}v_{start}^2)} = \sqrt{2(9.8 \times 60 + \frac{1}{2} \times 5^2)} = 34.7\ ms^{-1}$

(b) Total energy at the Start: $E_p + E_k = mgh_{start} + \frac{1}{2}mv_{start}^2$

It follows that $mgh_{start} + \frac{1}{2}mv_{start}^2 = mgh_{finish} + \frac{1}{2}mv_{finish}^2$

$\therefore\ v_{finish} = \sqrt{2(gh_{start} - gh_{finish} + \frac{1}{2}v_{start}^2)} = \sqrt{2(9.8 \times 60 - 9.8 \times 40 + \frac{1}{2} \times 5^2)} = 20.4\ ms^{-1}$

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20. (a) $E_{k_{gained}} = \frac{1}{2}mv^2 = \frac{1}{2} \times 66 \times 5^2 = 825\ J$

(b) $P = \frac{\Delta E}{t} = \frac{825}{2.4} = 344\ W$

21. $P = \frac{\Delta E}{t}\ \therefore\ \Delta E = Pt = 60 \times (8 \times 60 \times 60) = 1.73 \times 10^6\ J$

22. (a) The work done is equivalent to the gravitational potential energy gained.

$E_p = mgh\ \therefore\ h = \frac{E_p}{mg} = \frac{9.3 \times 10^3}{350 \times 9.8} = 2.7\ m$

(b) $P = \frac{\Delta E}{t} = \frac{9.3 \times 10^3}{12} = 780\ W$

23. $P = Fv = 120 \times 0.35 = 42\ W$

24. $P = Fv\ \therefore\ v = \frac{P}{F} = \frac{2400}{6300} = 0.38\ ms^{-1}$

25. (a) $sin50 = \frac{H}{10}\ \therefore\ H = 10 \times sin50 = 7.66\ m$

(b) The useful work done by the motor in lifting the object through this height is equivalent to the gravitational energy gained.

$E_p = mgh = 40 \times 9.8 \times 7.66 = 3000 = 3.00 \times 10^3$ J

(c) The work done in over-coming friction

$W = Fs = 30 \times 10 = 300 = 3.00 \times 10^2$ J

The actual work done = 3300 = 3.30×10^3 J

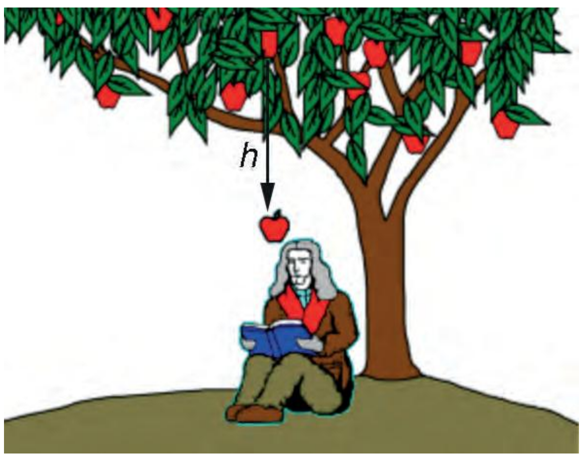
(d) $efficiency = \frac{useful\ energy}{total\ energy} = \frac{3000}{3300} = 0.909 =$

i.e. 90.9%

26. All three slides have the same vertical height. This means that the gravitational potential energy at the top of the slide is the same in all three cases. Using the law of conservation of energy, this gravitational potential energy is converted into kinetic energy as a person moves down the slide. The kinetic energy and therefore speed will be the same at the bottom in all three cases.

27. Solutions may vary. The following is a suggested solution to the question.

While the apple hangs from the tree it is suspended at a height and possesses gravitational potential energy. The amount of gravitational potential energy possessed by the apple is given by $E_p = mgh$. The gravitational potential energy possessed by the apple is directly proportional to the vertical height h through which it falls.



Using the law of conservation of energy, the gravitational potential energy of the apple is converted into kinetic energy as it falls. The taller the tree, the greater the value of h. It follows that the kinetic energy of the apple is greater by the time it hits Newton on the head. Since kinetic energy is given by $E_k = \frac{1}{2}mv^2$, it follows that the speed of impact is greater. In fact, $mgh = \frac{1}{2}mv^2$ leads to $v = \sqrt{2gh}$. The speed is directly proportional to the square root of the height through which the apple falls. If the height is double the speed will be $\sqrt{2}$ = 1.4 times larger. This is assuming the effects of air resistance are negligible so that the apple does not reach terminal speed. A greater speed on impact will cause more pain or potential injury.

4.2 Momentum

1. $\vec{p} = m\vec{v} = 30 \times 8 = 240\ kg\ ms^{-1}\ north$
2. $\vec{p} = m\vec{v} = 2000 \times \frac{80}{3.6} = 4.44 \times 10^4 kg\ ms^{-1}\ south$
3. $p = mv\ \therefore\ v = \frac{p}{m} = \frac{3.5}{0.625} = 5.60\ ms^{-1}$
4. (a) 0 ms^{-1}

   (b) $\Delta\vec{v} = \vec{v}_f - \vec{v}_i = 5\leftarrow -5\rightarrow = 5\leftarrow +5\leftarrow = 10\ ms^{-1}\leftarrow$ (i.e. 90° away from the wall)

   (c) $\Delta\vec{p} = m\Delta\vec{v} = 0.035 \times 10 = 0.35\ kg\ ms^{-1}\leftarrow$

   (d) $\vec{F}_{ball} = \frac{\Delta\vec{p}_{ball}}{\Delta t} = \frac{0.35}{0.05} = 7.0\ N\leftarrow$

   (e) Using Newton's Third Law, $\vec{F}_{wall} = -\vec{F}_{ball} = 7.0\ N\rightarrow$ (i.e. 90° towards the wall)
5. (a) $\Delta\vec{p} = m\vec{v}_f - m\vec{v}_i = 4.8 \times 10^{-27} \times 30\downarrow - 4.8 \times 10^{-27} \times 30\uparrow = 2.88 \times 10^{-25} kg\ ms^{-1}\downarrow$

   (b) $F = \frac{\Delta p}{\Delta t} = \frac{2.88 \times 10^{-25}}{1.5 \times 10^{-6}} = 1.92 \times 10^{-19}\ N\downarrow$

   (c) $1.92 \times 10^{-19}\ N\uparrow$
6. (a) $impulse = F\Delta t = 1.5 \times 10^2 \times 5 = 750\ sN$

   (b) $impulse = \Delta p = m\Delta v \qquad \Delta v = \frac{\Delta p}{m} = \frac{750}{95} = 7.9\ ms^{-1}$
7. (a) $impulse = F\Delta t\ \therefore\ F = \frac{impulse}{\Delta t} = \frac{2.5 \times 10^3}{4} = 625\ N$

   (b) $a = \frac{F}{m} = \frac{625}{50} = 12.5\ ms^{-2}$
8. The boxer's hand experiences a change in momentum over a given time. In the case of following through a punch, the change in momentum occurs over a longer period of time. Since $F = \frac{\Delta p}{\Delta t}$, then the greater the time over which the change in momentum occurs, the smaller the force on the boxer's hand. The punch hurts less.
9. The aim of the tennis player is to increase the momentum of the ball so that it has a greater speed. As the tennis racquet hits the ball, the ball experiences a change in momentum or impulse. The strength of the player limits the magnitude of the force that they can exert as they swing the tennis racquet. Since $\Delta p = Ft$, increasing the contact time will increase the impulse and hence change in momentum of the ball. The ball gains more speed.
10. (a) $Impulse = area\ under\ graph = \frac{1}{2} \times 50 \times 10 = 250\ sN$

    (b) $Impulse = \Delta p = mv_f - mv_i = mv_f$

    $v_f = \frac{\Delta p}{m} = \frac{250}{5} = 50\ ms^{-1}$
11. $E_k = \frac{1}{2}mv^2\ \therefore\ E_k = \frac{mv^2}{2} = \frac{m^2v^2}{2m}$ (*multiply top and bottom line by m*)

    it follows $E_k = \frac{m^2v^2}{2m} = \frac{p^2}{2m}$
12. Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

    $m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = m_T\vec{v}_f$

    $2.8 \times 10^3 \times 4\rightarrow + 0 = 6 \times 10^3 \times v_f$

    $1.12 \times 10^4 \rightarrow = 6 \times 10^3 \times v_f$

    $\therefore\ v_f = \frac{1.12 \times 10^4\rightarrow}{6 \times 10^3} = 1.9\ ms^{-1}\rightarrow$

    i.e. 1.9ms^{-1} in the initial direction that the 2.8×10^3 kg railway carriage was moving.
13. Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

    $m_1\vec{v}_{1i} + m_2\vec{v}_{2i} = m_1\vec{v}_{1f} + m_2\vec{v}_{2f}$

    $4 \times 10^3 \times 15\rightarrow + 2.8 \times 10^3 \times 35\leftarrow = 6.8 \times 10^3 v$

    $6 \times 10^4\rightarrow + 9.8 \times 10^4\leftarrow = 6.8 \times 10^3 \times v$

    $3.8 \times 10^4\leftarrow = 6.8 \times 10^3 \times v$

    $v = \frac{3.8 \times 10^4\leftarrow}{6.8 \times 10^3} = 5.6 ms^{-1}\leftarrow$

    i.e. 5.6 ms^{-1} to the left

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14. (a) Friction is minimal. This means that the system can be considered to be isolated and the law of conservation of momentum applies.

(b) Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

$$m_M\vec{v}_{Mi} + m_J\vec{v}_{Ji} = m_M\vec{v}_{Mf} + m_J\vec{v}_{Jf}$$

$$55\times 5\rightarrow +60\times 4\leftarrow = 55\times 1\leftarrow +60v$$

$$35\rightarrow = 55\leftarrow \; +60v$$

$$90\rightarrow = 60v$$

$$v = \frac{90\rightarrow}{60} = 1.50ms^{-1}\rightarrow$$

i.e. 1.50 ms^{-1} in the opposite direction that Jane was originally moving

15. (a) Using the law of conservation of momentum $\vec{p}_i = \vec{p}_f$

$$m_b\vec{v}_{bi} + m_{WB}\vec{v}_{WBi} = m_T\vec{v}_f$$

$$0.03\times 100\rightarrow +0 = 0.23\times v_f$$

$$3\rightarrow = 0.23\times v_f$$

$$\therefore \; v_f = \frac{3\rightarrow}{0.23} = 13.0ms^{-1}\rightarrow$$

(b) $E_K = \frac{1}{2}mv^2 = \frac{1}{2}\times 0.23\times 13^2 = 19.4\,J$

(c) Using the law of conservation of energy

$$E_K = E_p$$

$$\frac{1}{2}mv^2 = mgh$$

$$h = \frac{v^2}{2g} = \frac{13^2}{2\times 9.8} = 8.62\,m$$

16. (a) $E_p = mgh = 590 \times 9.8 \times 48.8 = 2.82 \times 10^5\,J$

(b) Law of conservation of energy: $mgh = \frac{1}{2}mv^2 = v = \sqrt{2gh}$

$v = \sqrt{2gh} = \sqrt{2\times 9.8\times 48.8} = 30.9\ ms^{-1}$

(a) $p = mv = 590 \times 30.9 = 1.82 \times 10^4\,sN$

(b) $F = \frac{\Delta p}{\Delta t}$

If the gondola crushes on impact with the ground, the time taken for the momentum to reduce from $1.82 \times 10^4\,sN$ to zero is greater. This reduces the force on the gondola and therefore its occupants.

17. (a) $v_B = \frac{s}{t} = \frac{0.08}{4\times 0.02} = 1.0\,ms^{-1}$

$v_A = \frac{s}{t} = \frac{0.06}{6\times 0.02} = 0.50\,ms^{-1}$

(b)

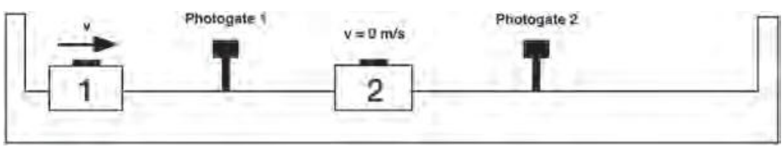
Trial 1
0.20
0.22
1.0
0.50

(a) $p_{before} = m_1v_{1i} + m_2v_{2i} = 0.2 \times 1.43 + 0 = 0.286 = 0.29\,sN\,(2sf)$

$p_{after} = (m_1 + m_2)\,v_f = (0.2 + 0.33) \times 0.55 + 0 = 0.292 = 0.29\,sN\,(2sf)$

Momentum is conserved

(b) A photogate (or light gate) can be used to determine the speed of Trolley 1 before and after the collision. Two are required. One is placed to the right of Trolley 1 so that it can measure its speed before it collides with Trolley 2 and one is placed to the right of Trolley 2 so that it can measure the speed of the trolleys after the collision. The arrangement is illustrated in the diagram below.



(c) Three trials are satisfactory but more trials (say 5 or 10) would increase the reliability of the conclusion reached.

Topic 5 : Waves

5.1 Wave model

1. A single vibration results in a pulse. A wave is created by a continuous vibration.
2. (a) Amplitude: The maximum displacement of the particles from the mean or equilibrium position of a wave.
   (b) Period: The time taken for one complete wave oscillation.
   (c) Wavelength: The distance between two points on the wave that are in phase.
   (d) Wave speed: The distance travelled by the wave per unit time.
3. (a) Two points on a wave are in phase if they are moving in the same direction with the same speed. Two points on a wave are out of phase if they are moving in the opposite direction with the same speed.
   (b) C and F.
   (c) B and D or E and G
   (d) $\frac{\lambda}{2}$
4. (a) Sound is a longitudinal wave. A longitudinal wave is wave in which the vibrations are parallel to the direction of wave propagation and travel as a series of compressions and rarefactions.

   For a sound wave compressions are positions of maximum pressure (the particles of the air are close together) and rarefactions are positions of minimum pressure (the particles of the air are spread out). For this reason sound waves are sometimes referred to as pressure waves.

   (b) (i) The tuning fork vibrates 440 times per second.
   (ii) $T = \frac{1}{f} = \frac{1}{440} = 2.3 \times 10^{-3}\ s$
   (c) $v = f\lambda \therefore \lambda = \frac{v}{f} = \frac{343}{440} = 0.78\ m$
5. (a) The wavelength of a wave is define as the distance between two points on the wave that are in phase.
   $\lambda = \frac{1.4}{49} = 2.86 \times 10^{-2}\ m$
   (b) $v = \frac{s}{t} = \frac{1.4}{4} = 0.350\ ms^{-1}$
   (c) $v = f\lambda \therefore f = \frac{v}{\lambda} = \frac{0.35}{2.86 \times 10^{-2}} = 12.2\ Hz$
6. $v = \frac{s}{t} \therefore s = vt = 1450 \times \frac{0.15}{2} = 109\ m$
7. (a) 3.0 cm
   (b) 20.0 ms = 0.02 s
   (c) $f = \frac{1}{T} = \frac{1}{0.02} = 50.0\ Hz$
   (d) $v = f\lambda = 50 \times 0.3 = 15.0\ ms^{-1}$
8. (a) A transverse wave is wave in which the vibrations are perpendicular to the direction of wave propagation. A transverse wave travels as a series of crests and troughs.
   (b) 4 m
   (c) 32.0 cm
   (d) $v = f\lambda \therefore f = \frac{v}{\lambda} = \frac{3}{4} = 0.75 = 0.8 Hz$
9. (a) As the police car approaches, the frequency of the sound heard by the student in the stationary car increases. This is because the waves bunch up in front of the police car. This reduces the wavelength and therefore increases the frequency as $f \alpha \frac{1}{\lambda}$.
   (b) The Doppler effect.
10. The period and frequency of a wave are inversely proportional.

    The rate at which you shake the hose will be the frequency of the wave produced. If you shake the hose three times faster, the frequency increases by a factor of three and the period becomes three times smaller.

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11. (a) A transverse wave is one in which the oscillations are perpendicular to the direction of wave propagation. A transverse wave travels as a series of crests and troughs.

(b) (i) 10 cm

(ii) 60 cm

(c) $v = f\lambda = \frac{\lambda}{T} = \frac{0.6}{0.4} = 1.5\ ms^{-1}$

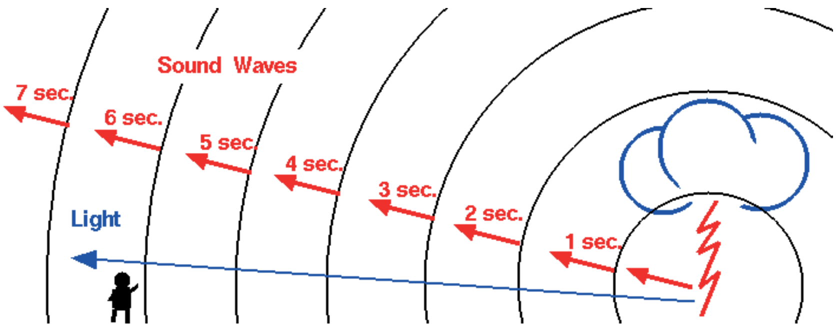
(d) Energy is required to vibrate the battle rope and create a wave along the rope. In addition, the person using the rope is in a squat position. The exercise engages many muscles of the body in creating the waves. This helps with weight loss and helps build muscle.

12. (a) $v = \frac{s}{t} = \frac{5.45 \times 10^3}{120} = 45.4\ ms^{-1}$

(b) $v = f\lambda \quad \therefore \quad f = \frac{v}{\lambda} = \frac{45.4}{52 \times 10^3} = 8.73 \times 10^{-4}\ Hz$

13. Solutions may vary. The following is a suggested solution to the question.

Light and sound are different types of waves. Light is a transverse wave that travels at a constant speed of 3.00×10^8 ms^{-1} while sound is a longitudinal wave and travels at a constant speed of around 330-340 ms^{-1} in air. Lightning is seen before thunder is heard because it travels much faster. Lightning can therefore reach an observer a significant distance away in a shorter time.



To determine the distance between the source of lightning and thunder and an observer, the observer needs to count or time the number of seconds between seeing the lightning and hearing the thunder. For example, they could count one-second, two-seconds, three-seconds etc or use a smart phone with a stopwatch app to measure this time more accurately. The observer could do this several times and calculate an average value.

The equation *s=vt* could then be used to calculate the distance between the observer and the source of the lightning and thunder. This is because waves travel with constant speed. In this case, *v* represents the speed of the sound and t represents the time between seeing the lightning and hearing the thunder. The greater the value of t, the further away the storm is.

5.2 Mechanical waves

1. (a) Resonance is the large amplitude vibration that occurs in an object when a forced vibration is the same as the object's natural frequency.

(b) As you push the child on the swing, they start to oscillate back and forth. When the force applied matches the natural frequency of the swing, resonance will occur. This increases the amplitude of the swinging motion. Little force is required to maintain this.

2. (a) Hard surfaces such as the wall will reflect sound waves. The sound waves produced from hitting the two pieces of wood together travel to the wall and are reflected back to the student. Since the wall is a large distance away, the time between the original sound and the reflection is long enough for a second sound or echo to be heard.

(b) $v = \frac{s}{t} \quad \therefore \quad t = \frac{s}{v} = \frac{480 \times 2}{340} = 2.8\ s$

3. (a) The principle of superposition states that whenever two waves meet in space, the amplitude of the resultant wave is a vector sum of the individual amplitudes of the original waves.

(b) (i) 4A

(ii) constructive superposition

(iii) 2A

(iv) destructive superposition

4. (a) The waves meet at P out of phase (crest meets a trough). Destructive superposition occurs which results in an amplitude of zero.

   (b) The string does not move.

5. (a) A crest is meeting a trough at the point P – destructive superposition occurs.

   (b) 0.5 λ

6. (a) $v = f\lambda \quad \therefore \quad \lambda = \frac{v}{f} = \frac{340}{1700} = 0.20\ m$

   (b) The path difference at P is 0.6 m. This is equivalent to $\frac{0.6}{0.2} = 3\lambda$.

   The sound waves meet in phase and undergo constructive superposition. The volume will be twice as loud.

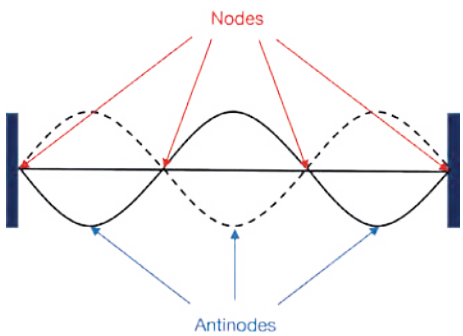
7. (a) Coherent light waves from the two slits, travel the same distance in reaching the centre of the screen. The light from each slit arrives in phase and undergoes constructive superposition. This results in maximum amplitude and therefore maximum light intensity.

   (b) (i) The pattern consists of a series of minima and maxima. These would appear as dark and bright bands respectively. The graph indicates that the band are of equal brightness and width (over the distance graphed).

   (ii) one wavelength or λ

8. (a) A standing wave pattern results when two waves with the same amplitude, frequency and wavelength travelling in the opposite direction meet and under go superposition.

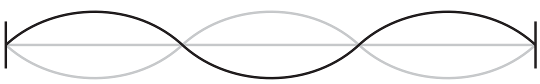
   (b) (i)



   (ii) $l = n\frac{\lambda}{2} = \frac{3\lambda}{2} \qquad \lambda = \frac{2l}{3} = \frac{2\times2}{3} = 1.33m$

9. (a) $f_1 = \frac{v}{2l} = \frac{110}{2\times0.5} = 110Hz$

   (b)



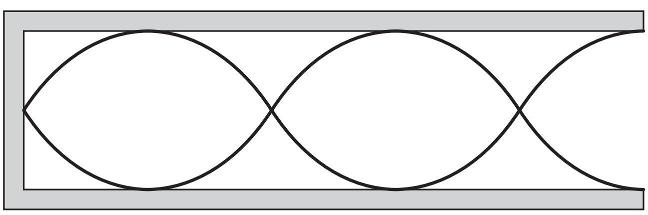
   (c) $l = \frac{3\lambda}{2} \quad \therefore \quad \lambda = \frac{2l}{3} = \frac{2\times0.5}{3} = 0.333m$

10. (a) $f_1 = \frac{v}{2l} \quad \therefore \quad v = 2lf_1 = 2\times0.45\times512 = 461Hz$

   (b) $Number\ of\ audible\ harmonics = \frac{20000}{f_1} = \frac{20000}{512} = 39$

11. (a) $f_1 = \frac{v}{4l} \quad \therefore \quad l = \frac{v}{4f_1} = \frac{340}{4\times200} = 0.43\ m$

   (b)



   $\ell = \frac{5\lambda}{4} \quad \therefore \quad \lambda = \frac{4\ell}{5} = \frac{4\times0.43}{5} = 0.34\ m$

   (c) The number of audible harmonics produced will determine the quality of the sound. The greater the number of audible harmonics, the better the quality of the sound. The piano string will produce harmonics that are an integer multiple of the fundamental. The quality of sound is better than an instrument that has a pipe open at one end only because such a pipe only produces harmonics that are an odd multiple of the fundamental i.e. half as any audible harmonics.

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12. (a) $f_1 = \frac{f_3}{3} = \frac{240}{3} = 80Hz$

(b) $f_1 = \frac{v}{4\ell} \quad \therefore \quad \ell = \frac{v}{2f_1} = \frac{150}{2 \times 80} = 0.94 \ m$

(c) $f_{180} = 180\ f_1 = 180 \times 80 = 14000Hz\ (2sf)$

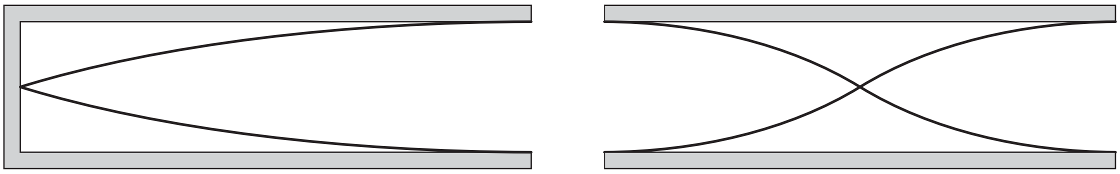
The human hearing range is 20 – 20 000 Hz. The180th harmonic is audible.

(d) $Number\ of\ audible\ harmonics = \frac{20000}{f_1} = \frac{20000}{80} = 250$

13. $v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{Tl}{m}} \quad \therefore \quad T = \frac{v^2 m}{l} = \frac{(100)^2 \times 10 \times 10^{-3}}{0.4} = 250N$

14. (a) $f_1 = \frac{v}{4\ell} \quad \therefore \quad \ell = \frac{v}{4f_1} = \frac{340}{4 \times 450} = 0.19m$

(b) (i)



(ii) $f_1 = \frac{v}{2\ell} \quad \therefore \quad \ell = \frac{v}{2f_1} = \frac{340}{2 \times 450} = 0.38 \ m$

The pipe open at at both ends is twice as long

(c) A pipe open at both ends produces harmonics that are an integer multiple of the fundamental. A pipe open at one end only produces harmonics that are an odd multiple of the fundamental i.e. half as any audible harmonics.

15. (a) The frequency of the sound waves produced by the guitars differs by a small amount. When the sound waves meet they undergo superposition. They will be periodically in and out of phase. This results in the volume varying periodically i.e. beats are produced.

(b) 3 .00Hz

(c) A beat frequency of 3.00 Hz means that the volume will vary from a minimum to a maximum three times every second.

5.3 Light

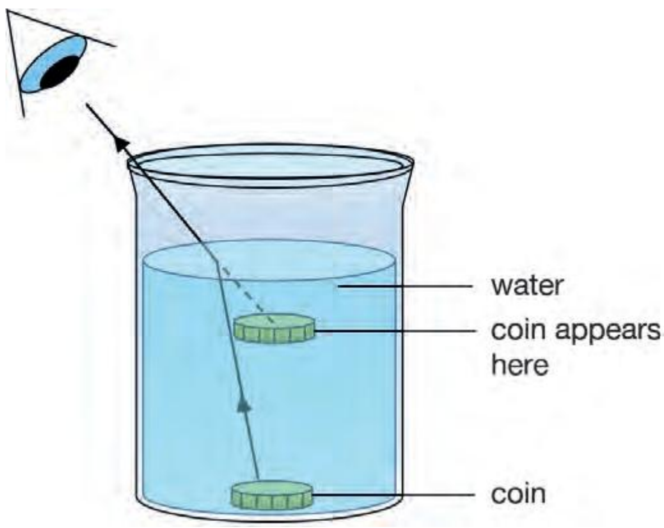
1. $v = f\lambda \quad \therefore \quad \lambda = \frac{v}{f} = \frac{3 \times 10^8}{107.1 \times 10^6} = 2.80m$

2. gamma rays, x-rays, visible light, infra-red, radiowaves

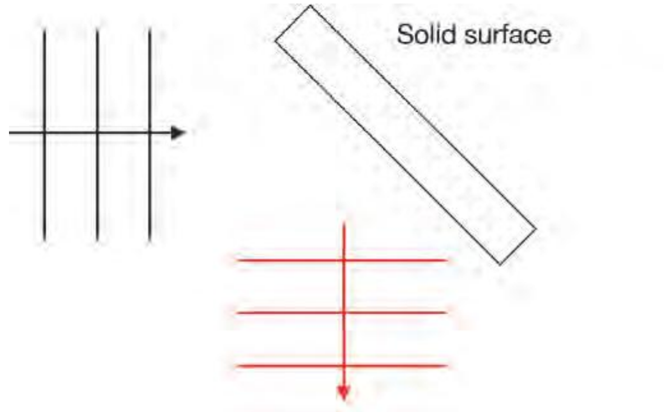
3. The word 'AMBULANCE' is laterally inverted so that when it is viewed through the rear view mirror by the driver of a vehicle in front of the ambulance it will read as AMBULANCE.

4. A concave mirror will enlarge the reflection. When working in a patient's mouth, cavities and other problems can be viewed clearly.

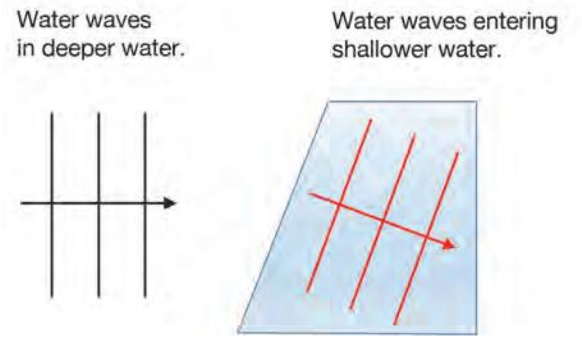
5. Light leaves the coin and travels towards our eye above the water's surface. The light bends away from the normal at the water-air boundary. Light travels in straight lines, so tracing the rays back, the coin appears higher in the water than it actually is.



6. (a)



(b)



7. (a) Snell's Law states that the ratio of sine of the angle of incidence to the sine of the angle of refraction is a constant and equal to the ratio of the speed of the wave in the incident medium to the speed in the refracting medium.

(b) (i) $\frac{\sin i}{\sin R} = \frac{n_2}{n_1}$ $\therefore$ $\frac{\sin 30}{\sin R} = \frac{1.33}{1}$ $\therefore$ $R = \sin^{-1}(\frac{\sin 30}{1.33}) = 22.1°$

(ii) $30 – 22.1 = 7.9°$

(iii) $\frac{n_2}{n_1} = \frac{v_1}{v_2}$ $\therefore$ $\frac{1.33}{1} = \frac{3\times10^8}{v_2}$ $\therefore$ $v_2 = \frac{3\times10^8}{1.33} = 2.26\times10^8 ms^{-1}$

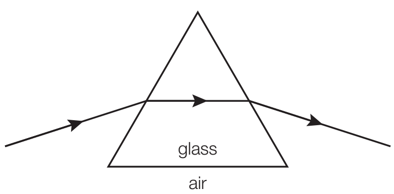
(iv) $\frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$ $\therefore$ $\frac{1.33}{1} = \frac{5.8\times10^{-7}}{\lambda_2}$ $\therefore$ $\lambda_2 = \frac{5.8\times10^{-7}}{1.33} = 4.36\times10^{-7} m$

8. (a) Towards the normal

(b) $\frac{\sin i}{\sin R} = \frac{n_2}{n_1}$ $\therefore$ $\frac{\sin i}{\sin 25} = \frac{1.5}{1}$ $\therefore$ $i = \sin^{-1}(\sin 25\times1.5) = 39°$

(c) $\frac{n_2}{n_1} = \frac{v_1}{v_2}$ $\therefore$ $\frac{1.5}{1} = \frac{3\times10^8}{v_2}$ $\therefore$ $v_2 = \frac{3\times10^8}{1.5} = 2.0\times10^8 ms^{-1}$

9.



10. (a) $gradient = \frac{0.75}{0.5} = 1.5$

(b) sin i = 1.5 sin R

(c) Snell's law states that the ratio $\frac{\sin i}{\sin R}$ is constant.

That is *sin i* is directly proportional to *sin R* (sin i α sin R). The straight line through the origin confirms this relationship.

(d) 1.5

11. (a) $\sin i_c = \frac{1}{n_1}$ $\therefore$ $\sin i_c = \frac{1}{1.45}$ $\therefore$ $i_c = \sin^{-1}(\frac{1}{1.45}) = 43.6°$

(b) The optical density or refractive index of the material that the light is totally internally reflected into is larger than the optical density of the material it would otherwise be refracted into.

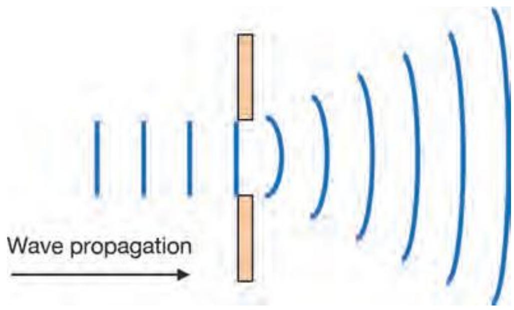
The angle of incidence must be greater than the critical angle.

12. $\sin i_c = \frac{1}{n_1}$ $\therefore$ $\sin 40 = \frac{1}{n_1}$ $\therefore$ $n_1 = \frac{1}{\sin 40} = 1.60$

13. $\frac{\sin i_c}{\sin 90} = \frac{n_2}{n_1}$ $\therefore$ $\frac{\sin i_c}{1} = \frac{1.45}{1.5}$ $\therefore$ $i_c = 75.2°$

When the ray of light is projected forward, the angle of incidence is 73.0°. This is less than the critical angle. The condition for total internal reflection is that the angle of incidence must be greater than the critical angle. The rays of light that enter the core at an angle of 17.0° will not be totally internally reflected.

14.



This phenomenon is called diffraction.

15. Electromagnetic waves consist of oscillating electric and magnetic fields. The electric and magnetic fields oscillate at right angles to one another and the direction of wave propagation.

16. (a) Electromagnetic waves are plane polarised if their plane of vibration is restricted to one plane only. The plane of polarisation is defined by the plane of the electric field.

(b) Electrons are forced to oscillate up and down along the length of the antenna. The electrons oscillate in the vertical plane and emit an electric field which oscillates in the vertical plane. By definition, the waves are vertically plane polarised.

Topic 6: Models and radioactivity

6.1 The nucleus

1. (a) The number of protons in the nucleus
   (b) The total number of protons and neutrons in the nucleus
   (c) A term to describe either a proton or a neutron.

2.

Nucleus	Protons	Neutrons	Nucleons
$^{23}_{11}Na$	11	12	23
$^{222}_{86}Rn$	86	136	222
$^{137}_{56}Ba$	56	81	137

3. (a) Electrons (approximately equal in number to the atomic charge of the nucleus) were embedded in a positive jelly like substance like plums in a pudding.
   (b) (i) positively charged alpha particles (or helium nuclei) were fired at very thin gold foil. To do this, alpha particles from a radioactive source (radium) were forced to pass through a hole in a block of lead (alpha particles are blocked by lead). Additional lead plates were used to form a beam.

   Any alpha particles that passed through the foil could be detected as a flash of light by a microscope fitted with a zinc sulfide screen. The microscope could rotate so that the number of alpha particles scattered at each angle could be counted over a fixed amount of time. The apparatus was evacuated to ensure that the alpha particles could reach the zinc sulfide screen without being scattered by the air particles.

   (ii) Most of the alpha particles passed straight through the foil with little or no deflection. The most significant result was that a number of alpha particles were back scattered (approximately 1 in every 10 000).

   (iii) A tiny positive nucleus was located at the centre of the atom. Electrons circled the nucleus and the rest of the atom was empty space.

4. (a) Isotopes of an element have the same atomic number but a different mass number.
   (b) (i) All three isotopes have 6 protons in the nucleus. They differ because carbon 12 has 6 neutrons, carbon 13 has 7 neutrons and carbon 14 has 8 neutrons. This increases the mass of each isotope.

   (ii) The chemical properties of an atom are determined by the number of electrons and their arrangement in the atom. A neutral atom has the same number of protons and electrons. Since isotopes have the same number of protons, it follows that they have the same number of electrons in the same arrangement. This makes them chemically identical.

5. (a) The nucleus is held together by a strong attractive short range nuclear force.

   It is very strong and opposes the repulsive force between protons. This force is also charge independent (acting equally between two protons, a proton and a neutron or two neutrons).

   (b) Neutrons separate the protons, increasing the distance between them so that the electrostatic force of repulsion is reduced and the strong nuclear force of attraction between nucleons can dominate.

6.2 Radioactive decay

1. (a) Alpha decay typically occurs in large unstable nuclei with atomic number greater than 83.
   (b) Beta minus decay occurs when a nucleus has an excess of neutrons.
   (c) Beta minus decay occurs when a nucleus has an excess of protons.
   (d) Gamma decay occurs when a nucleus is left with excess energy after an alpha or beta decay

2. (a) A = 226 Z = 88
   (b) A = 0 Z = –1
   (c) A = 137 Z = 56
   (d) A = 23 Z = 12
   (e) A = 225 Z = 97
   (f) A = 152 Z = 66
   (g) A = 227 Z = 89
   (h) A = 11 Z = 6

3. (a) $^{61}_{30}Zn \longrightarrow ^{61}_{31}Cu + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$

   (b) $^{144}_{60}Nd \longrightarrow ^{140}_{58}Ce + ^{4}_{2}\alpha$

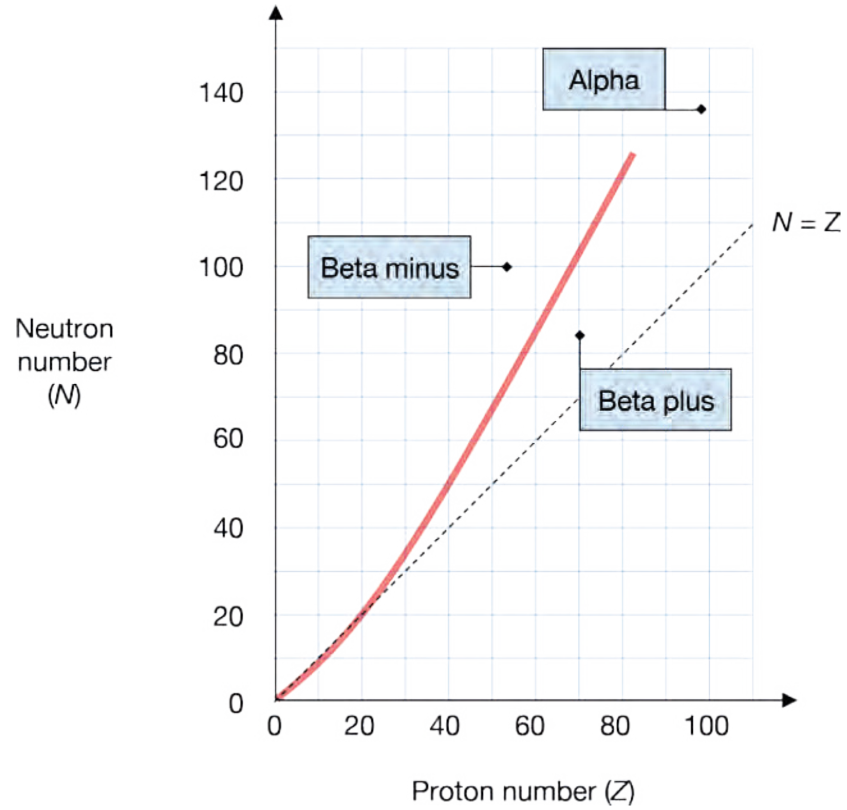
   (c) $^{40}_{18}Ar^{*} \longrightarrow ^{40}_{18}Ar + n^{0}_{0}\gamma$

4. $^{234}_{92}U \longrightarrow ^{A}_{Z}Y + 4^{4}_{2}\alpha + ^{0}_{-1}e + ^{0}_{0}\nu$

   Atomic number: 92 – 8 + 1= 85 (conservation of charge)

   Mass number: 234 – 16 = 218 (conservation of nucleon number)

5.



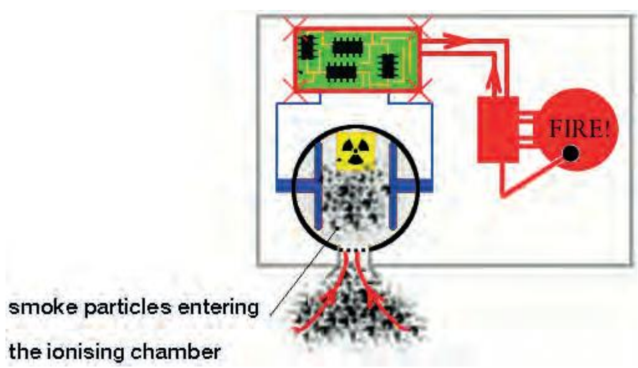
6. Ionising radiation can break chemical bonds in living matter. This can kill the cells or mutate the genetic material in cells (cause DNA mutations).

7. (a) The ionising ability of alpha decay is greater than the ionising ability of beta minus decay.

   (b) The penetration power of alpha decay is smaller than that of beta minus decay.

8. (a) Alpha decay has a low ability to penetrate matter. It is stopped within a few centimetres in air (due to its high ability to ionise the air particles). If the smoke detector is located on the ceiling of a room, it is unlikely that alpha particles will reach the occupants of the room.

   (b)



When smoke enters the ionising chamber, it disrupts the flow of ions between the two charged electrodes. This is because the smoke particles attach themselves to the ions stopping their flow. The circuit detects that the current has stopped flowing and sounds the alarm. When the smoke has cleared, and the chamber is no longer filled with smoke the ions begin flowing between the two charged electrodes and the smoke detector returns to its normal operation.

9. The sheet of steel will protect the worker from the beta decay but the gamma decay is likely to penetrate the steel. The worker should use a shield made of lead that is several centimetres thick.

10. 1. Increasing the distance from the ionising source.
    2. Limiting exposure time.
    3. Shielding yourself from the ionising source.

11. $^{238}_{92}U \longrightarrow {}^{206}_{82}Pb + 8\,^{4}_{2}\alpha + 6\,^{0}_{-1}e + 6\,^{0}_{0}\nu$

    Mass number has decreased by 238 – 206 = 32. This means that 8 alpha decay are released.

    The charge on the left hand side of the equation is 92. The charge on the right hand side of the equation is 82 + 16 = 98. This means 6 beta minus decay are emitted.

12. Solutions may vary. The following is a suggested solution to the question.

    Large, heavy, unstable nuclei with atomic number greater than 83 undergo alpha decay. An alpha particle or helium nucleus is emitted from the nucleus.

    A nucleus containing excess neutrons will undergo beta minus decay. A neutron turns into a proton during beta minus decay. An electron and (electron) antineutrino are emitted.

    A nucleus containing excess protons will undergo beta plus decay. A proton turns into a neutron. A positron and neutrino are emitted.

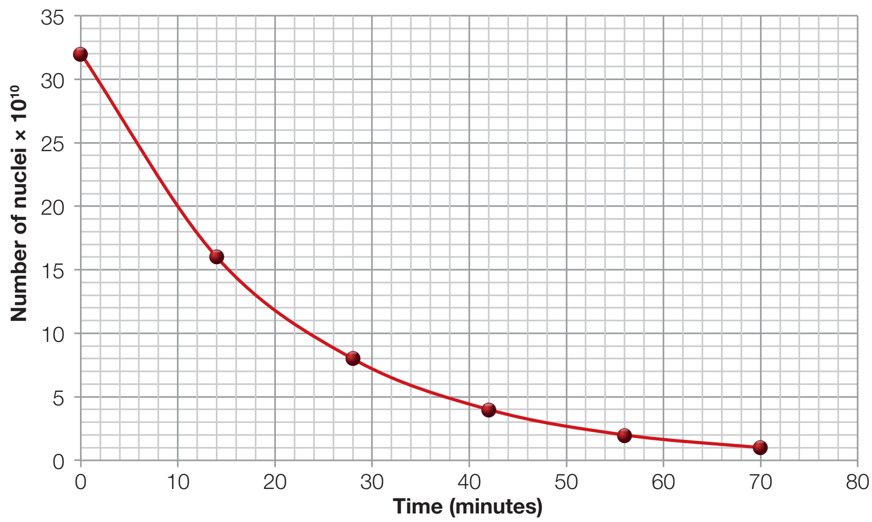
    Gamma decay often accompanies alpha and beta decay i.e. all radioactive nuclei.

    Gamma decay occurs when a nucleus is left with excess energy. It will decay emitting energy in the form of high-energy photons or gamma rays.

6.3 Radioactive half-life

1. (a) The time taken for half of the original number of nuclei to decay is called the half-life.

   (b) (i)



   (ii) 4

   (iii) 2×10^{10}

2. (a) 3 hours
   (b) 600 g left – 3400 g decayed
   (c) Activity is proportional to mass. The shape of the graph does not change. The half life of the activity is the same.

3. 7.2 minutes corresponds to 3 half-lives.

   $\frac{1}{8}$ of the mass remains i.e. $\frac{100}{8} = 12.5g$

4. (a) For the activity to reduce to 100 Bq, two half-lives must pass.

   i.e. 7.2 days

   (b) 18 days corresponds to 5 half-lives.

   The activity is reduced to $\frac{1}{32}$.

   $\frac{400}{32} = 12.5Bq$

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5. (a) 12 hours = 2 half-lives

   Activity = $\frac{240}{4} = 60Bq$

   (b) one day = 4 half-lives.

   Activity = $\frac{240}{16} = 15Bq$

6. (a) 10 days

   (b) A line that joins the points (0,80), (5,40), (10,20) etc.

   (c) No effect

   (d) If one quarter the isotope remains, then 2 half-lives have passed.

   i.e. 20 days

7. If 12.5% remain then 3 half-lives have passed.

   Age = 5730 × 3 = 17190 years

8. (a) Radioactive waste emits ionising radiation. This can break chemical bonds and or mutate DNA causing cancer. Radioactive waste must therefore be stored carefully so that living matter is not exposed to the ionising radiation.

   (b) Low level radioactive waste can be stored on site in lead lined steel containers. Radioactive waste with higher levels or radiation are buried deep below the Earth's surface in airtight lead lined steel containers.

6.4 Induced nuclear reactions

1. (a) Nuclear fission is the splitting of a heavy unstable nucleus into smaller more stable fragments when a neutron is captured.

   (b) The total mass of the reactants in a fission reaction is greater than that of the products. The difference in mass is converted into energy and released. The amount of energy released is given by $E = \Delta mc^2$, where Δm is the mass of the reactants minus the mass of the products.

2. E= the amount of energy released

   Δm = is the mass of the reactants minus the mass of the products.

   c = the speed of light (3.00×10^8 ms^{-1})

3. (a) A: 90 Z: 55

   (b) The products have excess neutrons. The products undergo beta minus decay i.e. a neutron is converted into a proton.

   (c) $^{90}_{37}Rb \longrightarrow ^{90}_{38}Y + ^{0}_{-1}e + ^{0}_{0}\bar{\nu}$

   (d) Mass of products

   $m_{Rb} + m_{Cs} + 3m_n = 1.41962 \times 10^{-25} + 2.20756 \times 10^{-25} + 3 \times 1.675 \times 10^{-27} = 3.67743 \times 10^{-25}$ kg

   Mass of reactant

   $m_U + m_n = 3.9017 \times 10^{-25} + 1.675 \times 10^{-27} = 3.91845 \times 10^{-25}$ kg

   $\Delta m = 3.91845 \times 10^{-25} - 3.67743 \times 10^{-25} = 2.4102 \times 10^{-26}$ kg

   Energy released $E = \Delta mc^2 = 2.4102 \times 10^{-26} (3 \times 10^8)^2 = 2.16 \times 10^{-9} J$

4. (a) During the induced fission of U-235, more than one neutron is emitted. These neutrons will be absorbed by other uranium 235 nuclei. These nuclei undergo induced fission and also release several neutrons. The process continues and a chain reaction results.

   (b) The most abundant isotope U-238 does not readily undergo induced fission. The isotope U-235 does, but constitutes less than one percent of all uranium reserves. Enrichment increases the fraction of U-235 in a sample and ensures that there are enough uranium nuclei that will undergo induced fission so that a chain reaction can proceed.

5. (a) The moderator slows neutrons down so that they are more likely to be captured by a uranium nucleus.

   A moderator has particles of a similar size to neutrons. When a neutron collides with a moderator particle, it loses a significant amount of kinetic energy and slows down within a few collisions to a speed that allows it to move to within 10^{-15} m of a uranium nucleus. This allows the strong attractive nuclear force to act so that the neutron can be absorbed .

(b) Hot pressurised liquid from the core at a temperature of approximately 320°C enters the heat exchanger and transfers heat energy to a separate supply of unpressurised water. This waster is easily heated it to boiling point producing steam that turns the blades of a turbine. The turbine rotates the generator to produce electricity.

6. (a) Nuclear fusion is the process in which two nuclei combine into a single nucleus.

(b) Fusion requires the colliding nuclei to possess a large amount of kinetic energy in order to overcome the large electrostatic repulsive forces between the positive nuclei. This will allow the nuclei to move to within 10^{-15} m of each other so that the strong attractive nuclear force can act and the nuclei can join. High temperatures give the nuclei the kinetic energy that they need for nuclear fusion to occur.

7. Mass of reactant

$2m_H = 2 \times 3.3445 \times 10^{-27} = 6.689 \times 10^{-25}$ kg

Mass of products

$mHe = 6.645 \times 10^{-27}$ kg

$\Delta m = 6.689 \times 10^{-27} - 6.645 \times 10^{-27} = 4.4 \times 10^{-29}$ kg

Energy released $E = \Delta mc^2 = 4.4 \times 10^{-29}\,(3 \times 10^8)^2 = 3.96 \times 10^{-12}\ J$

S

Appendices

Equation sheet

The following tables show the symbols of common quantities and the magnitude of physical constants used in the equations. Other symbols used are shown next to the equations. Vectors are indicated by arrows. If only the magnitude of a vector quantity is used, the arrow is not used.

Symbols of Common Quantities

acceleration	$\vec{a}$	wavelength	λ	momentum	$\vec{p}$
time	t	force	$\vec{F}$	potential energy	E_P
displacement	$\vec{s}$	charge	q	kinetic energy	E_K
velocity	$\vec{v}$	mass	m	temperature	T
period	T	potential difference	ΔV	electric current	I
frequency	f	resistance	R	power	P
work done	W	heat energy	Q or ΔQ	specific heat capacity	c

Magnitude of Physical Constants

Acceleration due to gravity	$9.80\ ms^{-2}$
Acceleration due to gravity on the moon	$1.67\ ms^{-2}$
Speed of light in a vacuum	$3.00 \times 10^8\ ms^{-1}$
Speed of sound in air	$330\ ms^{-1}$
Mass of an electron	$m_e = 9.11 \times 10^{-31}$ kg
Charge of an electron	$e = 1.60 \times 10^{-19}$ kg
Coulomb's Law constant	$\frac{1}{4\pi\varepsilon_0} = 9.00 \times 10^9\ Nm^2C^{-2}$
Specific heat capacity of water	$c_w = 4.20 \times 10^3\ Jkg^{-1}K^{-1}$
Latent heat of fusion of water	$L_f = 3.34 \times 10^5\ J\ kg^{-1}$
Latent heat of vaporisation of water	$L_f = 2.26 \times 10^6\ J\ kg^{-1}$

Topic 1: Linear Motion and Forces

$v = \frac{s}{t}$

$v_H = v\cos\theta$

$\vec{v} = \vec{v}_o + \vec{a}t$

$v_v = v\sin\theta$

$\vec{s} = \vec{v}_o t + \frac{1}{2}\vec{a}t^2$

$\vec{a} = \frac{\Delta\vec{v}}{\Delta t}$

$\vec{v}^2 = \vec{v}_o^2 + 2\vec{a}\vec{s}$

$\vec{F} = m\vec{a}$

$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$

$W = mg$

Topic 2: Electric Circuits

$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}$

$V_t = V_1 + V_2 + ..V_n$ $\quad R_t = R_1 + R_2 + ..R_n$

$\Delta V = \frac{Ep}{q}$

$I_t = I_1 + I_2 + ...I_n$ $\quad \frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + ..\frac{1}{R_n}$

$I = \frac{q}{t}$

$P = \frac{\Delta E}{t}$

$R = \frac{V}{I}$

$P = VI$

$R = \frac{\rho L}{A}$

$efficiency = \frac{useful\ energy\ /\ power\ output}{total\ energy\ /\ power\ input}$

Topic 3: Heat

$T(°C) = \frac{T(°F) - 32}{1.8}$

$Q = mc\Delta T$

$T(K) = T(°C) + 273$

$Q = mL$

Topic 4: Energy and Momentum

$W = Fs\cos\theta$

$P = \frac{W}{t} = Fv$

$E_k = \frac{1}{2}mv^2$

$\vec{p} = m\vec{v}$

$E_p = mgh$

$\vec{F} = \frac{\Delta\vec{p}}{\Delta t}$

Topic 5: Waves

$T = \frac{1}{f}$

$f_1 = \frac{v}{2l}$

$v = f\lambda$

$f_1 = \frac{v}{4l}$

$PD = m\lambda \quad (m = 0, 1, 2, 3\ldots)$

$f_{beat} = |f_1 - f_2|$

$l = n\frac{\lambda}{2}$

$\frac{\sin i}{\sin R} = \frac{v_1}{v_2} = \frac{n_2}{n_1} = \frac{\lambda_1}{\lambda_2}$

$l = (2n - 1)\frac{\lambda}{4}$

$v = \sqrt{\frac{T}{\mu}} = \sqrt{\frac{Tl}{m}}$

$\sin i_c = \frac{1}{n_1}$

Topic 6: Nuclear Models and Radioactivity

A = Z + N

$E = \Delta mc^2$

A = mass number

Z = atomic number

N = number of neutrons

Table of prefixes

Refer to the following table when answering questions that involve the conversion of units:

Prefix	tera	giga	mega	kilo	centi	milli	micro	nano	pico
Symbol	T	G	M	k	c	m	μ	n	p
Value	10^{12}	10^{9}	10^{6}	10^{3}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

A