National Curriculum (Vocational) Physical Science Level 2

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Contents

Subject Outcome XVIII. Chemical systems and industry: Identify and describe the impact of scientific knowledge of the hydrosphere on the quality of human, environmental, and socio-economic development

SUBJECT OUTCOME I

MECHANICS: IDENTIFY, DESCRIBE AND APPLY PRINCIPLES OF MOTION IN ONE DIMENSION

Subject outcome

Subject outcome 2.1: Identify, describe and apply principles of motion in one dimension.

Learning outcomes

- Describe motion and identify and define the components of motion, namely:
  - position
  - displacement and distance
  - speed and velocity, including average velocity, instantaneous velocity and uniform velocity
  - constant acceleration.
- Apply the concept of relative motion, i.e. motion quantities seen from two frames of reference.
- Do calculations on the components of motion.
- Solve problems using linear equations of motion (horizontal), namely:
  - $v_f = v_i + a\Delta t$
  - $s = v_i\Delta t + \frac{1}{2}a\Delta t^2$
  - $v_f^2 = v_i^2 + 2as$.
- Define and represent vectors and scalars and identify examples.
- Define resultant and equilibrant and determine resultant and equilibrant by construction.

Unit 1 outcomes

By the end of this unit you will be able to:

- Describe motion.
- Identify and describe the components of motion:
  - position
  - distance and displacement
  - speed and velocity (including average velocity, instantaneous velocity, uniform velocity)
  - acceleration.
- Apply the concept of relative motion.

Unit 2 outcomes

By the end of this unit you will be able to:

- Do calculations on components of motion.
- Solve problems using linear equations of motion (horizontal).

Unit 3 outcomes

By the end of this unit you will be able to:

- Define vectors and scalars.
- Identify examples of vectors and scalars.
- Represent vectors and scalars.

Unit 4 outcomes

By the end of this unit you will be able to:

- Define the resultant and equilibrant of vectors.
- Determine the resultant and equilibrant of vectors through construction.

Unit 1: Motion in one dimension

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Describe motion.
- Identify and describe the components of motion:
    - position
    - distance and displacement
    - speed and velocity (including average velocity, instantaneous velocity, uniform velocity)
    - acceleration.
- Apply the concept of relative motion.

What you should know

Before you start this unit, make sure you can:

- Convert units of length.
- Convert units of time.

Introduction

This unit[1] is about how things move along a straight line or, more scientifically, how things move in one dimension. Examples of this would be the movement (motion) of cars along a straight road or of trains along straight railway tracks.

Motion

There are three features of motion that we use to describe exactly how an object moves. They are:

- position, which tells us about an object's location, or displacement, which tells us about change of location
- speed, which tells us how fast the object is moving, or velocity, which tells us how fast the object is moving and where it is moving to; and
- acceleration, which tells us exactly how fast the object's speed and velocity are changing.

1. Parts of the text in this unit were sourced from *Siyavula Physical Science Gr 10 Learner's Book*, Chapter 21, released under a CC-BY licence at https://m.siyavula.com/read/science/grade-10/motion-in-one-dimension.

Position

A position is a measurement of a location from a reference point. With reference to the diagram in Figure 1 below, depending on which reference point we choose, we can say that the school is $300\ \text{m}$ from Kosma's house (with Kosma's house as the reference point or origin) or $500\ \text{m}$ from Kevin's house (with Kevin's house as the reference point or origin).

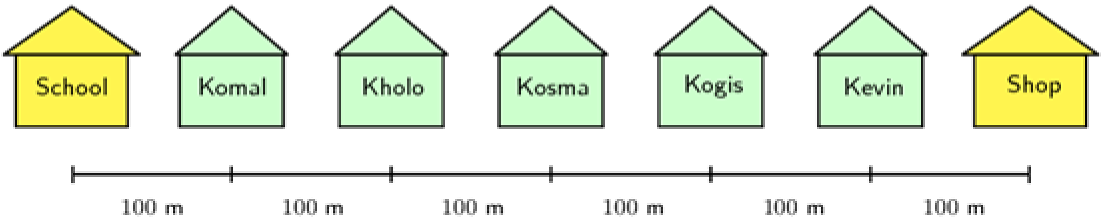


Figure 1: Diagram to illustrate positions from a reference point

The shop is also $300\ \text{m}$ from Kosma's house, but in the opposite direction to the school. When we choose a reference point, we choose a positive direction and a negative direction. If we choose the direction towards the school as negative, then the direction towards the shop is positive. A negative direction is always opposite to the direction chosen as positive.

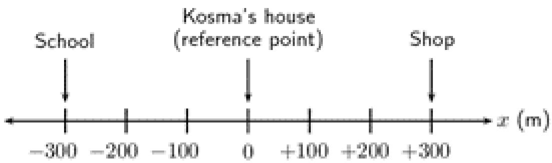


Figure 2: Graphical representation of position

The origin is at Kosma's house and the position of the school is $-300\ \text{m}$. In this instance, positions towards the left are defined as negative and positions towards the right are defined as positive.

Note that we could also choose the positive direction to be towards the school. In this case Kosma's house is still $300\ \text{m}$ away from the school, but it is now in the positive direction.

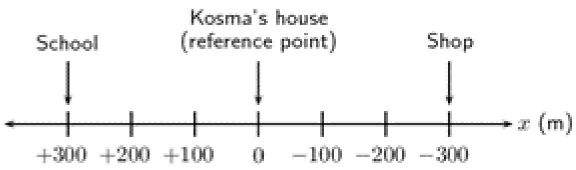
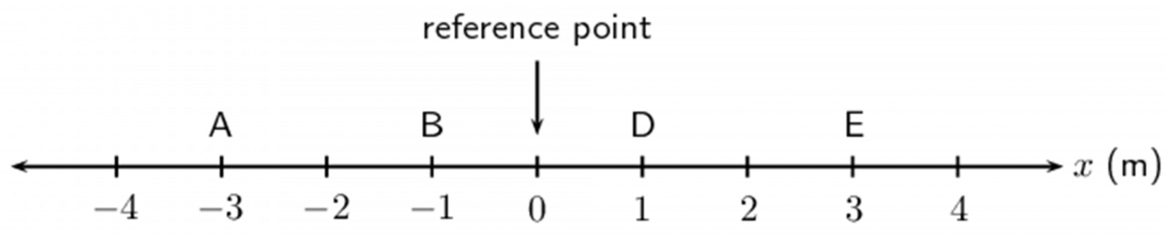


Figure 3: Graphical representation of position

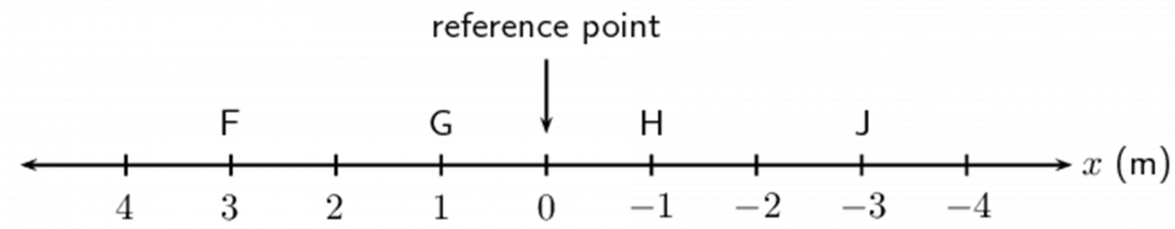
The origin is at Kosma's house and the position of the school is $300\ \text{m}$. In this instance, positions towards the left are defined as positive and positions towards the right are defined as negative.

Exercise 1.1

1. Write down the positions for objects at A, B, C and D. Do not forget units in your answer.



2. Write down the positions for objects at F, G, H and J.



The full solutions are at the end of the unit.

Distance and displacement

Distance is defined as the total length of the pathway from an initial position to a final position. The displacement of an object is defined as its change in position.

In the simple map in Figure 4 below, you can see the path from a school to a nearby shop is not straight because of obstacles on the route. The path is shown by a dashed line. Distance is the length of dashed line. It is how far you must walk along the path from the school to the shop. When stating the distance, it is not necessary to give a direction.

Displacement does not depend on the path travelled, but only on the initial and final positions. Displacement is the straight-line distance from the starting point to the endpoint, so from the school to the shop in Figure 4 below, as shown by the solid arrow. When stating the displacement, a frame of reference must be used to give the direction.

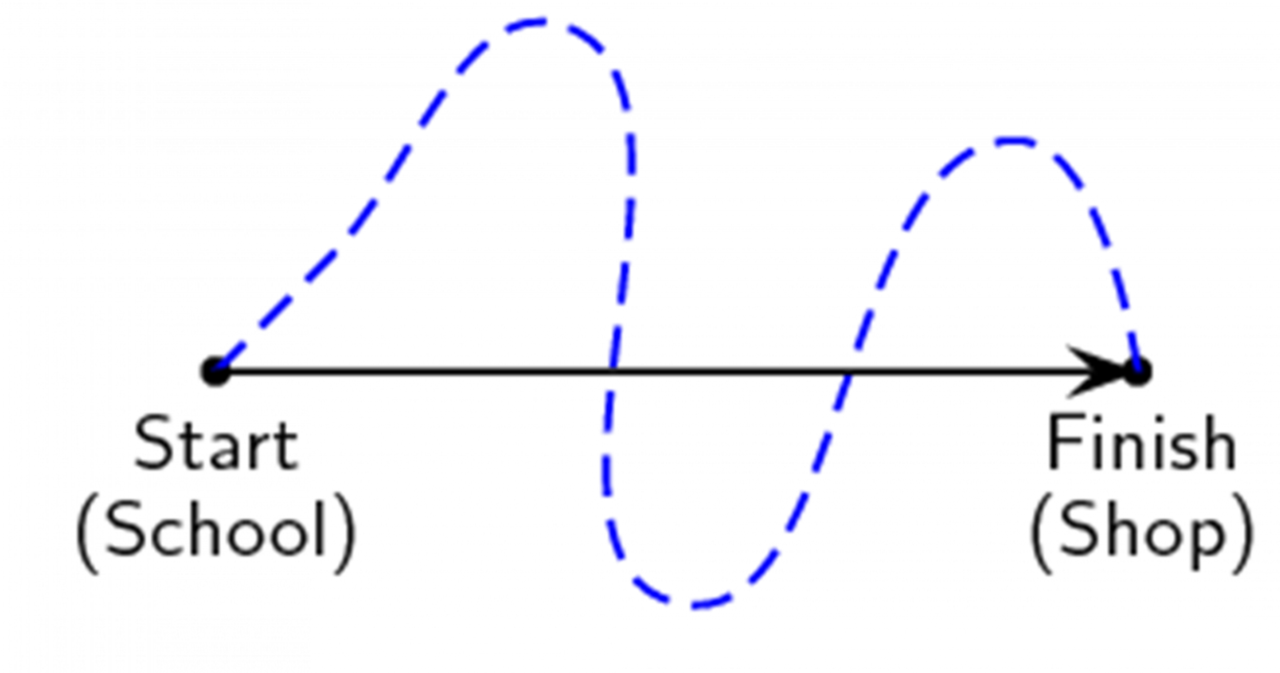
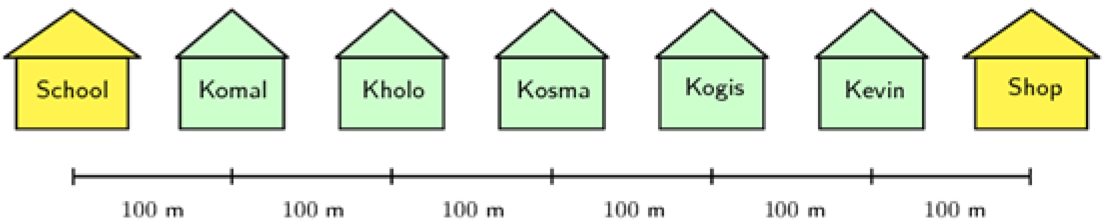


Figure 4: Distance and displacement from the school to the shop.

Example 1.1

Komal walks from his house to meet Kevin at Kevin's house before walking to school (see the figure below). What is Komal's displacement and what distance did he cover if he walks to school via Kevin's house? Take towards the school as positive.



Solution

Distance = $900\ \mathrm{m}$
Komal covers a distance of $400\ \mathrm{m}$ to Kevin's house and another $500\ \mathrm{m}$from Kevin's house to the school. He covers a total distance of $900\ \mathrm{m}$.

Displacement = 100 m towards the school.
This is because displacement only looks at the starting position (his house) and the end position (the school). It does not depend on the path he travelled. The frame of reference is Komal's house, so the direction is towards the school.

Exercise 1.2

Use the diagram in Example 1.1 to answer the following questions. Use the starting position as the reference point and towards the shop as the positive direction.

1. Kogis walks from her house to Kosma's house and then to school. What is her distance and displacement?
2. Kholo walks from her house to Kosma's house and then to school. What is her distance and displacement?
3. Komal walks from his house to the shop then to school. What is his distance and displacement?

The full solutions are at the end of the unit.

Note

It is possible to have a non-zero distance but a displacement of zero. This happens if a journey ends at the same place from which it started.

Speed and velocity

Speed is defined as the rate at which the distance (Δd) changes. It is calculated using the following formula:

$$\text{average speed} = \frac{\text{change in distance}}{\text{change in time}}$$

$$v \text{ (in m.s}^{-1}) = \frac{\Delta d \text{ (in m)}}{\Delta t \text{ (in s)}}$$

Note

Watch the video on Speed, distance and time to consolidate this concept (Duration: 3.12).

Velocity is defined as the rate of change in displacement (Δs). It is calculated using the following formula:

$$\text{average velocity (v)} = \frac{\text{change in displacement}}{\text{change in time}}$$

$$\vec{v}\ (\text{in m.s}^{-1}) = \frac{\Delta s\ (\text{in m})}{\Delta t\ (\text{in s})}$$

When calculating velocity, a direction must be given using a frame of reference.

Note

The symbol Δ is used to indicate the change in a quantity, which is the final value minus the initial value.

Example 1.2

James walks $2\ \text{km}$ away from home in 30 minutes. He then turns around and walks back home along the same path, also in 30 minutes. Calculate James' average speed and average velocity.

Solution

Step 1: Identify what information is given

The distance and time out: $2\ \text{km in } 30\ \text{minutes}$
The distance and time back: $2\ \text{km and } 30\ \text{minutes}$

Step 2: Check units

Units must be converted:
To convert km to m: $\text{x}\ 1\ 000$
To convert minutes to seconds: $\text{x}\ 60$

Step 3: Determine James' distance and displacement

James started at home and returned home, so his total distance is $4\ \text{km x}\ 1\ 000 = 4\ 000\ \text{m}$
His displacement will be $0\ \text{m}$, as his final position is the same as his starting position.

Step 4: Determine his total time

James took $30\,\text{min.} + 30\ \text{min.} = 60\ \text{min. x}\ 60 = 3\ 600\ \text{s}$.

Step 5: Determine his average speed

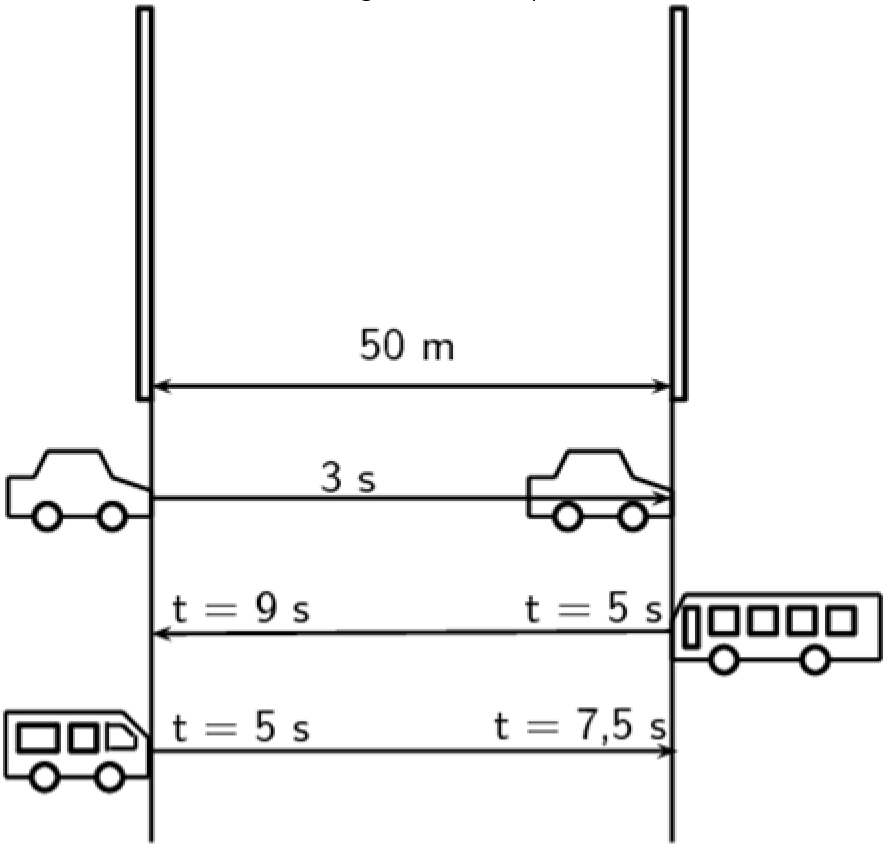
$$\begin{aligned} v &= \frac{\Delta d}{\Delta t} \\ &= \frac{4\ 000}{3\ 600} \\ &= 1.11\ \text{m.s}^{-1} \end{aligned}$$

Step 6: Determine his average velocity

$$\begin{aligned}\vec{v} &= \frac{\Delta s}{\Delta t} \\ &= \frac{0}{3\ 600} \\ &= 0\ \text{m.s}^{-1}\end{aligned}$$

Exercise 1.3

1. Bongani has to walk to the shop to buy some milk. After walking $100\ \text{m}$, he realises that he does not have enough money, and goes back home. If he arrives back home 4 minutes after he left, calculate the following:
   a. How long was he out of the house, in seconds?
   b. How far did he walk (his distance)?
   c. What was his displacement?
   d. What was his average velocity?
   e. What was his average speed?
2. Bridget is watching a straight stretch of road from her classroom window. She can see two poles which she earlier measured to be $50\ \text{m}$ apart. Using her stopwatch, Bridget notices that it takes $3\ \text{s}$ for most cars to travel left to right, from one pole to another.



   a. Calculate the velocity of a car.
   b. If Bridget calculates the velocity of another car to be $-16.67\ \text{m.s}^{-1}$, in which direction was it

travelling?

Bridget leaves her stopwatch running and notices that at $t = 5.0\ s$, a taxi passes the left pole and at the same time a bus passes the right pole. At $t = 7.5\ s$, the taxi passes the right pole and at $t = 9.0\ s$, the bus passes the left pole.

c. What was the average speed of the taxi?

d. What was the average velocity of the bus?

The full solutions are at the end of the unit.

Instantaneous velocity

Instantaneous velocity is the velocity at a specific instant in time. This can be different to the average velocity if the velocity is not constant. For example, the runners in a race will have different velocities at different stages of a race.

The instantaneous velocity (of an object) is the rate of displacement (change of position) per unit time measured over a very small time interval i.e. at an instant in time. Average velocity is the total displacement divided by the total time where the time frame is large. One can loosely state that the instantaneous velocity of an object is its speed at that moment with a direction.

Note

Watch the video on average speed for non-uniform velocity to consolidate the difference between instantaneous and average velocity (Duration: 4.13).

Uniform velocity

Uniform velocity occurs when the position of the object is changing at the same rate. Consider the following situation: Vivian uses an electrified wheelchair. She takes $100\ s$ at a constant pace to cover the $100\ m$ in a straight line to the bus stop from her house every morning. Her position changes by $1\ m$ in $1\ s$. She has a uniform velocity of $1\ m.s^{-1}$. This means that every second, she moved one more metre. For example, after $50\ s$ she will be $50\ m$ from home. Her instantaneous velocity will be the same at every point in the journey.

Acceleration

Acceleration is a measure of how fast the velocity of an object changes over time. We will only be dealing with constant acceleration (i.e. the increase in the velocity every second is the same). Acceleration can be calculated using the following formula:

$$\text{acceleration (in m.s}^{-2}\text{)} = \frac{\text{change in velocity (in m.s}^{-1}\text{)}}{\text{change in time (in s)}}$$

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

The change in velocity will be the final velocity (v_f) minus the initial velocity (v_i).

Like velocity, acceleration can be negative or positive. When the sign of the acceleration and the velocity are the same, the object is speeding up.

- If both velocity and acceleration are positive, the object is speeding up in a positive direction.
- If both velocity and acceleration are negative, the object is speeding up in a negative direction.
- If velocity is positive and acceleration is negative, then the object is slowing down.
- If the velocity is negative and the acceleration is positive the object is slowing down.

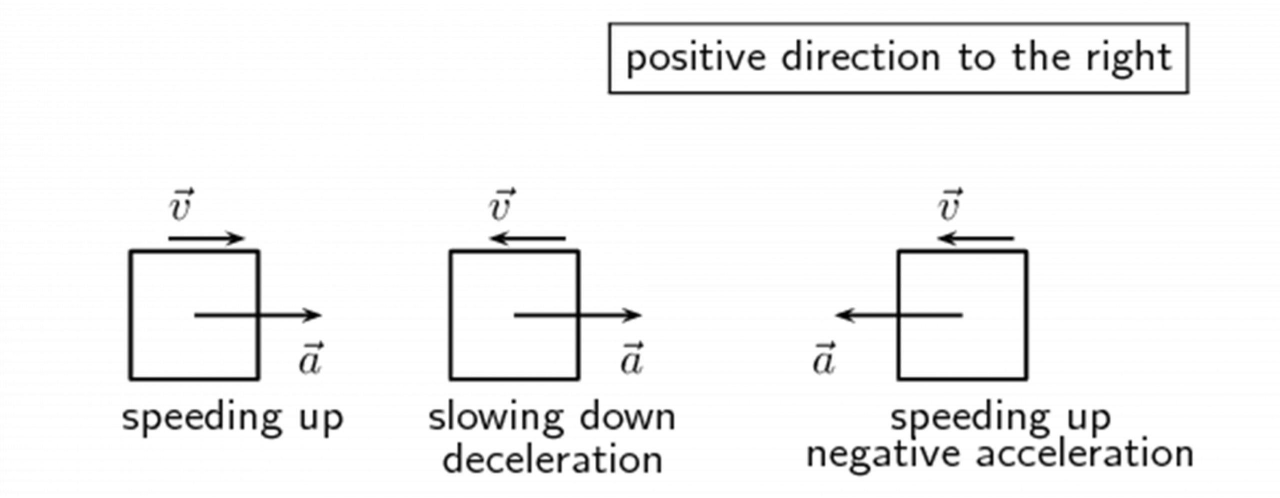


Figure 5: Direction of acceleration

Example 1.3

A car accelerates uniformly from an initial velocity of 2 m.s^{-1} to a final velocity of 10 m.s^{-1} in 8 s. It then slows down uniformly to a final velocity of 4 m.s^{-1} in 6 s. Calculate the acceleration of the car during the first 8 seconds and during the last 6 seconds.

Solution

Step 1: Choose a reference frame

We choose the point where the car starts to accelerate as the origin and the direction in which the car is already moving as the positive direction.

Step 2: Identify what information is given

Consider the motion of the car in two parts: the first 8 seconds and the last 6 seconds.

For the first 8 seconds:

$v_i = 2 \text{ m.s}^{-1}$
$v_f = 10 \text{ m.s}^{-1}$
$t = 8 \text{ s}$

For the last 6 seconds:

$v_i = 10\ \text{m.s}^{-1}$

$v_f = 4\ \text{m.s}^{-1}$

$t = 6\ \text{s}$

Step 3: Calculate the acceleration

For the first 8 seconds:

$$
\begin{aligned}
a &= \frac{\Delta v}{\Delta t} \\
&= \frac{10 - 2}{8} \\
&= 1\ \text{m.s}^{-2}
\end{aligned}
$$

For the next 6 seconds:

$$
\begin{aligned}
a &= \frac{\Delta v}{\Delta t} \\
&= \frac{4 - 10}{6} \\
&= -1\ \text{m.s}^{-2}
\end{aligned}
$$

During the first 8 seconds the car had a positive acceleration. This means that its velocity increased. The velocity is positive, so the car is speeding up. During the next 6 seconds the car had a negative acceleration. This means that its velocity decreased. The velocity is positive, so the car is slowing down.

Note

Watch the video What is Acceleration? (Physics in simple terms) to consolidate your understanding (Duration: 2.01).

Exercise 1.4

1. An athlete is accelerating uniformly from an initial velocity of $0\ \text{m.s}^{-1}$ to a final velocity of $4\ \text{m.s}^{-1}$ in 1 second. Calculate his acceleration. Let the direction that the athlete is running in be the positive direction.
2. A bus accelerates uniformly from an initial velocity of $15\ \text{m.s}^{-1}$ to a final velocity of $7\ \text{m.s}^{-1}$ in 4 seconds. Calculate the acceleration of the bus. Let the direction of motion of the bus be the positive direction.
3. An aeroplane accelerates uniformly from an initial velocity of $100\ \text{m.s}^{-1}$ to a velocity of $200\ \text{m.s}^{-1}$ in 10 seconds. It then accelerates uniformly to a final velocity of $240\ \text{m.s}^{-1}$ in 20 seconds. Let the direction of motion of the aeroplane be the positive direction.
   a. Calculate the acceleration of the aeroplane during the first 10 seconds of the motion.
   b. Calculate the acceleration of the aeroplane during the next 20 seconds of its motion.

The full solutions are at the end of the unit.

Relative motion

You can define different frames of reference for the same situation. For example, a boy is standing still inside a train as it pulls out of a station. You are standing on the platform watching the train move from left to right. To you it looks as if the boy is moving from left to right, because relative to where you are standing (the platform), he is moving. According to the boy, and his frame of reference (the train), he is not moving.

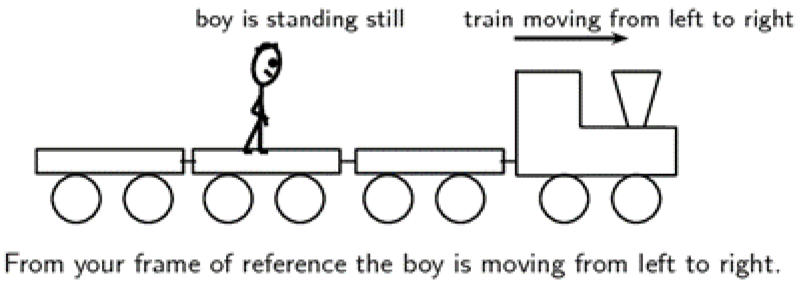


Figure 6: Watching a boy standing in a train

A frame of reference must have an origin (where you are standing on the platform) and a chosen positive direction. The train was moving from left to right, making moving to your right positive and to your left negative. If someone else was looking at the same boy, his frame of reference could be different. For example, if he was standing on the other side of the platform, the boy will be moving from right to left.

Note

Watch the video on relative velocity to consolidate this concept (Duration: 1.58).

Summary

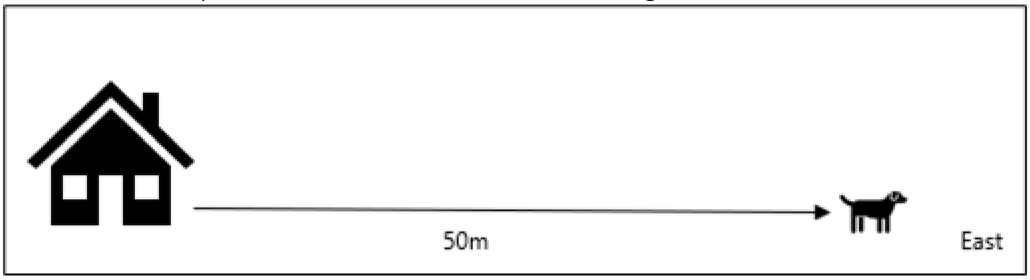
In this unit you have learnt the following:

- A reference point is a point from where you take your measurements.
- A frame of reference is a reference point with a set of directions.
- Your position is where you are located with respect to your reference point.
- The displacement of an object is how far it is from the reference point. It is the shortest disance between the object and the reference point.
- The distance of an object is the length of the path travelled from the starting point to the end point.
- Speed is the distance covered divided by the time taken: $v = \frac{\Delta d}{\Delta t}$.
- Average velocity is the displacement divided by the time taken: $\vec{v} = \frac{\Delta s}{\Delta t}$.
- Instantaneous speed is the speed at a specific instant in time.
- Instantaneous velocity is the velocity at a specific instant in time.
- Acceleration is the change in velocity over time: $a = \frac{\Delta v}{\Delta t}$.

Unit 1: Assessment

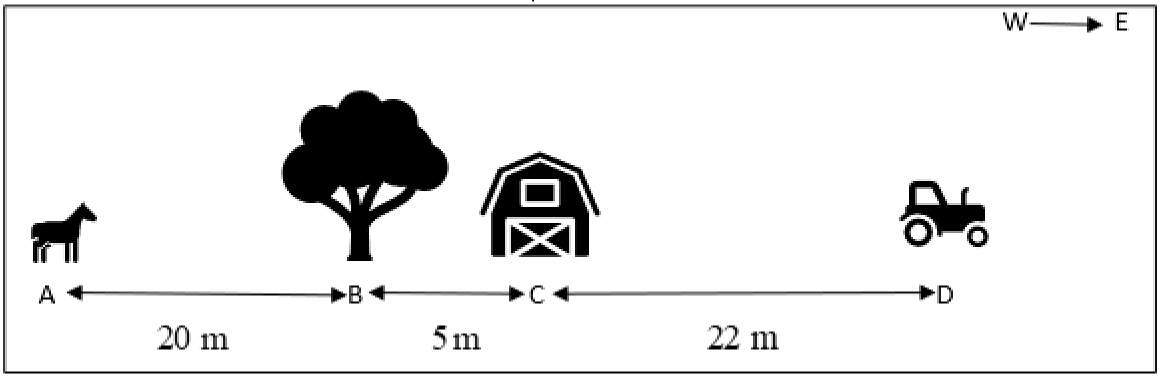
Suggested time to complete: 30 minutes

1. Take east as the positive direction and refer to the diagram:



   a. What is the position of the dog relative to the house?
   b. What is the position of the house relative to the dog?

2. Consider the sketch below and answer the questions:

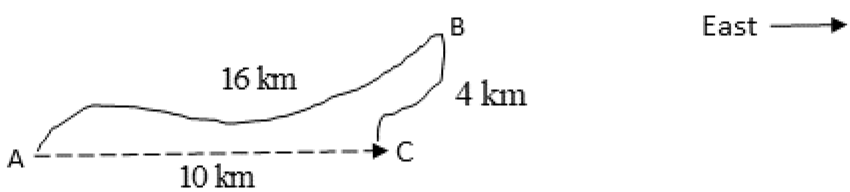


   Take east as the positive direction.

   a. Use the horse as the reference point, and describe the position of the tree, barn and tractor.
   b. Use the barn as the reference point, and describe the position of the horse, tree and tractor.
   c. Use the tractor as the reference point and describe the position of the horse, barn and tree.
   d. Use the tree as the reference point and describe the position of the horse, tractor and barn.

3. Differentiate between the concepts:
   a. distance and displacement.
   b. speed and velocity.
   c. instantaneous speed and average speed.

4. Consider the sketch below:



A man walks from A to B, and then to C. The man takes $2.5\ \text{hrs}$ to walk from A to B, and a further $0.5\ \text{hrs}$ to walk from B to C.

a. What distance does the man walk?

b. What is his displacement at point C?

c. What is his average speed?

d. What is his average velocity?

5. A girl jogs $500\ \text{m}$ from point P to point Q at an average speed of $2.5\ \text{m.s}^{-1}$ and then sprints back from Q to P in $120\ \text{s}$.

   a. How long does it take her to jog from P to Q?

   b. Calculate her average speed from Q to P.

   c. Calculate her average speed over the total distance.

   d. What is her velocity for the whole journey?

6. During a training session, Brian runs $50\ \text{m}$ north from the centre spot on the rugby field to point A in $10\ \text{s}$. He then runs to point B which is $25\ \text{m}$ due south of the centre spot in $15\ \text{s}$. Calculate:

   a. his average speed from the centre spot to point B.

   b. his average velocity from the centre spot to point B.

7. A truck is travelling at $25\ \text{m.s}^{-1}$ east and increases its speed to $50\ \text{m.s}^{-1}$in $10\ \text{s}$. What is the truck's acceleration? (Remember to put a direction in your answer.)

8. The truck in question 7, now travelling at $50\ \text{m.s}^{-1}$ approaches an intersection and the driver starts to apply the brakes. The truck comes to rest in $10\ \text{s}$. What is the truck's acceleration? (Remember to put a direction in your answer.).

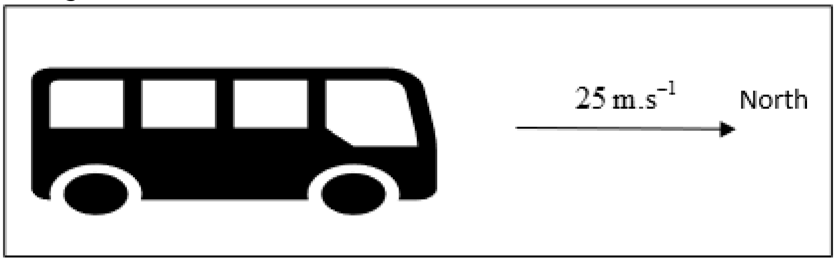
9. Anton starts skateboarding from rest down a slope and experiences an acceleration of $0.5\ \text{m.s}^{-2}$ down the slope. When he reaches the bottom of the slope, he is moving at $15\ \text{m.s}^{-1}$. When reaching the bottom, he needs to stop in $10\ \text{s}$ so as not to hit a barrier. Calculate:

   a. Anton's velocity after the first $8\ \text{s}$.

   b. how many seconds it takes (from rest) to reach $15\ \text{m.s}^{-1}$.

   c. the acceleration he has to undergo to stop in $10\ \text{s}$.

10. Lulu is sitting on a bus which is travelling north at a constant velocity of $25\ \text{m.s}^{-1}$. Her friend Thandi is sitting next to her.



   a. What is Lulu's velocity relative to the ground?

   b. What is Lulu's velocity relative to Thandi?

   Thandi gets up and walks to the front of the bus at $1.5\ \text{m.s}^{-1}$.

   c. What is Thandi's velocity relative to Lulu?

   d. What is Thandi's velocity relative to the ground?

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1.
   A: $-3\ \mathrm{m}$ from the reference point
   B: $-1\ \mathrm{m}$ from the reference point
   C: $1\ \mathrm{m}$ from the reference point
   D: $3\ \mathrm{m}$ from the reference point
2.
   F: $3\ \mathrm{m}$ from the reference point
   G: $1\ \mathrm{m}$ from the reference point
   H: $-1\ \mathrm{m}$ from the reference point
   J: $-3\ \mathrm{m}$ from the reference point

[Back to Exercise 1.1]

Exercise 1.2

1. $\Delta d = 100 + 300 = 400\mathrm{m}$
   $\Delta s = -300 + (-100) = -400\ \mathrm{m}$ from her house
2. $\Delta d = 100 + 300 = 400\mathrm{m}$
   $\Delta s = 100 + (-300) = -200\ \mathrm{m}$ from her house
3. $\Delta d = 500 + 600 = 1\ 100\mathrm{m}$
   $\Delta s = 500 + (-600) = -100\ \mathrm{m}$ from his house

[Back to Exercise 1.2]

Exercise 1.3

1.
   a. $4\ \mathrm{mins\ x}\ 60 = 240\ \mathrm{s}$
   b. $100 + 100 = 200\ \mathrm{m}$
   c. 0 (end point is at starting point)
   d. 0 (if $\Delta s = 0$, then $\vec{v} = 0$)
   e. $v = \dfrac{\Delta d}{\Delta t} = \dfrac{200}{240} = 0.83\ \mathrm{m.s}^{-1}$
2.
   a. $\vec{v} = \dfrac{\Delta s}{\Delta t} = \dfrac{50}{3} = 16.67\ \mathrm{m.s}^{-1}$ left to right
   b. right to left
   c. $v = \dfrac{\Delta d}{\Delta t} = \dfrac{50}{7.5 - 5.0} = 20\ \mathrm{m.s}^{-1}$
   d. $\vec{v} = \dfrac{\Delta s}{\Delta t} = \dfrac{-50}{9 - 5} = -12.5\ \mathrm{m.s}^{-1}$ (left to right)

[Back to Exercise 1.3]

Exercise 1.4

1.
$$v_i = 15 \text{ m.s}^{-1\rightarrow} \ v_f = 7 \text{ m.s}^{-1} \ \ \triangle \text{ t} = 4 \text{ s}$$
$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{7-15}{4} = -2 \text{ m.s}^{-2} = 2 \text{ m.s}^{-2} \text{ backwards}$$

2.
$$v_i = 15 \text{ m.s}^{-1\rightarrow} \ v_f = 7 \text{ m.s}^{-1} \ \ \triangle \text{ t} = 4 \text{ s}$$
$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{7-15}{4} = -2 \text{ m.s}^{-2} \text{ backwards}$$

3.
   a.
   $$v_i = 100 \text{ m.s}^{-1} \ v_f = 200 \text{ m.s}^{-1} \ \ \triangle \text{ t} = 10 \text{ s}$$
   $$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{200-100}{10} = 10 \text{ m.s}^{-2} \text{ forward}$$
   b.
   $$v_i = 200 \text{ m.s}^{-1} \ v_f = 240 \text{ m.s}^{-1} \ \ \triangle \text{ t} = 20 \text{ s}$$
   $$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{240-200}{20} = 2 \text{ m.s}^{-2} \text{ forward}$$

Back to Exercise 1.4

Unit 1: Assessment

1.
   a. 50 m east
   b. $-50 \text{ m} = 50 \text{ m west}$
2.
   a. tree: 20 m east
   barn: 25 m east
   tractor: 47 m east
   b. horse: $-25 \text{ m} = 25 \text{ m west}$
   tree: $-5 \text{ m} = 5 \text{ m west}$
   tractor: 22 m east
   c. horse: $-47 \text{ m} = 47 \text{ m west}$
   barn: $-22 \text{ m} = 22 \text{ m west}$
   tree: $-27 \text{ m} = 27 \text{ m west}$
   d. horse: $-20 \text{ m} = 20 \text{ m west}$
   tractor: 27 m east
   barn: 5 m east
3.
   a. Distance is the total length of the pathway from an initial position to a final position whereas displacement is the straight line from the initial position to the final position.
   b. Speed is the rate at which the distance is covered whereas velocity is the rate at which the displacement changes.
   c. Average speed is the total distance divided by the total time. This may not be the actual speed of the object at any point if the speed is not constant. Instantaneous speed is the distance over a very short time interval and indicates the speed at that moment.
4.

a. $16 + 4 = 20\ \text{km}$

b. $10\ \text{km east}$

c. $v = \dfrac{\Delta d}{\Delta t} = \dfrac{20\ \text{km}}{(2.5 + 0.5)\ \text{hr}} = 6.67\ \text{km.h}^{-1}$

d. $\vec{v} = \dfrac{\Delta s}{\Delta t} = \dfrac{10\ \text{km}}{(2.5 + 0.5)\ \text{hr}} = 3.33\ \text{km.h}^{-1}\ \text{east}$

5.

a.

$$v = \frac{\Delta d}{\Delta t}$$
$$2.5 = \frac{500}{\Delta t}$$
$$\Delta t = 200\ \text{s}$$

b.

$$v = \frac{\Delta d}{\Delta t}$$
$$v = \frac{500}{120}$$
$$= 4.17\ \text{m.s}^{-1}$$

c.

$$v = \frac{\Delta d}{\Delta t}$$
$$v = \frac{500 + 500}{200 + 120}$$
$$= 3.13\ \text{m.s}^{-1}$$

d. 0 (girl ends at her starting point – P)

6. If north is chosen as positive:

a. $v = \dfrac{\Delta d}{\Delta t} = \dfrac{(50 +\ 50\ +\ 25)}{(10 + 15)} = 5\ \text{m.s}^{-1}$

b. $\vec{v} = \dfrac{\Delta s}{\Delta t} = \dfrac{(-25)}{(10 + 15)} = 1\ \text{m.s}^{-1}\ \text{south}$

7.

$v_i = 25\ \text{m.s}^{-1}\ v_f = 50\ \text{m.s}^{-1}\ \Delta\text{t} = 10\ \text{s}$

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{50 - 25}{10} = 2.5\ \text{m.s}^{-2}\ \text{east}$$

8.

$v_i = 50\ \text{m.s}^{-1}\ v_f = 0\ \Delta\text{t} = 10\ \text{s}$

$$a = \frac{\Delta v}{t\Delta} = \frac{v_f - v_i}{\Delta t} = \frac{0 - 50}{10} = -5\ \text{m.s}^{-2} = 5\ \text{m.s}^{-2}\ \text{west}$$

9.

a.

$v_i = 0\ a = 0.5\ \text{m.s}^{-2}\ \Delta\text{t} = 8\ \text{s}$

$$a = \frac{\Delta v}{\Delta t}$$
$$0.5 = \frac{v_f - v_i}{\Delta t} = \frac{0 - v_f}{8}$$
$$\text{v}_f = -0.5\ \text{x}\ 8 = 4\ \text{m.s}^{-1}\ \text{down the slope}$$

b.

$$v_i = 0 \ v_f = 15 \text{ m.s}^{-1} \ a = 0.5 \text{ m.s}^{-2}$$

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

$$0.5 = \frac{v_f - v_i}{\Delta t} = \frac{15 - 0}{\Delta t}$$

$$\Delta \text{t} = \frac{15}{0.5} = 7.5 \text{ s}$$

c.

$$v_i = 15 \text{ m.s}^{-1} \ v_f = 0 \ \Delta \text{t} = 10 \text{ s}$$

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{\Delta t} = \frac{0 - 15}{10} = -1.5 \text{ m.s}^{-2} = 1.5 \text{ m.s}^{-2} \text{ backwards}$$

10.

a. 25 m.s^{-1} north (same as the bus because she is sitting still in the bus)

b. 0 (the girls are not moving relative to each other; they are both sitting still)

c. 1.5 m.s^{-1} north (from Lulu's point of view, she is moving away at walking speed)

d. 26.5 m.s^{-1} north $(25 \text{ m.s}^{-1} + 1.5 \text{ m.s}^{-1})$
This would be from the point of view of someone standing outside the bus on the ground, so Thandi's velocity with be the sum of her velocity and the velocity of the bus.

Back to Unit 1: Assessment

Media Attributions

Unit 2: Calculations on motion in one dimension

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Do calculations on components of motion.
- Solve problems using linear equations of motion (horizontal).

What you should know

Before you start this unit, make sure you can:

- Describe motion.
- Identify and define the components of motion.

Introduction

In this unit[1] you will apply your understanding of the components of motion in one dimension using linear equations. This will help you to solve problems about motion in one direction and equip you to understand how these concepts apply to everyday life.

There are three equations for linear motion with constant acceleration. They can be used to calculate, and therefore predict, the outcome of motion when three out of the four variables are known.

Equations for linear motion

The symbols for the variables in the equations for linear motion are:

$v_i = \text{initial velocity (in m.s}^{-1})$

$v_f = \text{final velocity (in m.s}^{-1})$

$a = \text{acceleration (in m.s}^{-2})$

$s = \text{displacement/distance in a straight line (in m)}$

$\Delta t = \text{time (in s)}$

You must learn the symbols and the units in which they are measured. Any variables given in other units must be converted before they are substituted into the equations.
The equations for linear motion are:

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 21, released under a CC-BY licence.

$v_f = v_i + a\Delta t$ equation 1

$s = v_i\Delta t + \frac{1}{2}a\Delta t^2$ equation 2

$v_f^2 = v_i^2 + 2as$ equation 3

These equations do not need to be learnt off by heart. They will be given to you on a data sheet.

Each equation has four variables. You will need any three known quantities to be able to calculate the fourth unknown one.

Strategy for problem solving

This useful strategy will help you solve problems about motion in one dimension.

1. Read the question carefully and identify the known variables. Write them down.
2. Identify the variable that needs to be calculated. Write it down.
3. Find the equation that uses the four variables you have written down. Write it down.
4. Check units of given variables and convert if required. (to convert km.h^{-1} to m.s^{-1} $\div$ by 3.6)
5. Choose a direction as positive (usually forward). If the object is slowing down, and the value of the acceleration is given in the question, give it a negative sign.
6. Substitute values into the equation (you must show this step).
7. Calculate the answer.
8. Give the answer with the appropriate units and use the sign (+ or -) of the answer to give a direction (this will not apply if you are calculating time).
9. If there are different parts of a journey, these steps must be done for each part.

Note

Sometimes there is implied information in the question. Take note of the following:

- If an object 'starts from rest', then $v_i = 0$.
- If an object 'comes to rest' OR stops, then $v_f = 0$.
- Slowing down means acceleration is negative while still moving in a positive direction.
- Constant velocity means $a = 0$ and $v_f = v_i$ (you can use this formula: $\vec{v} = \frac{\Delta s}{\Delta t}$).

Example 2.1

A racing car is travelling north. It accelerates uniformly covering a distance of $725\ \text{m}$ in $10\ \text{s}$. If it has an initial velocity of $10\ \text{m.s}^{-1}$, find its acceleration.

Solution

Step 1: Identify what information is given and what is asked for, and choose a direction as positive

We are given:

$s = 725 \text{ m}$
$v_i = 10 \text{ m.s}^{-1}$
$\Delta t = 10 \text{ s}$
$a = ?$

Let north be positive

Step 2: Find an equation of motion with these four variables

We can use equation 2

$$s = v_i \triangle t + \frac{1}{2}a\Delta t^2$$

Step 3: Check units of given variables

All units are correct.

Step 4: Substitute your values in and find the answer

$$725 = 10(10) + \frac{1}{2}(a)(10)^2$$
$$a = 12.5 \text{ m.s}^{-2}$$

Step 5: Quote the final answer with a direction

The racing car is accelerating at 12.5 m.s^{-2} north (because answer is positive and we chose north as positive).

Example 2.2

A motorcycle, travelling east, starts from rest, moves in a straight line with a constant acceleration and covers a distance of 64 m in 4 s. Calculate:

a. its acceleration
b. its final velocity
c. at what time the motorcycle had covered half the total distance
d. what distance the motorcycle had covered in half the total time.

Solution

Step 1: Identify what information is given and what is asked for, and choose a direction as positive

We are given:

$s = 64 \text{ m}$
$v_i = 0$
$\Delta t = 4 \text{ s}$
$a = ?$
$v_f = ?$

Information changes for question c and d. We will list these later.

Let east be positive.

Step 2: Check units

All units are correct.

Step 3: Find the correct equations, substitute and calculate answers

For acceleration we can use equation 2:

$$\begin{aligned} s &= v_i \Delta t + \frac{1}{2} a \Delta t^2 \\ 64 &= 0 + \frac{1}{2}(a)(4)^2 \\ a &= 8 \text{ m.s}^{-2} \text{ east} \end{aligned}$$

For final velocity we can use equation 1:

$$\begin{aligned} v_f &= v_i + a \Delta t \\ &= 0 + 8(4) \\ &= 32 \text{ m.s}^{-1} \text{ east} \end{aligned}$$

Step 4: Change information for question c)

$$\begin{aligned} s &= 32 \text{ m} \\ v_i &= 0 \\ a &= 8 \text{ m.s}^{-2} \\ \Delta t &= ? \end{aligned}$$

We can use equation 2:

$$\begin{aligned} s &= v_i \Delta t + \frac{1}{2} a \Delta t^2 \\ 32 &= 0 + \frac{1}{2}(8) \Delta t^2 \\ \Delta t &= 2.83 \text{ s} \end{aligned}$$

Step 5: Change information for question d)

$$\begin{aligned} s &= ? \\ v_i &= 0 \text{ (starts from rest - still applies)} \\ \Delta t &= 2 \text{ s (half the time)} \\ a &= 8 \text{ m.s}^{-2} \text{ (still applies)} \end{aligned}$$

We can use equation 2:

$$\begin{aligned} s &= v_i \Delta t + \frac{1}{2} a \Delta t^2 \\ &= 0 + \frac{1}{2}(8)(2)^2 \\ &= 16 \text{ m east} \end{aligned}$$

Exercise 2.1

1. A car starts off at $10\ \text{m.s}^{-1}$ and accelerates at $1\ \text{m.s}^2$ for $10\ \text{s}$. What is its final velocity?
2. A train starts from rest and accelerates at $1\ \text{m.s}^2$ for $10\ \text{s}$. How far does it move?
3. A bus is going $30\ \text{m.s}^{-1}$ and stops in $5\ \text{s}$. What is its stopping distance for this speed?
4. A racing car going at $20\ \text{m.s}^{-1}$ stops in a distance of $20\ \text{m}$. What is its acceleration?
5. A train has a uniform acceleration of $4\ \text{m.s}^{-2}$. Assume the ball starts from rest. Determine the velocity and displacement at the end of $10\ \text{s}$.
6. A motorcycle has a uniform acceleration of $1.4\ \text{m.s}^{-2}$. The motorcycle has an initial velocity of $20\ \text{m.s}^{-1}$. Determine the velocity and displacement at the end of $12\ \text{s}$.

The full solutions are at the end of the unit.

Applications of linear equations of motion in real life

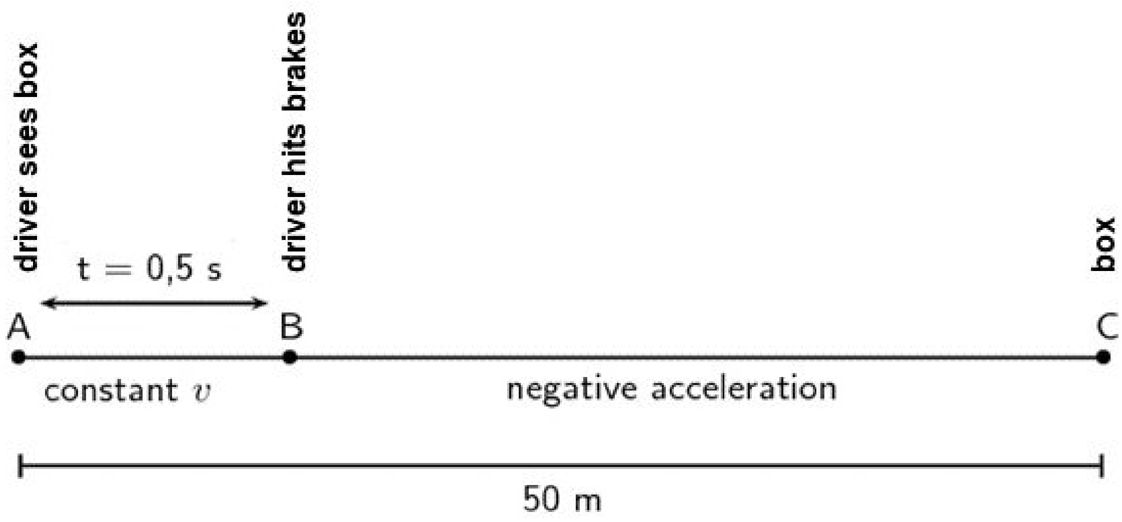
What we have learnt in this chapter can be directly applied to road safety. We can analyse the relationship between speed and stopping distance. The following example illustrates this application.

Example 2.3

A truck is travelling at a constant velocity of $10\ \text{m.s}^{-1}$ when the driver sees a box $50\ \text{m}$ in front of him in the road. He hits the brakes to stop the truck. The truck decelerates at a rate of $1.25\ \text{m.s}^{-2}$. His reaction time to hit the brakes is $0.5\ \text{s}$. Will the truck hit the box?

Solution

Step 1: Analyse the problem and identify what information is given
It is useful to draw a timeline like this one:



We need to know the following:

- What distance the driver covers before hitting the brakes.
- What distance it takes the truck to stop after hitting the brakes.
- What total distance the truck covers to stop.

Step 2: Calculate the distance AB

Before the driver hits the brakes, the truck is travelling at constant velocity. There is no acceleration and therefore the equations of motion are not used. To find the distance travelled, we use:

$$\begin{aligned}\vec{v} &= \frac{\Delta s}{\Delta t}\\ 10 &= \frac{\Delta s}{0.5}\\ \Delta s &= 5\ \text{m}\end{aligned}$$

The truck covers $5\ \text{m}$ before the driver hits the brakes.

Step 3: Calculate the distance required to stop

We have the following for the motion:

Let forward be positive

$$\begin{aligned}v_i &= 10\ \text{m.s}^{-1}\\ v_f &= 0\ \text{(truck must stop)}\\ a &= -1.25\ \text{m.s}^{-2}\ \text{(slowing down so } a \text{ is negative)}\\ s &= ?\end{aligned}$$

We can use equation 3:

$$\begin{aligned}v_f^2 &= v_i^2 + 2as\\ 0 &= 10^2 + 2(\text{-}1.25)s\\ s &= 40\ \text{m}\end{aligned}$$

The truck will need another $40\ \text{m}$ to come to a stop.

Step 4: Calculate the total distance for the truck to stop and compare to distance AC

Total distance for truck to stop $= 5{+}40 = 45\ \text{m}$

Distance AC $= 50\ \text{m}$

The truck will not hit the box.

Summary

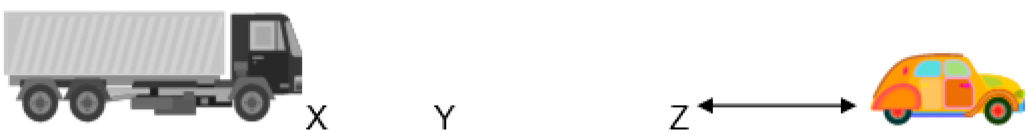
In this unit you have learnt the following:

- The equations of linear motion can be used to predict the outcome of the motion of an object.
- The equations can be used for linear motion only.
- The equations can only be used when the acceleration is constant/uniform.

Unit 2: Assessment

Suggested time to complete: 30 minutes

1. A car is moving at $30\ \text{m.s}^{-1}$ east when a driver steps on the brakes. The car's velocity decreases uniformly to $20\ \text{m.s}^{-1}$ in $10\ \text{s}$. Calculate:
   a. the acceleration of the car
   b. the displacement of the car during the braking.
2. A car is driven at $25\ \text{m.s}^{-1}$ in a municipal area. When the driver sees a traffic officer at a speed trap, he realises he is travelling too fast. He immediately applies the brakes of the car while still $100\ \text{m}$ away from the speed trap.
   a. Calculate the magnitude of the minimum acceleration which the car must have to avoid exceeding the speed limit if the municipal speed limit is $16.6\ \text{m.s}^{-1}$.
   b. Calculate the time from the instant the driver applied the brakes until he reaches the speed trap. Assume that the car's velocity, when reaching the trap, is $16.6\ \text{m.s}^{-1}$.
3. A bus on a straight road starts from rest at a bus stop and accelerates at $2\ \text{m.s}^{-2}$ until it reaches a speed of $20\ \text{m.s}^{-1}$. Then the bus travels for $20\ \text{s}$ at a constant speed until the driver sees the next bus stop in the distance. The driver applies the brakes, stopping the bus in a uniform manner in $5\ \text{s}$.
   a. How long does the bus take to travel from the first bus stop to the second bus stop?
   b. What is the average speed of the bus during the trip?
4. A boy on a bicycle cycles at a constant speed of $15\ \text{m.s}^{-1}$. When he passes the driver of a stationary car, the driver starts to accelerate the car uniformly. If the boy and the driver are in line with one another 7 seconds later:
   a. Calculate how far the car has travelled in those 7 seconds.
   b. Calculate the acceleration of the car.
   c. Calculate the velocity of the car as it passes the boy.
5. A truck is moving forward at a constant speed of $20\ \text{m.s}^{-1}$ on a horizontal road. At point X the driver sees a stationary car ahead and hits the breaks $0.35\ \text{s}$ later at Y. The magnitude of the average acceleration of the truck is $2.5\ \text{m.s}^{-2}$. The truck manages to stop $2\ \text{m}$ away from the car at point Z.



   a. What is the reaction time of the driver?
   b. Calculate how far the truck travels before the brakes are applied.
   c. Calculate how long it takes before the truck comes to rest from the moment the car is seen.
   d. Calculate the braking distance of the truck.
   e. Write down how far point X is from the car.
6. At the regional championships, Mandla ran the first $20\ \text{m}$ of the $100\ \text{m}$ race in a time of $3.4\ \text{s}$.
   a. Calculate his average speed for the first $20\ \text{m}$ of the race.
   b. For the first $20\ \text{m}$ Mandla's acceleration is uniform. Calculate the acceleration.
   c. Calculate his speed after the first $20\ \text{m}$ of the race.
   d. Will Mandla be able to better his personal best time of $10.8\ \text{s}$ if he maintains his speed after the first $20\ \text{m}$ of the race? Motivate your answer with a calculation.

7. In 1938, a British train, the 'Mallard' set a world record for the fastest steam train of $200\ \mathrm{km.h^{-1}}$. The train passed Stoke Summit travelling at $34\ \mathrm{m.s^{-1}}$. It then accelerated uniformly reaching a maximum speed of $56\ \mathrm{m.s^{-1}}$after covering a distance of $9\ 600\ \mathrm{m}$.
   a. Convert $200\ \mathrm{km.h^{-1}}$ to $\mathrm{m.s^{-1}}$.
   b. Calculate the acceleration of the train from the time it passed Stoke Summit to when it reached its maximum speed.

      Once the train had reached its maximum speed it continued at this speed for a further $500\ \mathrm{m}$ when it was decided to stop the train. It took $120\ \mathrm{s}$ to bring the train uniformly to a standstill.
   c. Calculate the distance covered from the moment the train reached maximum speed.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. Let forward be positive
   $v_i = 10\ \mathrm{m.s^{-1}}$
   $a = 1\ \mathrm{m.s^{-2}}$
   $\Delta t = 10\ \mathrm{s}$
   $v_f = ?$
   $v_f = v_i + a\Delta t$
   $= 10{+}1(10)$
   $= 20\ \mathrm{m.s^{-1}}\ \text{forward}$
2. Let forward be positive
   $v_i = 0$
   $a = 1\ \mathrm{m.s^{-2}}$
   $\Delta t = 10\ \mathrm{s}$
   $s = ?$
   $s = v_i \Delta t + \frac{1}{2} a \Delta t^2$
   $= 0 + \frac{1}{2}(1)(10)^2$
   $= 50\ \mathrm{m}$
3. Let forward be positive

$v_i = 30 \text{ m.s}^{-1}$

$v_f = 0$

$\Delta t = 5 \text{ s}$

$s = ?$

$v_f = v_i + a\Delta t$

$0 = 30 + a(5)$

$a = -6 \text{ m.s}^{-2}$

$s = v_i\Delta t + \frac{1}{2}a\Delta t^2$

$= 30(5) + \frac{1}{2}(-6)(5)^2$

$= 75 \text{ m forward}$

4. Let forward be positive

$v_i = 20 \text{ m.s}^{-1}$

$v_f = 0$

$s = 20 \text{ m}$

$a = ?$

$v_f^2 = v_i^2 + 2as$

$0 = (20)^2 + 2(a)(20)$

$a = -10 \text{ m.s}^{-2}$

$= 10 \text{ m.s}^{-2} \text{ backwards}$

5. Let forward be positive

$a = 4 \text{ m.s}^{-2}$

$v_i = 0$

$\triangle t = 10 \text{ s}$

$v_f = ?$

$s = ?$

$v_f = v_i + a \triangle t$

$= 0 + 4(10)$

$= 40 \text{ m.s}^{-1} \text{ forward}$

$s = v_i \triangle t + \frac{1}{2}a \triangle t^2$

$= 0 + \frac{1}{2}(4)(10)^2$

$= 200 \text{ m forward}$

6. Let forward be positive

$a = 1.4 \text{ m.s}^{-2}$

$v_i = 20 \text{ m.s}^{-1}$

$\Delta t = 12 \text{ s}$

$s = ?$

$v_f = v_i + a\Delta t$

$= 20 + 1.4(12)$

$= 36.8 \text{ m.s}^{-1} \text{ forward}$

$s = v_i\Delta t + \frac{1}{2}a\Delta t^2$

$= 20(12) + \frac{1}{2}(1.4)(12)^2$

$= 340.8 \text{ m forward}$

Back to Exercise 2.1

Unit 2: Assessment

1. Let east be positive
    a.
    $v_i = 30 \text{ m.s}^{-1}$
    $v_f = 20 \text{ m.s}^{-1}$
    $\Delta t = 10 \text{ s}$
    $v_f = ?$
    $a = ?$
    $v_f = v_i + a\Delta t$
    $20 = 30 + a(10)$
    $a = -1 \text{ m.s}^{-2}$
    $= 1 \text{ m.s}^{-2} \text{ west}$
    b.
    $s = ?$
    $s = v_i \Delta t + \frac{1}{2} a \Delta t^2$
    $= 30(10) + \frac{1}{2}(-1)(10)^2$
    $= 250 \text{ m east}$
2. Let forward be positive
    a.
    $v_i = 25 \text{ m.s}^{-1}$
    $v_f = 16.6 \text{ m.s}^{-1}$
    $s = 100 \text{ m}$
    $a = ?$
    $v_f^2 = v_i^2 + 2as$
    $16.6^2 = 25^2 + 2a(10)$
    $a = -1.75 \text{ m.s}^{-2}$
    $= 1.75 \text{ m.s}^{-2} \text{ backwards}$
    b.
    $v_f = v_i + a\Delta t$
    $16.6 = 25 + (\text{-}1.75)t$
    $t = 4.8 \text{ s}$
3.
    a. Let forward be positive
    Find time from A to B
    $v_i = 0$
    $v_f = 20 \text{ m.s}^{-1}$
    $a = 2 \text{ m.s}^{-2}$
    $\Delta t = ?$
    $v_f = v_i + a\Delta t$
    $20 = 0 + 2\Delta t$
    $\Delta \text{t} = 10 \text{ s}$

$\text{Total time} = 10_{\text{AB}} + 20_{\text{BC}} + 5_{\text{CD}} = 35 \text{ s}$

b. Need to find the total distance from A to D

$s_{\text{AB}} = v_i \Delta t + \frac{1}{2} a \Delta t^2$

$= 0 + \frac{1}{2}(2)(10)^2$

$= 100 \text{ m}$

$s_{\text{BC}}\ v = \frac{\Delta s}{\Delta t}$ (constant velocity)

$20 = \frac{\Delta s}{20}$

$\Delta s_{BC} = 400 \text{ m}$

$s_{CD} : v_i = 20 \text{ m.s}^{-1}\ v_f = v_i + a\Delta t$

$v_f = 0\ 0 = 20 + a(5)$

$\Delta \text{t} = 5 \text{ s}\ a = -4 \text{ m.s}^{-2}$

$v_f^2 = v_i^2 + 2as$

$0 = 20^2 + 2(-4)(s)$

$s = 50 \text{ m}$

$\text{Total distance} = 100 + 400 + 50 = 550 \text{ m}$

$v_{av} = \frac{s_{total}}{t_{total}} = \frac{550}{35} = 15.71 \text{ m.s}^{-1}$ forward

4. Let forward be positive

Boy: $v_i = 15 \text{ m.s}^{-1}$ (constant velocity) Car: $v_i = 0$

$\Delta t = 7 \text{ s}\ \Delta t = 7 \text{ s}$

a.

$\Delta s_{\text{boy}} = \Delta s_{\text{car}}$ (when the car and boy are in line)

$v_{\text{boy}} = \frac{\Delta s}{\Delta t}$

$15 = \frac{\Delta s}{7}$

$\Delta s_{\text{boy}} = \Delta s_{\text{car}} = 105 \text{ m}$ forward

b.

$s = v_i \Delta t + \frac{1}{2} a \Delta t^2$

$105 = 0 + \frac{1}{2} a(7)^2$

$a = 4.29 \text{ m.s}^{-2}$ forward

c.

$v_f = v_i + a\Delta t$

$= 0 + 4.29(7)$

$= 30 \text{ m.s}^{-1}$ forward

5.

a. reaction time $= 0.35 \text{ s}$

b. constant velocity during reaction time:

$v = \frac{\Delta s}{\Delta t}$

$20 = \frac{\Delta s}{0.35}$

$\Delta s = 7 \text{ m}$

c. Calculate time while braking:

$v_i = 20 \text{ m.s}^{-1}$

$v_f = 0$

$a = -2.5 \text{ m.s}^{-2}$ (slowing down, therefore negative)

$\Delta t = ?$

$v_f = v_i + a\Delta t$

$0 = 20 + (-2.5)\Delta t$

$\triangle t = 8 \text{ s}$

Total time from X to Z $= 0.35 + 8 = 8.35$ s

d.

$$s = v_i\Delta t + \frac{1}{2}a\Delta t^2$$

$$= 20(8) + \frac{1}{2}(-2.5)(8)^2$$

$$= 80 \text{ m}$$

e.

X to Y $= 7$ m

Y to Z $= 80$ m

Z to car $= 2$ m Total distance $= 89$ m

6. Let forward be positive

a.

$s = 20$ m

$\Delta t = 3.4$ s

$$v_{av} = \frac{\Delta s}{\Delta t}$$

$$= \frac{20}{3.4}$$

$$= 5.88 \text{ m.s}^{-1}$$

b.

$v_i = 0$

$s = 20$ m

$\Delta t = 3.4$ s

$$s = v_i\Delta t + \frac{1}{2}a\Delta t^2$$

$$20 = 0 + \frac{1}{2}a(3.4)^2$$

$a = 3.46 \text{ m.s}^{-2}$ forward

c.

$v_f = v_i + a\Delta t$

$= 0 + 3.46(3.4)$

$= 11.76 \text{ m.s}^{-1}$

d.

$s = 80 \text{ m}$

$v = 11.76 \text{ m.s}^{-1}$

$\Delta t = ?$

$v = \frac{\Delta s}{\Delta t}$

$11.76 = \frac{80}{\Delta t}$

$\Delta t = 6.8 \text{ s}$

$\text{Total } t = 3.4 + 6.8 = 10.2 \text{ s}$

$\text{This is better than his personal best of } 10.8 \text{ s}$

7.

a. $200 \div 3.6 = 55.56 \text{ m.s}^{-1}$

b. Let forward be positive

$v_i = 34 \text{ m.s}^{-1}$

$v_f = 56 \text{ m.s}^{-1}$

$s = 9\ 600 \text{ m}$

$v_f^2 = v_i^2 + 2as$

$56^2 = 34^2 + 2a(9\ 600)$

$a = 0.1 \text{ m.s}^{-2} \text{ forward}$

c.

$v_i = 56 \text{ m.s}^{-1}$

$v_f = 0$

$\Delta t = 120 \text{ s}$

$s = ?$

$v_f = v_i + a\Delta t$

$0 = 56 + a(120)$

$a = -0.47 \text{ m.s}^{-2}$

$v_f^2 = v_i^2 + 2as$

$0 = 56^2 + 2(-0,47)s$

$s = 3\ 336.17 \text{ m}$

$\text{Total distance} = 500 + 3\ 336.17 = 3\ 836.17 \text{ m}$

Back to Unit 2: Assessment

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Unit 3: The concepts of vectors and scalars

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Define vectors and scalars.
- Identify examples of vectors and scalars.
- Represent vectors and scalars.

Introduction

In this unit[1] you will learn that some quantities are expressed only in terms of their size, whereas others are expressed in terms of size and direction. These are called scalars and vectors. Understanding the difference between these concepts will allow you to identify examples of the different quantities in everyday life.

We come into contact with many physical quantities in the natural world on a daily basis. For example, things like time, mass, weight, force, and electric charge, are physical quantities with which we are all familiar. We know that time passes, and physical objects have mass. Things have weight due to gravity. We exert forces when we open doors, walk along the street and kick balls. We experience electric charge directly through static shocks in winter and through using anything which runs on electricity.

There are many physical quantities in nature, and we can divide them up into two broad groups called scalars and vectors.

Scalars

Scalars are physical quantities that have only a number value or a size (magnitude). A scalar tells you how much of something there is. For example, a person buys a tub of margarine which is labelled with a mass of $500\ \text{g}$. The mass of the tub of margarine is a scalar quantity. It only needs a number and a unit to describe it, in this case, $500\ \text{g}$.

Examples of scalar quantities:

- mass has only a value, no direction
- electric charge has only a value, no direction
- time has only a value, no direction.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 21, released under a CC-BY licence.

Vectors

Vectors are different because they are physical quantities which have a size and a direction. A vector tells you how much of something there is and in which direction it acts. For example, a car is travelling east along a highway at $100\ \text{km.h}^{-1}$. What we have here is a vector called the velocity. The car is moving at $100\ \text{km.h}^{-1}$ (this is the magnitude) and we know where it is going – east (this is the direction). These two quantities, the speed and direction of the car (a magnitude and a direction), together form a vector we call velocity.

Examples of vector quantities:

- Force has a value and a direction. You push or pull something with some strength (magnitude) in a particular direction.
- Weight has a value and a direction. Your weight is proportional to your mass (magnitude) and is always in the direction towards the centre of the earth.
- Displacement is measured from a starting point to an ending point in a particular direction.
- Velocity indicates both the speed at which an object is travelling as well as the direction in which it is moving.
- Acceleration can be speeding up or slowing down depending on the direction of the force causing the change in the speed.

Exercise 3.1

Classify the following as vector or scalar:

1. length
2. time
3. force
4. weight
5. density
6. temperature
7. height
8. speed
9. energy
10. distance

The full solutions are at the end of the unit.

Graphical representation of vectors

Vectors are drawn as arrows. An arrow has both a magnitude (how long it is) and a direction (the direction in which it points). The starting point of a vector is known as the tail and the end point is known as the head.

A force of $50\ \text{N}$ east would be represented like this: 

Because vectors must have a direction, we need to use one of various methods to describe the direction:

- relative direction
- compass direction

- bearing.

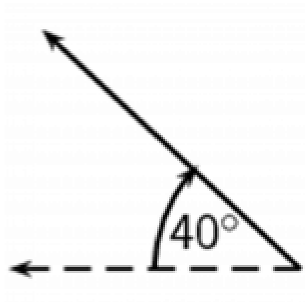
Relative direction

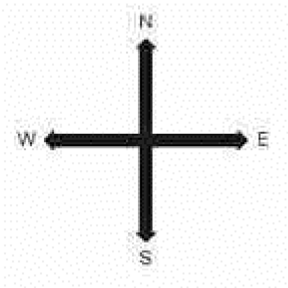
The simplest way to show direction is with relative directions: to the left, to the right, forward, backward, up, and down, or relative to a fixed point, for example at an angle to a riverbank, or at an angle to the floor.

Compass direction

Another common method of expressing directions is to use the points of a compass: north, south, east, and west. If a vector does not point exactly in one of the compass directions, then we use an angle. For example, we can have a vector pointing 40^0 north of west. Start with the vector pointing along the west direction (look at the dashed arrow in Figure 1 below), then rotate the vector towards the north until there is a 40^0 angle between the vector and the west direction (the solid arrow below). The direction of this vector can also be described as: $\mathrm{W}\ 40^0\ \mathrm{N}$ or $\mathrm{N}\ 50^0\ \mathrm{W}$

Figure 1: Vector in a direction $\mathrm{W}\ 40^0\ \mathrm{N}$





Bearing

A further method of expressing direction is to use a bearing. A bearing is a direction relative to a fixed point. Given just an angle, the convention is to define the angle clockwise with respect to north. So, a vector with a direction of 110^0 has been rotated clockwise 110^0 relative to north as in Figure 2 below. A bearing is always written as a three-digit number, for example 080^0 (for $\mathrm{N}\ 80^0\ \mathrm{E}$).

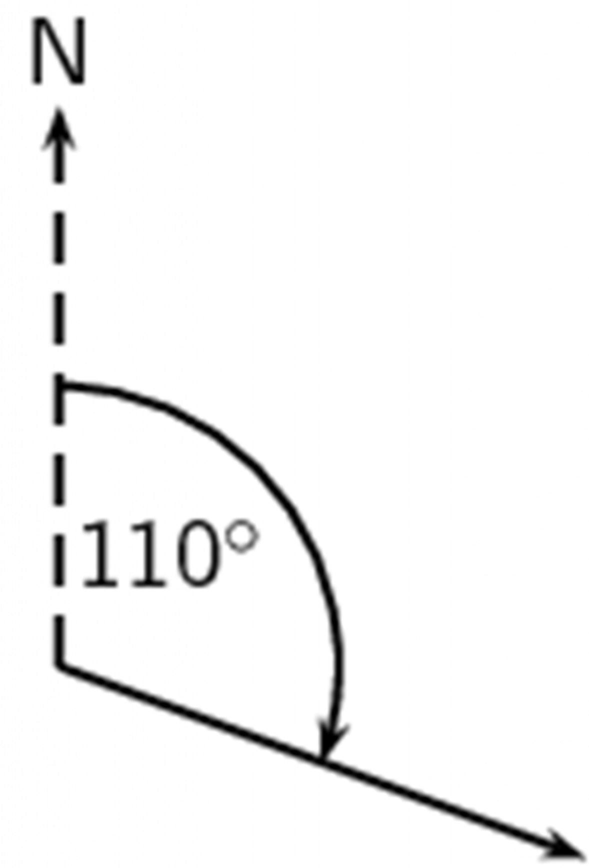
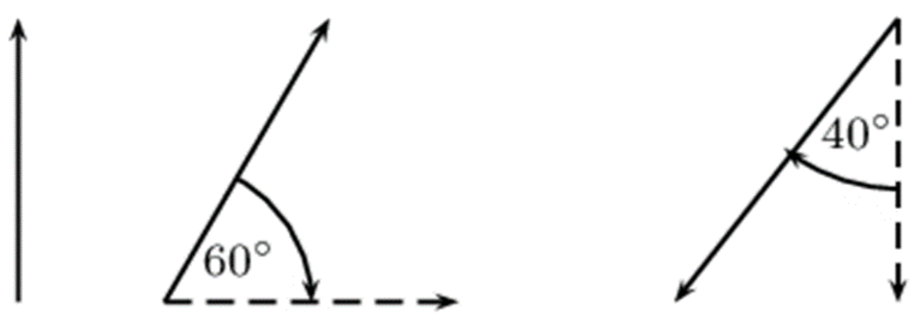


Figure 2: Vector bearing of 110^0

Exercise 3.2

Give the directions of the vectors represented below using two different methods:

1. 2. 3.



The full solutions are at the end of the unit.

Drawing vectors

In order to draw a vector accurately we must represent its magnitude properly and include a reference direction in the diagram. A scale allows us to translate the length of the arrow into the vector's magnitude. For instance if one chooses a scale of $1\ \text{cm} = 2\ \text{N}$ ($1\ \text{cm represents}\ 2\ \text{N}$), a force of $20\ \text{N}$ towards the east would be represented as an arrow $10\ \text{cm}$ long pointing towards the right.

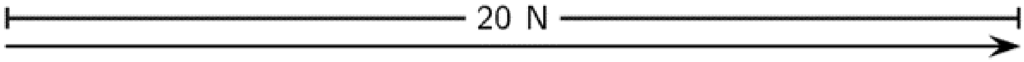


Figure 3: Representation of a vector

To draw a vector:

1. Decide upon a scale and write it down.
2. Decide on a reference direction.
3. Determine the length of the arrow representing the vector by using the scale.
4. Draw the vector as an arrow. Make sure that you fill in the arrowhead.
5. Fill in the magnitude of the vector.

Example 3.1

Draw the following vector quantity: $6\ \text{m.s}^{-1}$ north.

Solution

Step 1: Decide on a scale and write it down

$1\ \text{cm} = 2\ \text{m.s}^{-1}$

Step 2: Decide on a reference direction

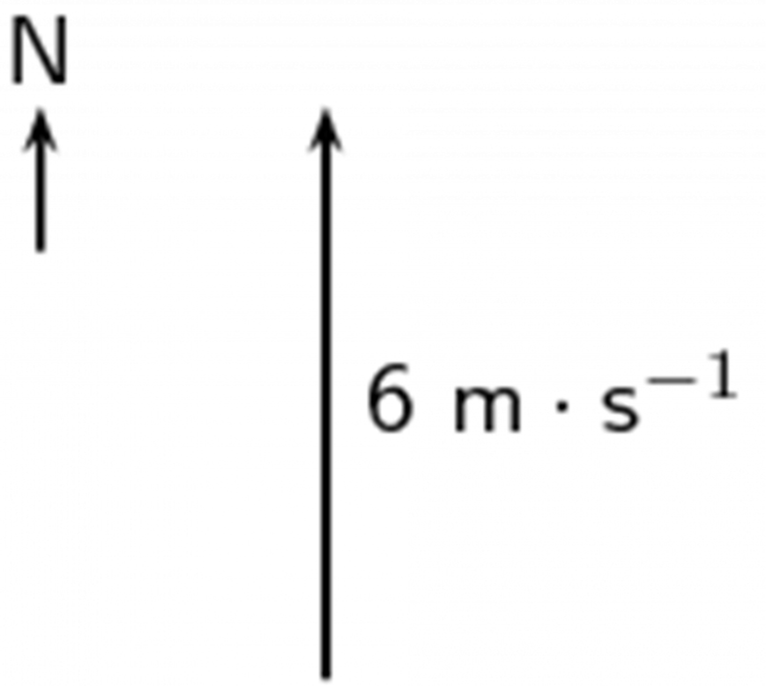
North will point to the top of the page.

Step 3: Determine the length of the arrow at the specific scale

If $1\ \text{cm} = 2\ \text{m.s}^{-1}$, then $6\ \text{m.s}^{-1} = 3\ \text{cm}$.

Step 4: Draw the vector as an arrow

Scale $1\ \text{cm} = 2\ \text{m.s}^{-1}$



Example 3.2

Draw the following vector quantity: $16\ \text{m}$ east.

Solution

Step 1: Decide on a scale and write it down

$1\ \text{cm} = 4\ \text{m}$

Step 2: Decide on a reference direction

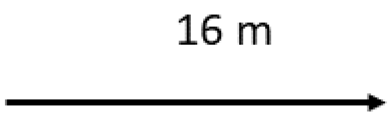
North will point to the top of the page.

Step 3: Determine the length of the arrow at the specific scale

If $1 \text{ cm} = 4 \text{ m}$, then $16 \text{ m} = 4 \text{ cm}$.

Step 4: Draw the vector as an arrow

Scale $1 \text{ cm} = 4 \text{ m}$ N



$4 \text{ cm} = 16 \text{ m}$

Exercise 3.3

Draw each of the following vectors to scale. Indicate the scale you have chosen.

1. 12 km south
2. $1.5 \text{ m N } 45^0 \text{ W}$
3. $10 \text{ m.s}^{-1} \ 20^0 \text{ east of north}$
4. $50 \text{ km.h}^{-1} \text{ bearing } 080^0$
5. $5 \text{ mm, } 225^0$

The full solutions are at the end of the unit.

Summary

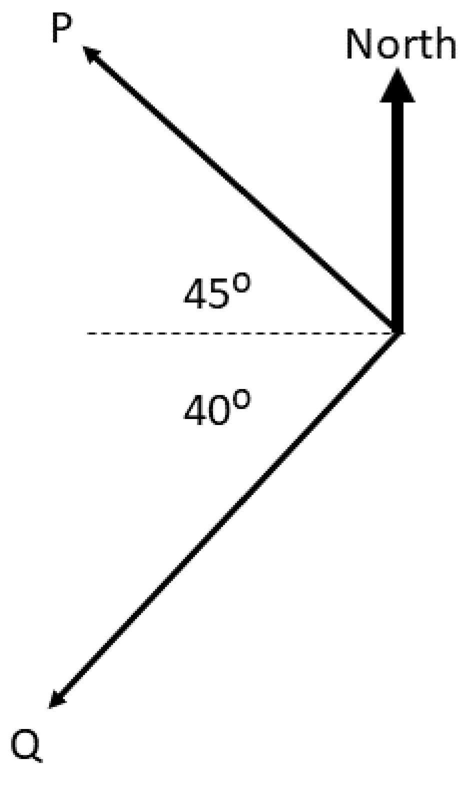
In this unit you have learnt the following:

- A scalar is a physical quantity with magnitude only.
- A vector is a physical quantity with magnitude and direction.
- Vectors may be represented as arrows where the length of the arrow indicates the magnitude, and the arrowhead indicates the direction of the vector.
- The direction of a vector can be indicated by referring to another vector or a fixed point (e.g. 30^0 from the river bank); using a compass direction (e.g. $\text{N } 30^0 \text{ E}$); or a bearing (e.g. 053^0).

Unit 3: Assessment

Suggested time to complete: 15 minutes

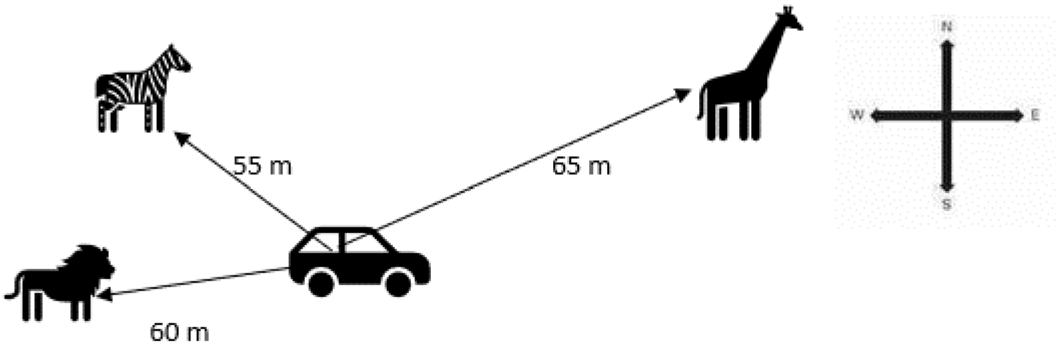
1. Which of the following contains two vectors and a scalar?
   A. Distance, acceleration, speed
   B. Displacement, velocity, acceleration
   C. Distance, mass, speed
   D. Displacement, speed, velocity
2. Give the direction of the four main compass points as bearings.
3. Give the directions of vectors P and Q in three different ways:



4. During a visit to a game park, a tourist simultaneously observes a lion, a zebra and a giraffe. The diagram shows the position of his car and the animals as seen from a helicopter above. The lion is $60\ \text{m}$

from the car in the direction $\mathrm{W}\ 10^0\ \mathrm{S}$. The zebra is $55\ \mathrm{m}$ from the car in the direction $\mathrm{W}\ 24^0\ \mathrm{N}$ and the giraffe is $65\ \mathrm{m}$ from the car, but the direction is unknown. The giraffe is directly east of the zebra.

Use this information to answer the following questions by using an accurate scale drawing with the aid of a protractor, a compass, and a ruler.



a. Determine the bearing of the giraffe from the car.
b. How far is the giraffe from the zebra?
c. What is the position of the zebra relative to the lion?

The full solutions are at the end of the unit.

Unit 3: Solutions

Exercise 3.1

1. length – scalar
2. time – scalar
3. force – vector
4. weight – vector
5. density – scalar
6. temperature – scalar
7. height – vector
8. speed – scalar
9. energy – scalar
10. distance – scalar

Back to Exercise 3.1

Exercise 3.2

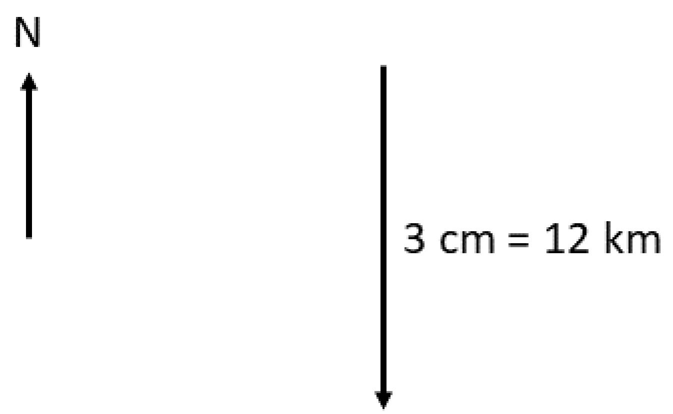
1. North OR bearing 000^0
2. $\mathrm{E}\ 60^0\ \mathrm{N}$ or $\mathrm{N}\ 30^0\ \mathrm{E}$ or bearing 030^0

3. S 40^0 W or W 50^0 S or bearing 220^0

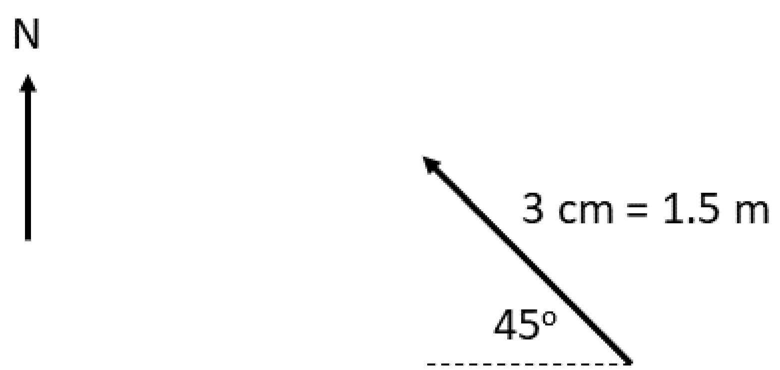
Back to Exercise 3.2

Exercise 3.3

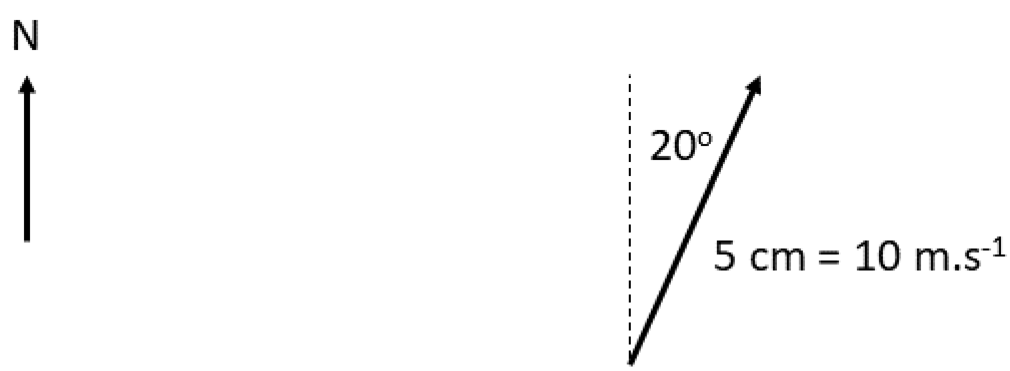
1. Scale $1\ \mathrm{cm} = 4\ \mathrm{km}$



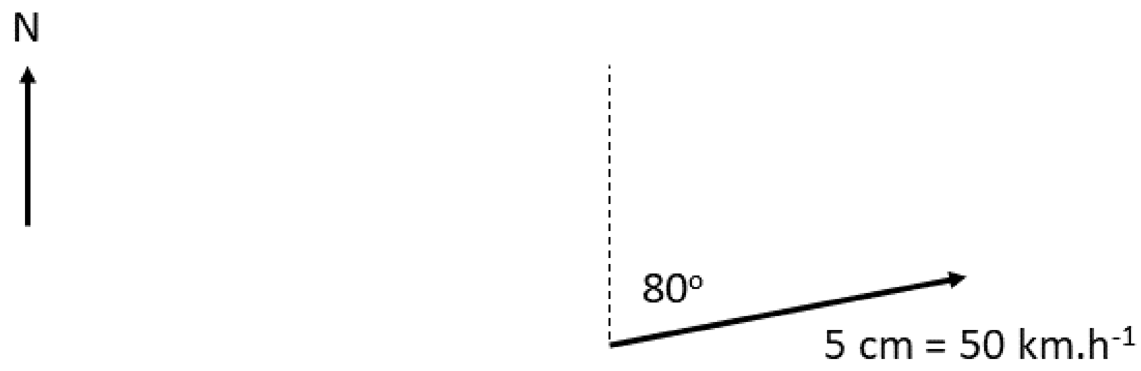
2. Scale $1\ \mathrm{cm} = 0.5\ \mathrm{m}$



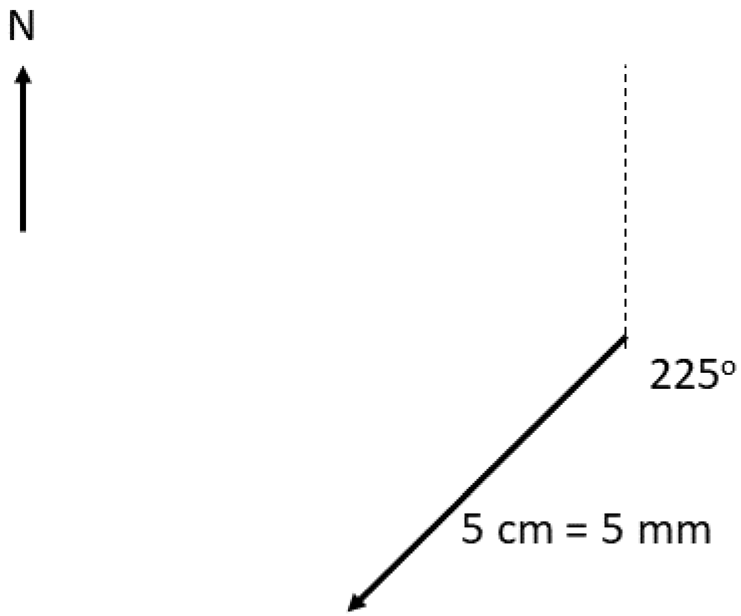
3. Scale $1\ \mathrm{cm} = 2\ \mathrm{m.s^{-1}}$



4. Scale $1\ \mathrm{cm} = 10\ \mathrm{km.h^{-1}}$



5. Scale $1 \text{ cm} = 1 \text{ mm}$



Back to Exercise 3.3

Unit 3: Assessment

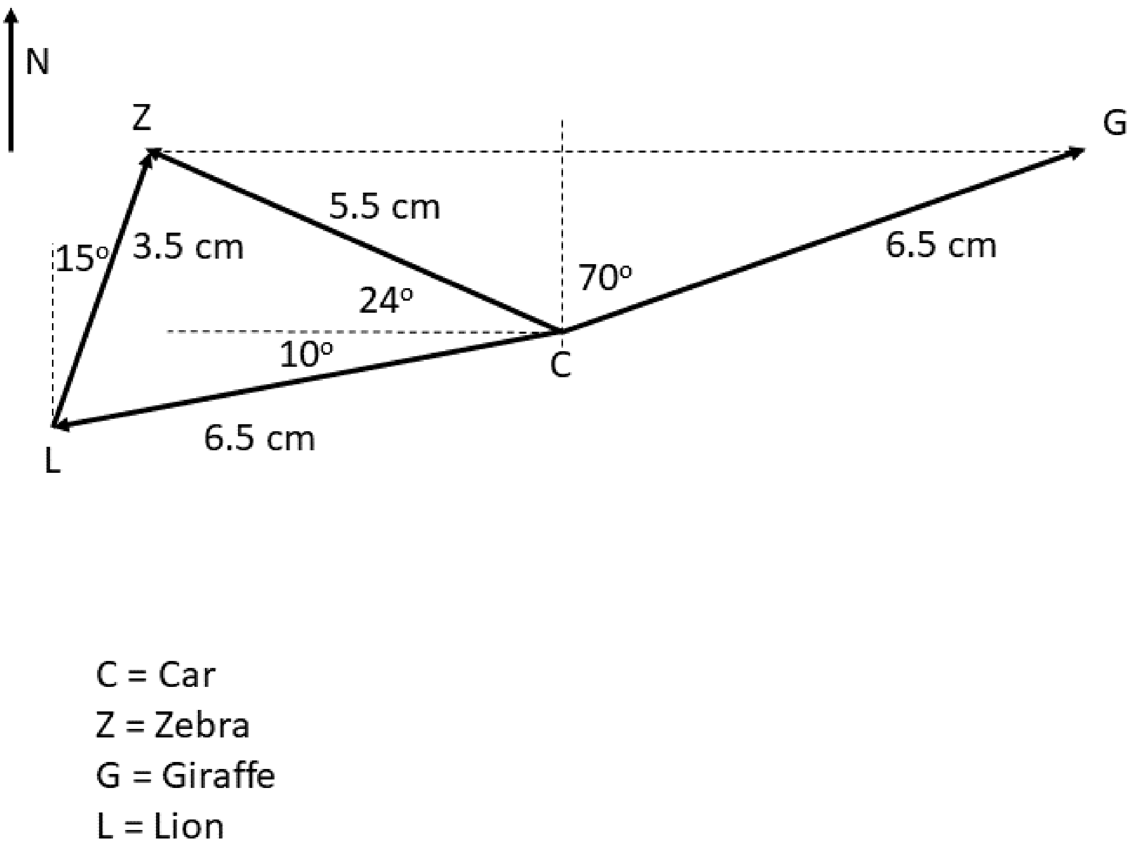
1. D (displacement and velocity are vectors, speed is scalar)
2. North: 000^0
   South: 180^0
   West: 270^0
   East: 090^0
3. P: 315^0 or $\text{W } 45^0 \text{ N}$ or $\text{N } 45^0 \text{ W}$
   Q: 230^0 or $\text{W } 40^0 \text{ S}$ or $\text{S } 50^0 \text{ W}$
4. Choose a suitable scale e.g. $1 \text{ cm} = 10 \text{ m}$
   Choose a suitable position for the car.
   a. First find the position of the zebra: From the car, draw a west reference line, measure an angle of 24^0 towards the north and draw a line of length 5.5 cm.
      To find the position of the giraffe: Draw an east reference line from the zebra, then measure 6.5 cm

with your compass and draw an arc from the car to cut the east reference line. This is the position of the giraffe. Draw the line from the car to the giraffe.
To find the direction of the giraffe from the car: draw a north reference line at the car and measure the angle from north to the line from the car to the giraffe.
Answer: E

b. Measure the east reference line from the zebra to the giraffe and convert using your chosen scale.
Answer: $\pm$ $110\ \mathrm{m}$ east

c. To find the position of the lion: Draw a west reference line at the car and measure an angle of 10^0 towards the south. Draw a line of length 6.5 cm.
Draw a line from the lion's position to the zebra's position. Measure the line and convert to scale to find the magnitude.

To find the direction of the zebra from the lion, draw a north reference line at the lion and measure the angle from this reference line to the vector from the lion to the zebra.
Answer: $\pm\ 35\ \mathrm{m}\ \mathrm{N}\ 15^0\ \mathrm{E}$



Back to Unit 3: Assessment

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Unit 4: Working with vectors and scalars

LEIGH KLEYNHANS

Unit 4 outcomes

By the end of this unit you will be able to:

- Define the resultant and equilibrant of vectors.
- Determine the resultant and equilibrant of vectors through construction.

What you should know

Before you start this unit, make sure you can:

- Describe the difference between vectors and scalars. Revise Subject outcome 2.1 Unit 3 to help you with this.

Introduction

In this unit[1] you will learn about the practical applications of vectors and be able to determine the end result of vector action.

You will also learn to represent vectors by constructing a scale diagram, and how to find the overall result when more than one vector is taking place.

Vectors in one dimension

When vectors occur in one dimension, we use positive and negative signs to indicate direction. A negative vector is a vector which points in the direction opposite to the reference direction. For example, if in a particular situation, we define the upward direction as the positive reference direction, then a vector acting downwards will be negative, as it is opposite to that of the positive reference direction.

Two or more vectors acting in the same direction

When vectors are added, we need to take into account both their magnitudes and their directions.
For example, imagine the following: you and a friend are trying to move a heavy box. You stand behind it and push it forwards with a force $\vec{F}_1 = 20 \text{ N}$ and your friend stands in front and pulls it towards them with a force $\vec{F}_2 = 15 \text{ N}$. See Figure 1.

positive reference direction = to the right

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 21, released under a CC-BY licence.

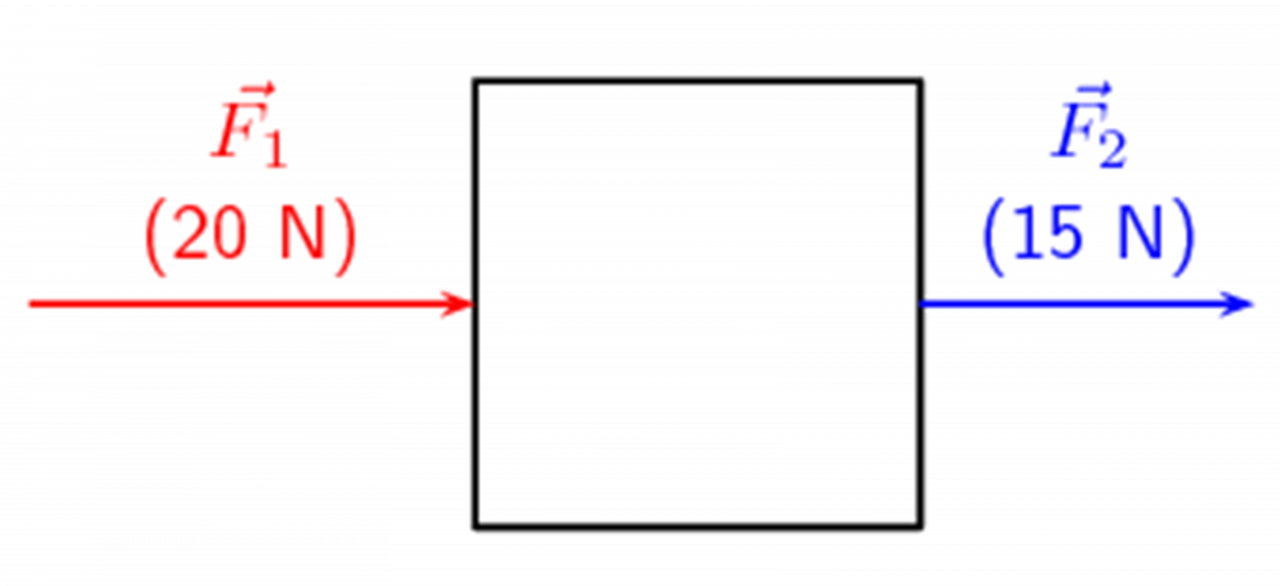


Figure 1: Two vectors in the same direction

The two forces are in the same direction (i.e. to the right). If to the right is chosen as the positive direction, both vectors will be positive. and the total force acting on the box is calculated as follows:

$\vec{F}_1 + \vec{F}_2 = 20 + 15 = 35\ \mathrm{N}$ to the right

The force of $35\ \mathrm{N}$ to the right is called the resultant vector ($\vec{F_R}$) as it is the result of both vectors acting on the box.

Two or more vectors acting in opposite directions

If you now turn around and pull the box towards you and your friend continues to pull the box towards them, the vectors would be acting in the opposite direction. See Figure 2.

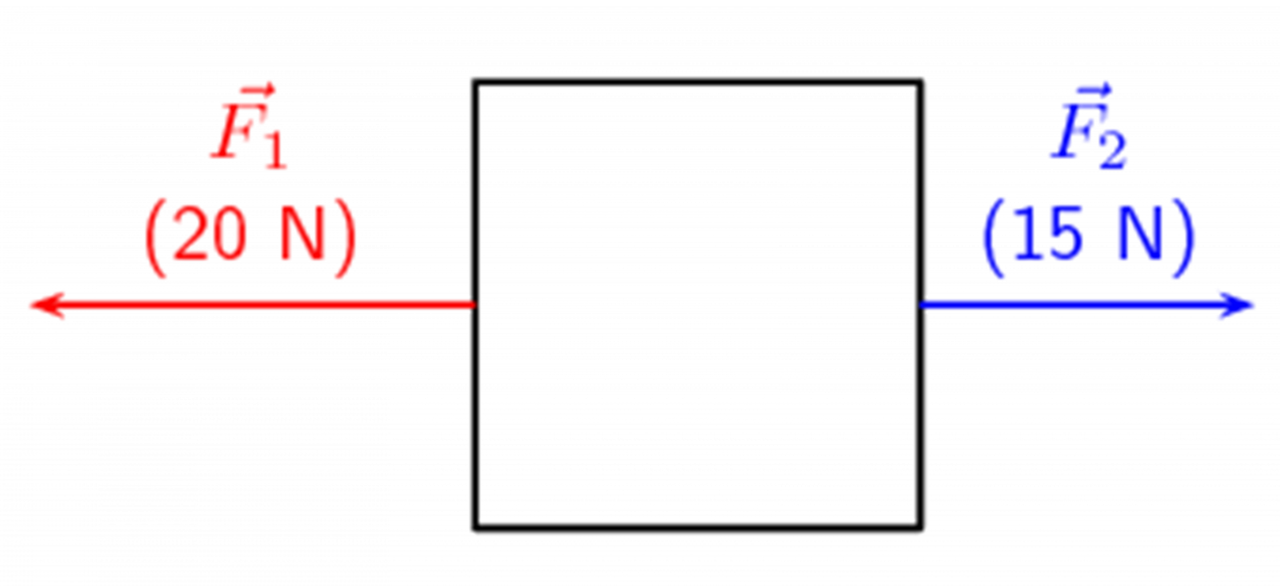


Figure 2: Vectors acting in opposite directions

The two forces are in the opposite direction. If to the right is chosen as the positive direction, $\overrightarrow{F_2}$ will be positive but $\overrightarrow{F_1}$ will be negative and so the total force acting on the box is calculated as follows:

$\overrightarrow{F}_1 + \vec{F}_2 = -20 + 15 = -5\ \mathrm{N}$

The resultant ($\overrightarrow{F_R}$) of the two forces is now $-5\ \mathrm{N}$. The negative sign means the direction is opposite to the reference direction. The resultant vector in this case is therefore $5\ \mathrm{N}$ to the left.

There is a special name for the vector which has the same magnitude as the resultant vector but acts in the opposite direction: the equilibrant ($\overrightarrow{F_E}$). If you add the resultant vector and the equilibrant vectors together, the answer is always zero because the equilibrant cancels out the resultant. We then refer to the situation as being in equilibrium.

If you refer to the pictures of the heavy box in Figures 1 and 2, the equilibrants for the two situations are shown in Figures 3 and 4 below:

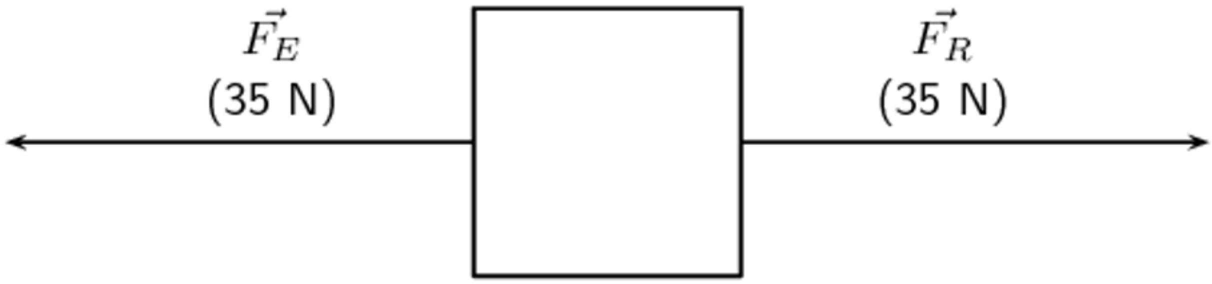


Figure 3: Diagram showing the resultant ($\overrightarrow{F_R}$) of $35\ \mathrm{N}$ to the right and the equilibrant ($\overrightarrow{F_E}$) of $35\ \mathrm{N}$ to the left.

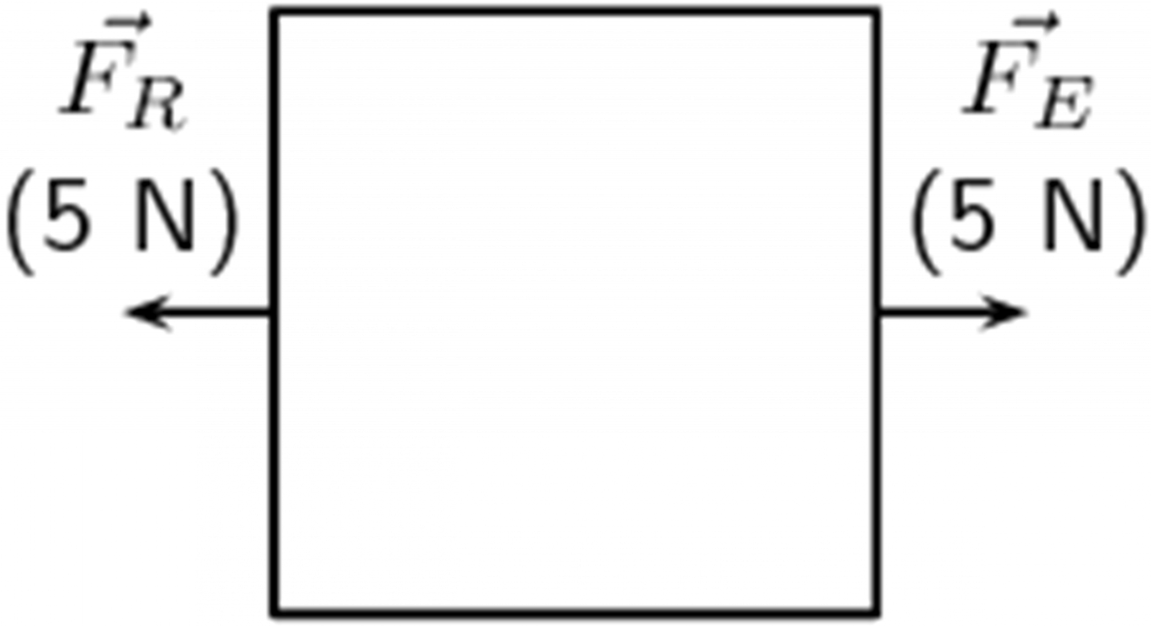


Figure 4: Diagram showing the resultant $(\vec{F}_R)$ *of* $5\ \mathrm{N}$ *to the left and the equilibrant* $(\vec{F}_E)$ *of* $5\ \mathrm{N}$ *to the right.*

This method of determining resultants and equilibrants can be used for any vector quantities in one dimension.

Example 4.1

A tennis ball is rolled towards a wall which is $10\ \mathrm{m}$ away from the ball. If, after striking the wall, the ball rolls $2.5\ \mathrm{m}$ along the ground away from the wall, calculate the ball's resultant displacement.

Solution

Step 1: Choose a positive reference direction

Let towards the wall be positive: $\vec{s}_1 = 10\mathrm{m}$ $\vec{s}_2 = -2.5\ \mathrm{m}$

Step 2: Add the vectors

$\vec{s}_R = \vec{s}_1 + \vec{s}_2 = 10 + (-2.5) = 7.5$

Step 3: Use the sign of the answer to describe the resultant vector

The answer is positive, therefore the resultant displacement is $7.5\ \mathrm{m}$ towards the wall.

Exercise 4.1

1. Find the resultant of the following vectors:
   a. $20\ \text{m.s}^{-1}$ north and $5\ \text{m.s}^{-1}$ north
   b. $6\ \text{km}$ east and $22\ \text{km}$ west
   c. $14\ \text{m.s}^{-2}$ upwards and $20\ \text{m.s}^{-2}$ downwards
2. Find both the resultant and the equilibrant of the following force vectors:
   a. $60\ \text{N}$ to the left and $45\ \text{N}$ to the left
   b. $12\ \text{N}$ west and $17\ \text{N}$ east

The full solutions are at the end of the unit.

Vectors in two dimensions

Finding the resultant of vectors in two dimensions involves drawing accurate scale diagrams. The method we will use is called the head-to-tail method because the arrowhead of the first vector is at the tail of the second vector:

Method: Head-to-tail method of vector addition

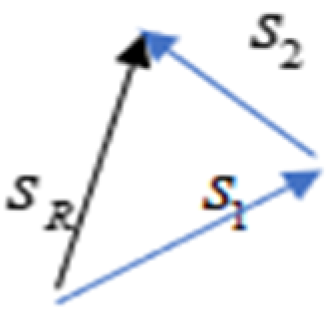
1. Draw a rough sketch of the situation.
2. Choose a scale and include a reference direction.
3. Choose any of the vectors and draw it as an arrow in the correct direction and of the correct length. Remember to put an arrowhead on the end to denote its direction.
4. Take the next vector and draw it as an arrow starting from the arrowhead of the first vector in the correct direction and of the correct length.
5. Continue until you have drawn each vector, each time starting from the head of the previous vector. In this way, the vectors to be added are drawn one after the other head-to-tail.
6. The resultant is then the vector drawn from the tail of the first vector to the head of the last. Its magnitude can be determined from the length of its arrow using the scale. Its direction can be determined by measuring an angle in the scale diagram.

Example 4.2

Harold walks to school. He starts by walking $600\ \text{m}$ northeast (s_1) and then $500\ \text{m N } 40^0\ \text{W}$($s_2$). Determine his resultant displacement (s_R) by using an accurate scale drawing.

Solution

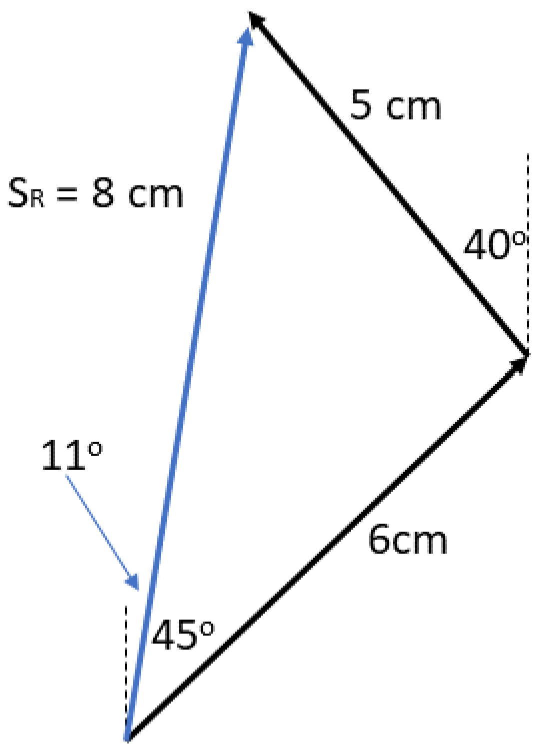
Step 1: Draw a rough sketch of the situation



Step 2: Choose a scale and a reference direction

Scale $1\ \text{cm} = 100\ \text{m}$ N

Step 3: Draw s_1 and then s_2, head-to-tail; draw the resultant from the starting point of s_1 to the ending point of s_2



Step 4: Measure the resultant (s_R) and convert to scale. Measure angle and give direction of s_R

Answer: $8\ \text{cm} = 800\ \text{m N } 11^0\ \text{E}$

Exercise 4.2

Find the resultant vector for the following:

1. $8\ \mathrm{N}$ east and $6\ \mathrm{N}$ south
2. $250\ \mathrm{m}$ west and $300\ \mathrm{m}$ north
3. $600\ \mathrm{m.s^{-1}}$ east and $450\ \mathrm{m.s^{-1}}$ northwest

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- The resultant is the single vector that has the same effect as individual vectors acting together.
- If vectors are in one dimension, the resultant can be calculated by vector addition using a positive reference direction.
- If vectors are in two dimensions, the resultant can be determined by using a scale diagram.
- The equilibrant is a vector that has the same magnitude as the resultant but acts in the opposite direction.
- The resultant and the equilibrant balance each other, and the result will be an equilibrium situation.

Unit 4: Assessment

Suggested time to complete: 30 minutes

1. Choose the letter of the correct answer:
    a. Two vectors act at the same point. What should the angle between them be in order to obtain a maximum resultant?
        A. 90^0
        B. 180^0
        C. 270^0
        D. 0^0
    b. Two forces of $4\ \mathrm{N}$ and $11\ \mathrm{N}$ act on the same point. Which of the following CANNOT be the resultant force?
        A. $8\ \mathrm{N}$
        B. $16\ \mathrm{N}$
        C. $15\ \mathrm{N}$
        D. $7\ \mathrm{N}$
2. Find the resultant and the equilibrant of the following vectors:
    a. $6\ \mathrm{N}$ north and $8\ \mathrm{N}$ south
    b. $50\ \mathrm{m}$ east and $18\ \mathrm{m}$ west
    c. $8\ \mathrm{m.s^{-1}}$ to the right and $17\ \mathrm{m.s^{-1}}$ to the left
3. If the resultant of two force vectors is $63\ \mathrm{N}$ south, and one of the vectors is $10\ \mathrm{N}$ north, what is the magnitude and direction of the second force?

4. Three force vectors each have a magnitude of $5\ \mathrm{N}$.
    a. What is the maximum possible resultant that can be obtained from these three forces?
    b. What is the minimum possible resultant that can be obtained from these three forces?
5. Find the resultant velocity of an aeroplane if it is flying at $200\ \mathrm{m.s^{-1}}$ in the direction 080^0 in a wind of $25\ \mathrm{m.s^{-1}}$ south. Use an accurate scale diagram.

The full solutions are at the end of the unit.

Unit 4: Solutions

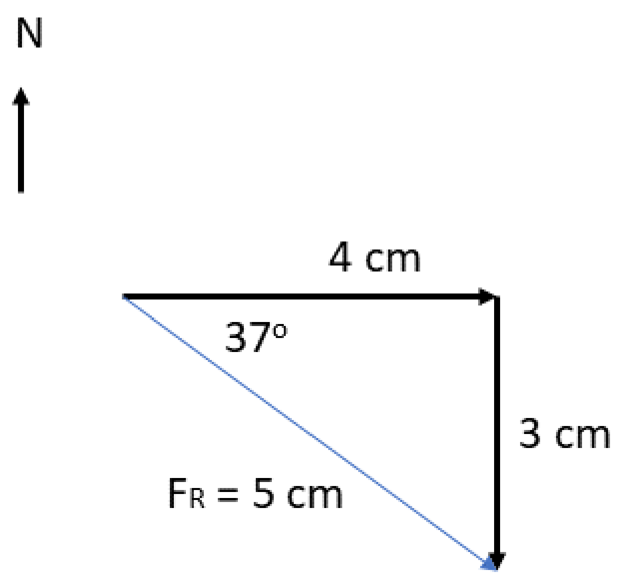
Exercise 4.1

1.
    a. Positive reference direction = north
    $\vec{v}_R = \vec{v}_1 + \vec{v}_2 = 20 + 5 = 25\ \mathrm{m.s^{-1}}$ north
    b. Positive reference direction = east
    $\vec{s}_R = \vec{s}_1 + \vec{s}_2 = 6 + (-22) = -16 = 16\ \mathrm{km}$ west
    c. Positive reference direction = downwards
    $\vec{a}_R = \vec{a}_1 + \vec{a}_2 = -14 + 20 = 6\ \mathrm{m.s^{-2}}$ downwards
2.
    a. Positive reference direction = left
    $\vec{F}_R = \vec{F}_1 + \vec{F}_2 = 60 + 45 = 105\ \mathrm{N}$ left
    $E_E = 105\ \mathrm{N}$ right
    b. Positive reference direction = east
    $\vec{F}_R = \vec{F}_1 + \vec{F}_2 = -12 + 17 = 5\ \mathrm{N}$ east
    $\vec{E}_E = 5\ \mathrm{N}$ west

Back to Exercise 4.1

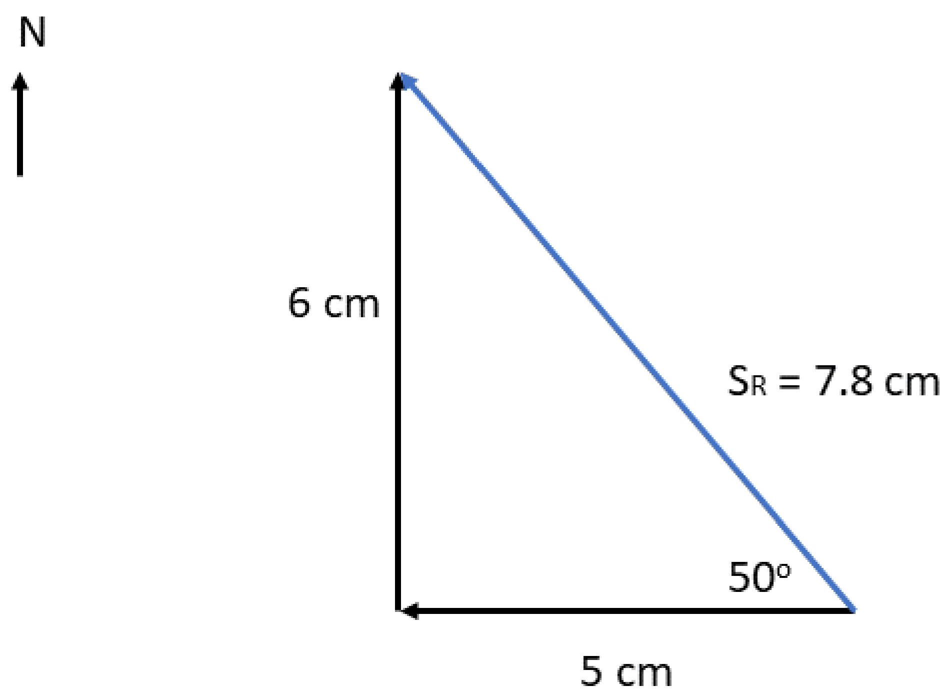
Exercise 4.2

1. scale $1\ \mathrm{cm} = 2\ \mathrm{N}$



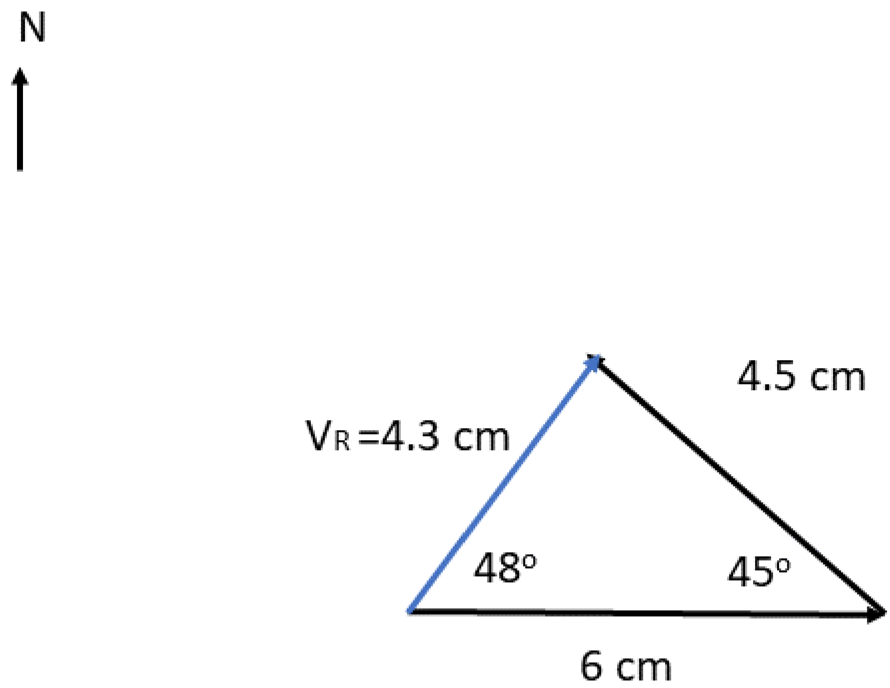
$F_R = 5\text{cm} = 10\text{ N at E } 37^0\text{ S}$

2. scale $1\text{ cm} = 50\text{ m}$



$s_R = 7.8\text{ cm} = 390.5\text{ m W } 50^0\text{ N}$

3. scale $1\text{ cm} = 100\text{ m.s}^{-1}$

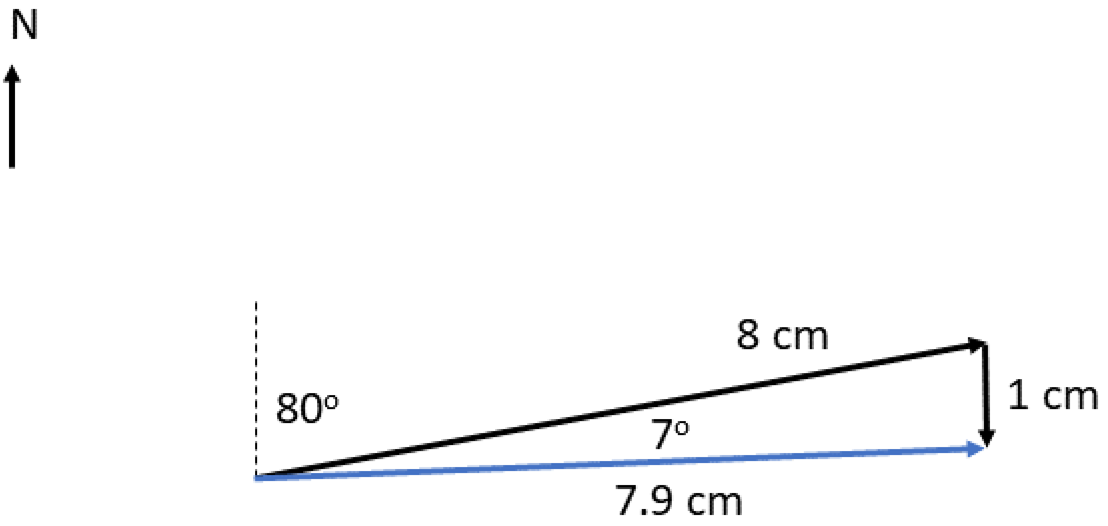


$v_R = 4.3 \text{ cm} = 430 \text{ m.s}^{-1} \text{ E } 48^0 \text{ N}$

Back to Exercise 4.2

Unit 4: Assessment

1.
   a. D (if the angle between the vectors is 0^0, the vectors will be in the same direction and the resultant will be the sum of the two positive values)
   b. B (the maximum resultant can only be $4 + 11 = 15$ N, which is when both forces are in the same direction)
2.
   a. positive reference direction = north
      $F_R = F_1 + F_2 = 6 + (-8) = -2 = 2 \text{ N South}$
   b. positive reference direction = east
      $\vec{s}_R = \vec{s}_1 + \vec{s}_2 = 50 + (-18) = 32 \text{ m east}$
   c. positive reference direction = right
      $\vec{v}_R = \vec{v}_1 + \vec{v}_2 = 8 + (-17) = -9 = 9 \text{ m.s}^{-1} \text{ to the left}$
3. positive reference direction = south
   $\vec{F}_R = \vec{F}_1 + \vec{F}_2$
   $63 = (\text{-}10) + \vec{F}_2$
   $\vec{F}_2 = 73 \text{ N south}$
4.
   a. If all vectors act in the same direction: $\vec{F}_R = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = 5 + 5 + 5 = 15 \text{ N}$
   b. If two vectors act in the same direction and one acts in the opposite direction:
      $\vec{F}_R = \vec{F}_1 + \vec{F}_2 + \vec{F}_3 = 5 + 5 + (-5) = 5 \text{ N}$
5. $1 \text{ cm} = 25 \text{ m.s}^{-1}$



Answer: $7.9 \text{ cm} = 198 \text{ m.s}^{-1} \text{ N } 87^{0} \text{ E}$

Back to Unit 4: Assessment

Media Attributions

SUBJECT OUTCOME II

MECHANICS: IDENTIFY AND APPLY PRINCIPLES OF FORCE

Subject outcome

Subject outcome 2.2: Identify and apply principles of force.

Learning outcomes

- Define force, describe different types of force and identify examples.
- Identify and draw diagrams indicating action–reaction forces.
- Define gravitational acceleration: g.
- Describe and calculate weight.
- Differentiate between mass (m) and weight (or $F_{gravitation}$).

Unit 1 outcomes

By the end of this unit you will be able to:

- Define a force.
- Describe different types of forces.
- Identify examples of different types of forces.
- Describe that forces work in pairs.
- Identify interacting force pairs as applies to:
  - contact forces
  - non-contact forces.

Unit 2 outcomes

By the end of this unit you will be able to:

- Identify the system of interest on which forces act.
- Draw diagrams to show interacting force pairs acting on a system.

- Interpret force diagrams to predict the net effect of forces acting on a system.

Unit 3 outcomes

By the end of this unit you will be able to:

- Define gravitational acceleration: *g*
- Describe weight.
- Differentiate between mass (m) and weight ($F_{gravitation}$).
- Calculate weight.

Unit 1: What is a force?

LINDA PRETORIUS

Unit outcomes

By the end of this unit you will be able to:

- Define a force.
- Describe different types of forces.
- Identify examples of different types of forces.
- Describe that forces work in pairs.
- Identify interacting force pairs as applies to:
  - contact forces
  - non-contact forces.

What you should know

Before you start this unit, make sure you can:

- Define a frame of reference. Subject Outcome 2.1, Unit 1.
- Distinguish between a vector and a scalar quantity. Subject Outcome 2.1, Unit 3.

Introduction

In this unit you will learn what a force is and find out about different types of forces. This will allow you to identify forces at work in your everyday life and understand the effects of forces.

Activity 1.1: Think about forces

Time required: 5 minutes

What you need:

- an internet connection
- a cellphone with a QR scanner

What to do:

Watch the video clip.

Describe to a friend, someone at home or just for yourself what you see happening.

What did you find?

In the video, we see a ball lying still on the ground. We say it is at rest. When the boy kicks the ball, it lifts off the ground and moves through the air, towards the net. When it hits the net, the ball's motion changes. The shape of the net also changes. The ball then falls to the ground, rolls along for a while, and then comes to rest again. The net wobbles in the frame for some time, until it, too, stops moving.

Definition of force

Everything we saw happening in the video was caused by forces. The easiest way to think about force is that it is a push or a pull. But an important additional point to understand is that a push or a pull is the result of one object interacting with another.

Figure 1: A pushing force


Figure 2: A pulling force

The video clip in Activity 1.1 shows us some important things about forces and how they work.

> The interaction between objects can happen because of their direct contact with each another. This is called a contact interaction.

At the start, the ball was at rest on the ground. Because the ball touched the ground and the ground touched the ball, we know that this was a contact interaction. Understanding force as the result of an interaction between objects, we can say that the ball exerted a force on the ground and that the ground exerted a force on the ball.

When the boy kicked the ball, his foot touched the ball and the ball also touched his foot. Through the contact interaction, the boy's foot exerted a force on the ball and the ball exerted a force on his foot.

> The interaction between objects can be caused by invisible surrounding fields interacting with each other. This is called a field interaction.

At the end of the video clip, we see the ball dropping down to the ground, without contact with another object. This is the result of the interaction between the gravitational fields around two objects, namely the Earth and the ball. Field interactions are non-contact interactions because the objects are not touching each other.

Every object that has mass also has a surrounding gravitational field. The Earth's gravitational field is much bigger than that of the ball. This is because the Earth has much more mass than the ball and so exerts a bigger force on the ball than the ball on the Earth.

Forces work as interacting pairs.

As force is the result of an interaction between two objects, it follows that the objects will each exert a force on the other, in opposite directions. For example, the ball lying on the ground pushes down on the ground, and the ground pushes up on the ball.

Force is a vector quantity. It has size *and* direction.

Force is measured in newtons (N). When we describe a force, we must mention both its magnitude (size) and its direction. For example:

- The ball lying at rest exerts a force of a certain magnitude downwards.
- The boy's foot on the ball exerts a force of a certain magnitude forward and to the right.

When we describe a force quantitatively – in other words, as a numerical value – the number tells us its size, and the sign – positive or negative – tells us its direction relative to a predefined frame of reference. For example, if we define up as the positive vertical direction, we know that a force with a negative value acts downwards.

Note

Look back to Subject Outcome 2.1, Unit 1 if you need to revise the concept of a frame of reference.

We cannot see forces themselves, only their effects.

We can see the effect of a force by looking at an object's shape or motion. A force can cause an object to remain as it is or cause a change in its shape or motion. In the video clip we saw:

- force causing a change in an object's shape when the ball hit the net and made the net bulge out
- force affecting the speed at which an object moves, when the boy kicked the stationary ball to make it move, or the ball rolling slower and slower along the ground until it eventually stopped
- force affecting the direction in which an object moves, such as when the ball hit the net and rolled away from the net.

A change in an object's shape or motion is caused by unbalanced forces acting on the object. When the forces acting on an object are balanced, its shape or motion will remain unchanged.

The ball fell to the ground because the gravitational force of the Earth pulling the ball downwards was bigger than the gravitational force of the ball on the Earth. That means that in this interacting force pair, the force acting downwards and the one acting upwards were unbalanced, and so the ball's motion changed.

When the ball lay on the ground, it was acted on by the force of gravity. Yet it lay still; its motion or shape did not change. This tells us that a force equal in size but opposite in direction was also acting on the object. We say two such counteracting forces acting on an object balance each other.

The effect of a force is the sum of all the forces acting on an object.

Forces are additive, like all vector quantities. If the two forces in an interacting pair have equal magnitudes but opposite signs, the resultant force will be zero. If the two forces have unequal magnitudes, the sum will be a non-zero value, which means the net effect will be in the direction of the force with the bigger magnitude.

Note

Resultant force is also called net force.

Take note!

If you want to explore the effects of pushes and pulls and the effect of the resultant force on an object, try this simulation. See how the amount of force changes when you change the mass of the object you are trying to move.

Types of force

Understanding a force as the result of an object's interaction with another object allows us to classify forces according to two broad categories:

- Contact forces result from contact interactions, in other words when two objects touch each other.
- Non-contact forces result from objects interacting with each other at a distance, without direct contact between them. These interactions are due to the fields around objects interacting with each other.

In the next two activities, you will explore different types of forces in each category. Being able to correctly identify the types of forces acting on an object will help you to draw force diagrams, which you will learn about in the next unit.

To identify the types of force acting on an object, always ask how the object is interacting with its surroundings.

Activity 1.2 Investigate non-contact forces

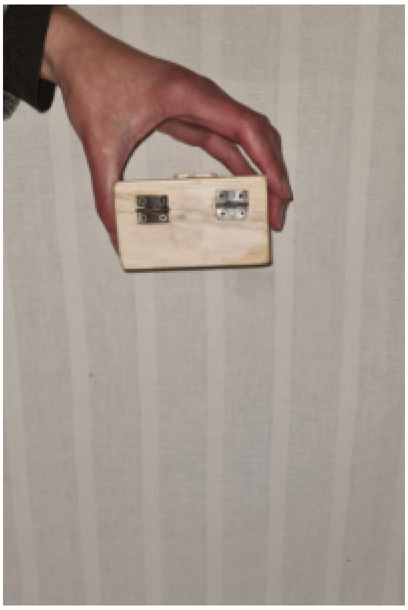
Time required: 5 minutes

What you need:

- a (non-fragile) object made of wood, plastic or metal
- two magnets
- some metal paper clips or drawing pins
- a plastic ruler
- a dust cloth
- small pieces of paper

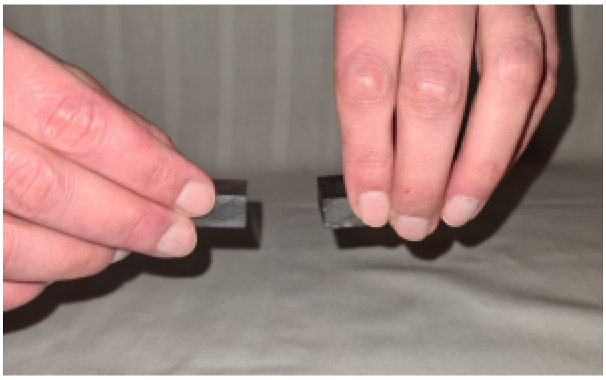
What to do:

1. Hold the wooden, plastic or metal object above the ground. Then release your grip. What do you observe?



2.
   a. Put the paper clips or drawing pins on a flat surface. What happens when you hold the magnet over them?

2.
   b. Take the two magnets and bring them towards each other. What do you observe?



3. Rub the ruler vigorously with the dust cloth. Then hold the ruler over the pieces of paper. Describe your observations.

What did you find?

From your observations you will be able to describe examples of non-contact forces:

- When you released the object you held above the ground, it fell downwards. As you know by now, the motion or shape of an object changes when an unbalanced force acts on it. Therefore, a force must have been acting on the object to make it fall down.

  The force at work here was a **gravitational force**, often simply called gravity. We can write it as FG. Gravity is a non-contact force that exists between any two objects with mass because they attract each other. This is known as the law of universal gravitation. You will learn more about this in Unit 3.

  The effect of gravitational force is most notable when one of the objects is much more massive than the other. This is what we experience on Earth: the Earth's gravitational force is much bigger than other objects on Earth, and so all objects close to the Earth's surface are attracted downwards, towards the Earth.
- When you held the magnet above the paper clips or pins, you would have noticed that they were attracted towards the magnet, without direct contact exerting a force. Similarly, when you brought the two magnets towards each other (whether with opposite or like poles facing each other), you would have felt either a pull or a push between them, again without their touching each other. Both these effects are caused by **magnetic force**, which results from the items interaction with the magnetic field.
- When you rubbed the plastic ruler with the dust cloth, the ruler became electrostatically charged. This means it had an excess of one type of charge. When you held the charged ruler above the pieces of paper, they were attracted to the ruler. This is due to the interaction of electric fields between the ruler and the paper, which caused an **electric force**. The size of the field around the charged ruler was stronger than that around the pieces of paper, and therefore the pieces of paper moved in the direction of the ruler.

Note

- If there is a magnet near an object, there will be a magnetic force.
- If there is a charged object near an object, there will be an electric force.
- If there is a planet (or other massive body) near an object, there will be a gravitational force. All objects on Earth are therefore acted on by the Earth's gravitational force.

Activity 1.3 Investigate contact forces

Time required: 10 minutes

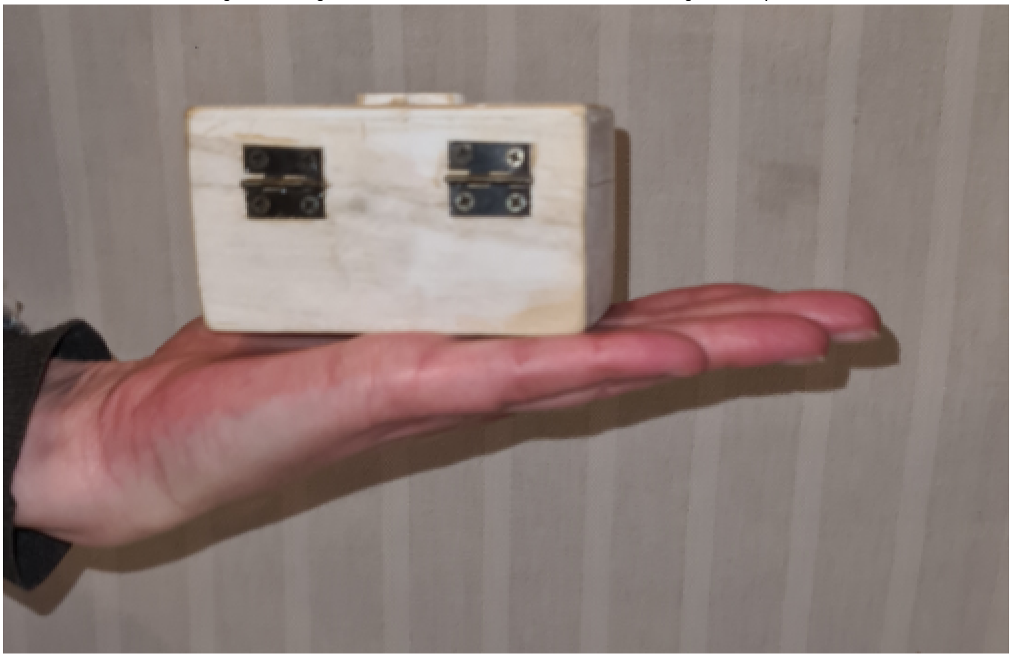
What you will need:

- two different objects, each with a flat surface and ideally of different masses, e.g. a plastic tub, a block of wood, a brick, a book, etc.; you should be able to hold the object in your hand
- a flat surface, e.g. a small table, a chair or a cutting board
- an elastic band
- rope or string

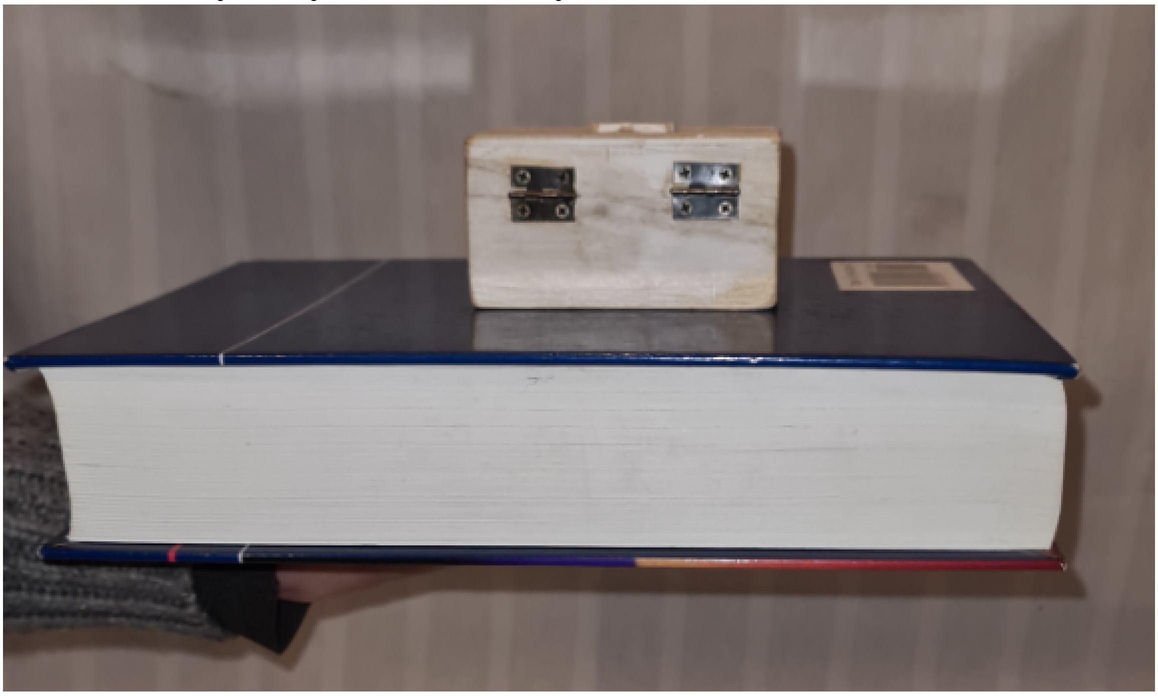
- a bottle top
- a marble or small stone
- a bowl of water

What to do:

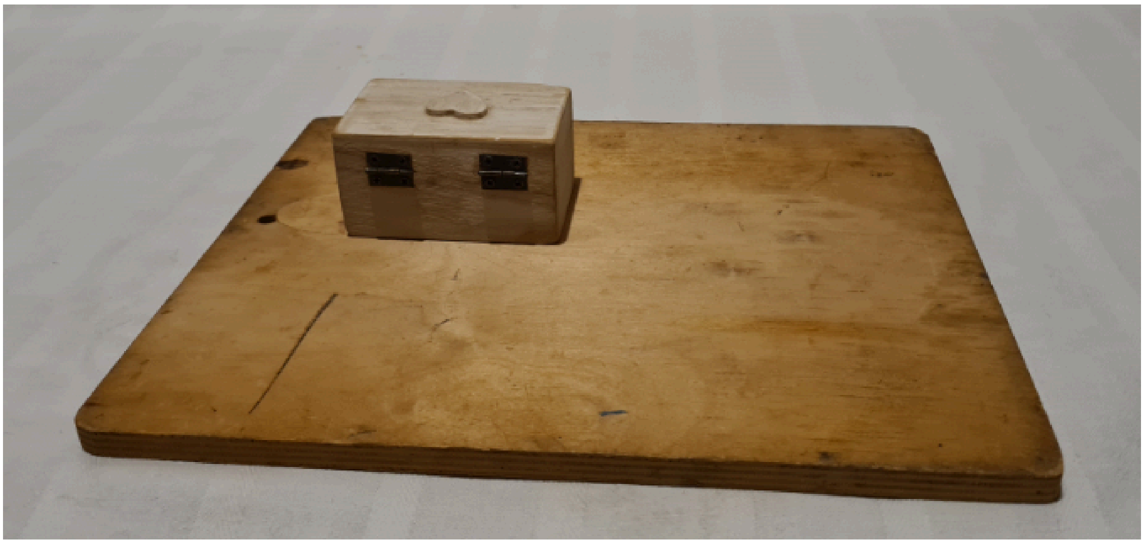
1. Hold one of the objects in your hand, as shown. What do you experience?



2. Now hold both objects in your hand. What do you notice now?



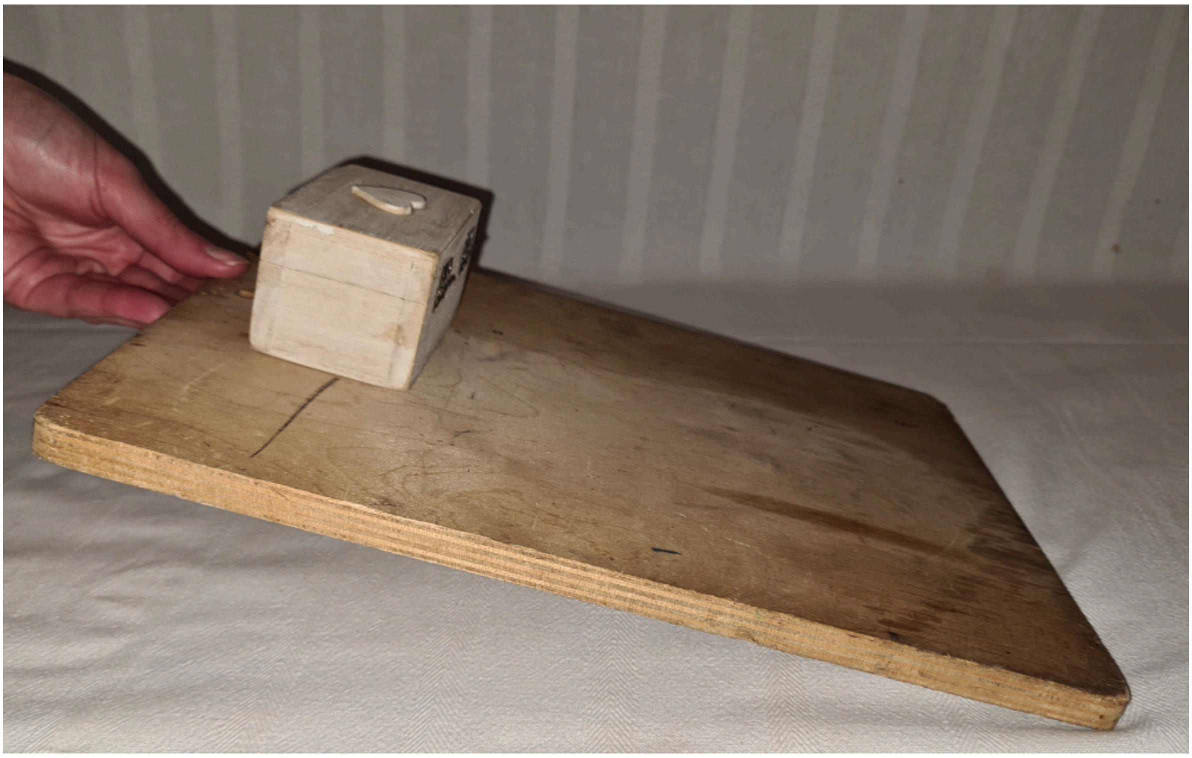
3.
    a. Place one of the items on a flat surface. What do you notice?



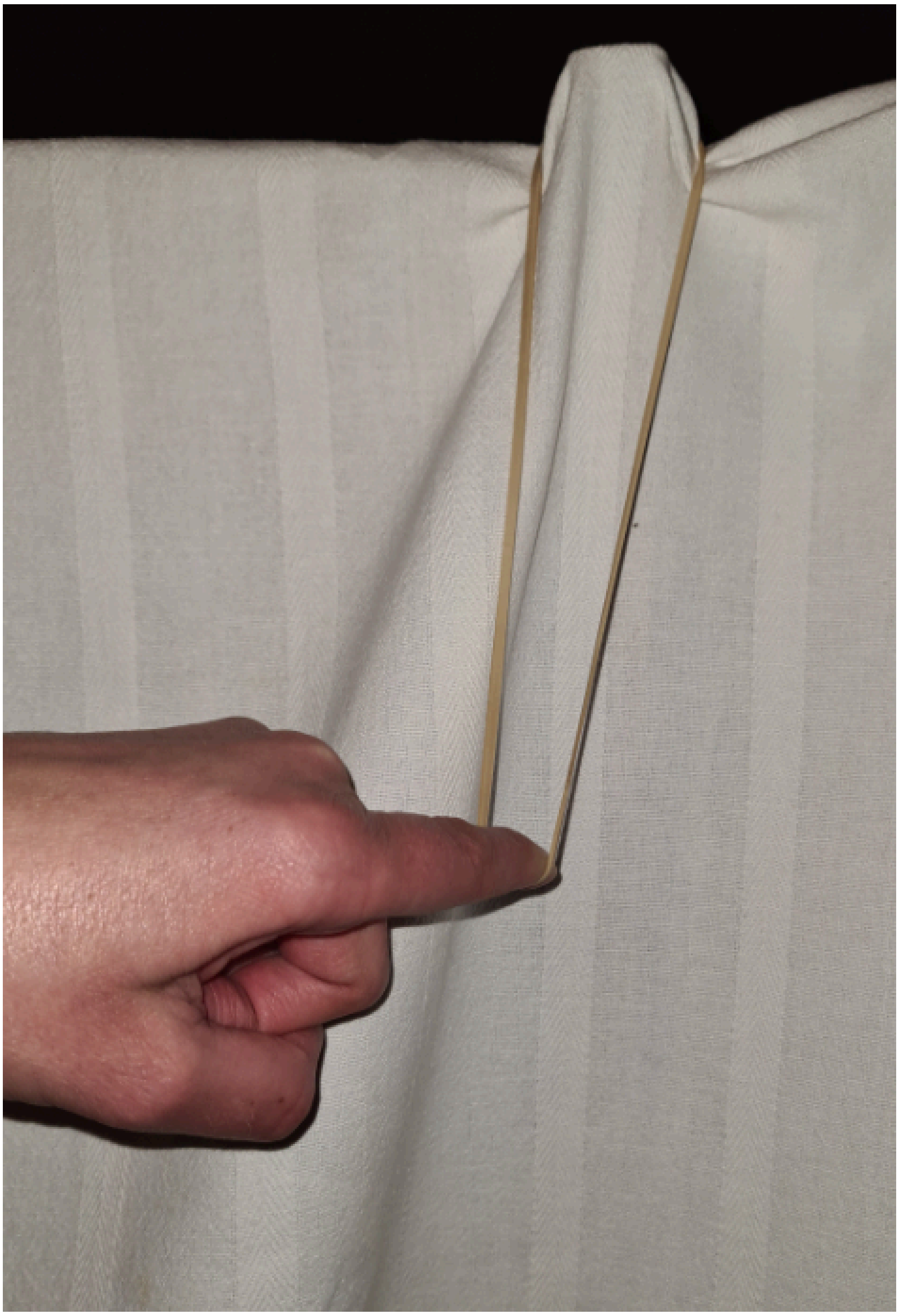
b. Push against the object to make it move forward. Did you have to push hard or only a little? Does it keep on moving indefinitely?

c. Repeat steps a) and b) with the other object. What is different? What is the same?

4. Tilt the surface slightly upwards. What happens to the object? What happens when you tilt the surface even more?



5. Attach the elastic band to a fixed point. Hook your finger through the free end and pull on it, and then release a little. What interactions do you observe?



6. Tie the rope around a fixed point (e.g. the leg of a table, a lamp post or tree). Pull on the rope. What do you observe?

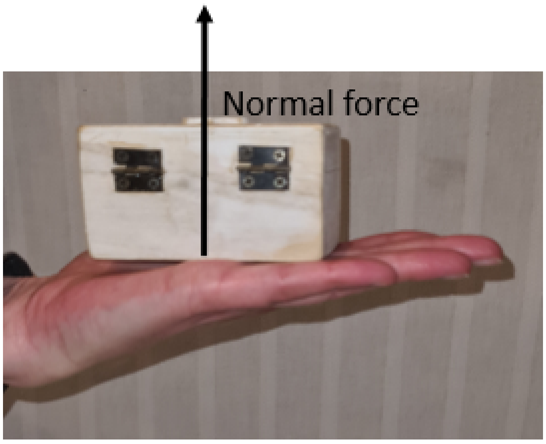
7.

a. Put the bottle top in the bowl of water. What do you notice? How is this brought about by forces?

b. Now put the marble or small stone in the water. Is the effect the same as when you put the bottle top in the water? Why do you think this happens?

What did you find?

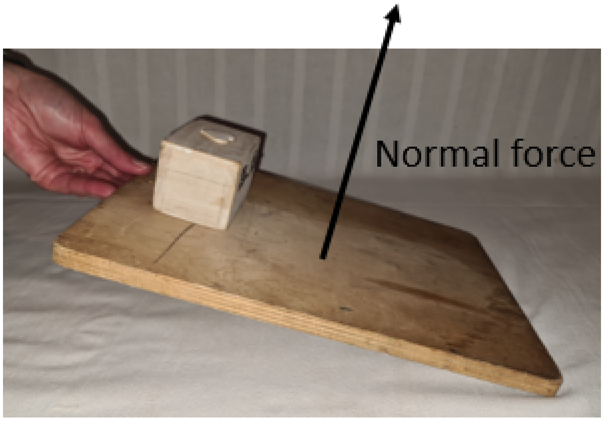
- When you held an object in your hand, you would have experienced two forces acting on it. You already know that all objects on Earth are acted on by the Earth's gravitational force, which acts downwards. But you also know that forces work in interacting pairs. So, because the object was at rest in your hand, your hand must have exerted a force equal in size to the gravitational force, but opposite in direction. In other words, the counteracting force must have acted upwards on the object. This upward force is called the **normal force**. The normal force is always present when an object rests on a surface and always acts perpendicular to the surface. Normal force is often written as F_N.



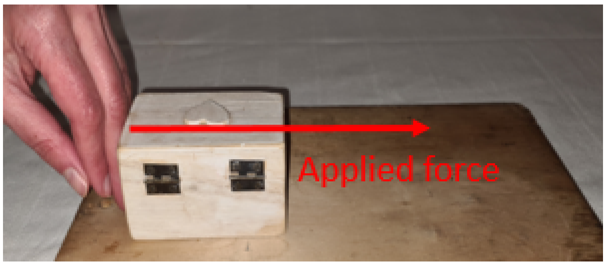
Note

In physics, ‘normal’ means ‘perpendicular’.

- When you held both objects in your hand, you would have experienced the effect of gravity and the counteracting normal force in an even more pronounced way. Gravity acted downwards on both objects and a combined normal force of equal magnitude acted upwards. Remember that although there were two different interactions (between the bottom object and your hand, and between the bottom and top object), the individual downward and upward forces added up (and balanced out).
- When you placed the object on the flat surface, both gravity and the normal force acted on the object. Again, they balanced each other, and so the object did not move up or down. Gravity and the normal force would also have acted when you tilted the surface. However, in this case the two forces would not have been in directly opposite directions, because gravity acts vertically down, whereas the normal force acts perpendicular to the surface on which the object rests.



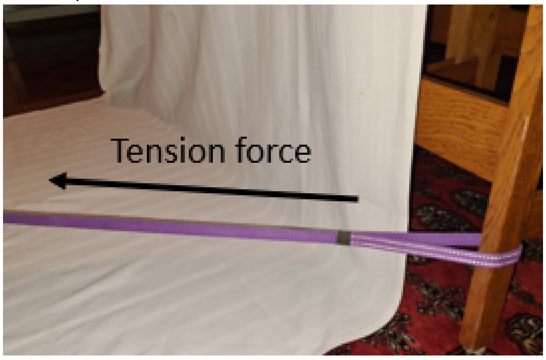
- When you pushed against the object to make it move over the flat surface, it experienced an unbalanced **applied force** in the horizontal direction. We can write this as F_A.



- The object later slowed down and eventually came to rest due to a **frictional force**, often written as $F_{friction}$ or F_f. Friction is a force that opposes motion and acts in the direction opposite to that of the motion. Friction always exists when two surfaces are in contact with each other, but is most notable when a surface moves over another.

  All surfaces exert a frictional force to some extent. For an object to move over another, the inherent frictional force must be overcome. This is why an object will remain at rest up to a certain point on an inclined plane. You will learn more about this in the next unit.
- An object that can stretch and return to its original length exerts an **elastic force**. You observed this when you tied the elastic band to a fixed point and hooked your finger through the free end to pull on it. As your finger pulled on the elastic band, it pulled back in the opposite direction. When you reduced the amount of force exerted by your finger, the force exerted by the elastic band pulled your finger back in the opposite direction.
- When you pulled on the rope tied to a fixed point, you would have experienced a **tension force**.

Tension force exists in a rope, cable, chain or string pulled tight. This is not an elastic force because the rope or cable does not stretch further than its original length when it is pulled tight.



- Objects placed in water experience a **buoyant force**. When an object floats, like the bottle top, it means the downward force exerted by the object on the water is balanced by the upward force of the water on the object. However, when an object sinks, like when you put the marble in the bowl of water, it means that the object exerts a bigger downward force on the water than the upward force of the water on the object.
- **Air and water resistance** are two further examples of contact forces, but we did not explore them in the activity. Air or water resistance is a force that opposes the motion of an object that moves through a fluid such as a gas or a liquid. Air or water resistance can also be called a drag force.

Take note!

Explore the forces acting on an object in this simulation:

Create an applied force and see the resulting friction force and total force acting on the object. You can also view the diagrams to see how gravity and the normal force apply.

Summary

In this unit you have learnt the following:

- A force is a push or a pull that results from the interaction between two objects.
- Interactions can involve direct contact or occur at a distance. We therefore distinguish between contact interactions and non-contact interactions.
- Because forces are the result of interactions, we can distinguish between contact forces and non-contact forces.
  - Examples of non-contact forces are gravitational force, magnetic force and electric force.

- Examples of contact forces include the normal force, friction, tension, air or water resistance, buoyant force, elastic force and applied force.
- Forces act in interacting pairs on an object.
- We cannot see a force, only its effects.
- Force is a vector: it has both size and direction. Like all vectors, forces are additive.
- Forces affect an object's shape or motion. If a force changes an object's shape or motion, it means a non-zero resultant force acts on the object.

Take note!

Watch the video called 'How objects interact' (duration: 03:17) for a quick recap of forces.

Unit 1: Assessment

Suggested time to complete: 15 minutes [1]

1. An unbalanced force acts on an object. Name three effects that the force can have on the object.
2. Identify each of the following forces as either contact or non-contact forces.
   a. The force between a magnet and a paper clip.
   b. The force required to open the door of a taxi.
   c. The force required to stop a soccer ball.
   d. The force causing a ball, dropped from a height, to fall to the floor.
3. Watch the following video clip:

1. Questions 1 and 2 were sourced from Siyavula Physical Science Gr 11 Learner's Book, p. 120, released under a CC-BY licence at https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-06.

a. Identify one push and one pull force acting in the video.

b. Classify each of the forces in (a) as a contact force or a non-contact force. Give a reason for each answer.

c. Look at the person handling the kite. Do his hands exert a force on the kite? Give a reason for your answer.

d. Look at the rock in the video. What is the resultant force acting on the rock, and in which direction does it act? Describe how you formulated your answer.

4. The photo shows a bakkie with a trailer loaded with logs parked alongside the road. Identify two interacting force pairs in the photo.

5. In each picture, identify the force(s) acting on the indicated object and say whether they are balanced or unbalanced.

   a. The book at the top of the stack

b. The skydiver

c. The signboard

The full solutions are at the end of the unit.

Unit 1: Solutions

Unit 1: Assessment

1. The force can change the shape of the object.
   The force can change the direction in which the object is moving.
   The force can change the speed at which the object is moving (make it move from rest; cause it to accelerate or slow down; make it stop).
2.
   a. Non-contact force
   b. Contact force
   c. Contact force
   d. Non-contact force
3.
   a. Examples of push forces: water pushing against the rock; air pushing against the kite.
      Examples of pull forces: man pulling on the strings of the kite; gravity acting on person’s feet; tide pulling wave back into the sea.
   b. Contact forces apply between objects or surfaces that are in contact with each other. For example: water pushing against the rock; air pushing against the kite; man pulling on the strings of the kite (tension).

      A non-contact force acts at a distance, without making contact with the object on which it acts. For example: the Earth’s gravity pulling objects downwards; the Moon’s gravity acting on the Earth to cause the tides (and therefore the waves rolling into the beach and pulling back).
   c. No, his hands are applying a force to the strings. The strings are pulling on the kite.
   d. The resultant force is zero, because the rock is stationary. There is no movement in the vertical

direction, which means the force of gravity and the normal force are of equal magnitude but in direct opposite directions. There also is no movement in the horizontal direction, which means the force of the water against the rock does not overcome the frictional force exerted by the sea floor on the rock.

4. Possible answers:
    - The trailer pulls to the left on the bakkie's tow bar, and the tow bar pulls to the right on the trailer.
    - The wheels push down on ground and the ground pushes up on the wheels.
    - The pile of wood pushes down on the base of the trailer and the base of the trailer pushes up on the pile of wood.
    - One log pushes down on another and the other pushes up on the log above.

5.
    a. Gravitational force acting downwards; normal force of the surface (of the stack of books) acting upwards. The forces in the vertical direction are balanced, because the book is stationary.
    b. Gravitational force only, acting downwards; air resistance is negligible. The forces in the vertical direction are unbalanced because the skydiver is falling downwards.
    c. Gravitational force acting downwards on the board; two upward tension forces acting upwards, one at each chain. The forces in the vertical direction are balanced because the board is hanging still.

Back to Unit 1: Assessment.

Media Attributions

Unit 2: Force diagrams

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Unit outcomes

By the end of this unit you will be able to:

- Identify the system of interest on which forces act.
- Draw diagrams to show interacting force pairs acting on a system.
- Interpret force diagrams to predict the net effect of forces acting on a system.

What you should know

Before you start this unit, make sure you can:

- Distinguish between a vector and a scalar. Subject Outcome 2.1, Unit 3.
- Define a force. Subject Outcome 2.2, Unit 1.
- Identify different types of forces. Subject Outcome 2.2, Unit 1.

Introduction

Almost everything that happens in the world around us, and much of what we study in physics, is the result of forces. In the previous unit you learnt what a force is and how to identify different types of forces. This knowledge will help you to draw force diagrams. Force diagrams help us to visualise forces at work, and predict or understand the observed effect of forces.

What is a force diagram?

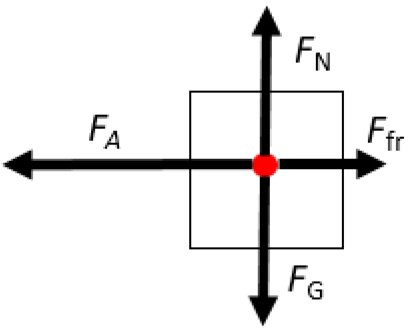
You already know from Unit 1 that we can see only the effects of forces on an object, not the forces themselves. A force diagram is a useful tool to help us visualise forces acting on an object and gives us information about the object's motion. We often use force diagrams when solving calculations involving the forces acting on an object.

Here is an example. Imagine you want to visualise the forces acting on a Formula 1 race car as it accelerates towards the finish line.

Figure 1: Which forces are acting on the race car?

Instead of drawing the actual car and trying to show in picture form that it is accelerating, we simply draw:

- a box to represent the car
- arrows to show the forces affecting its movement.



The force diagram shows us that the forces acting on the object in the vertical direction are balanced, these are the gravitational force F_G and the normal force F_N, because they are drawn at equal lengths. The forces in the horizontal direction, namely the applied force F_A and the opposing frictional force F_{fric}, are unbalanced; therefore the arrow representing F_A is longer than that of F_{fric}.

Notice the following important aspects of a force diagram:

- The object is drawn as a simple shape, usually a box or a big dot.
- Arrows are drawn from the centre of the object.
- Arrows represent the *external* forces acting on the object.
- The arrows are labelled to show the types of force, the size of the forces, or a combination of the information.
- Each arrow points in the direction of the force it represents.
- The length of an arrow shows the relative strength of the force.

Note

A force diagram is often also called a free-body diagram.

Working with force diagrams

Drawing and interpreting force diagrams starts to become easy when you remember that the diagram represents the external forces acting on an object and you know how to define the object.

We often refer to the object as a 'system of interest', especially when a collection of items act as if they are one object, such as a cart full of boxes being pushed by a person, or a car with a driver and a passenger inside the cabin and the engine in front. A force diagram therefore **does not** show:

- any internal forces acting within the system; for example, the forces exerted by a driver on the seat or steering wheel
- the forces acting on other objects in the surroundings; for example, forces on other cars surrounding the one we are interested in
- the forces exerted by the system itself; for example, the forces the car exerts on the road or its surroundings.

The following is a good strategy to help you draw and interpret force diagrams:

1. **Analyse the situation.** What is the object or system of interest and how is it behaving? Always look out for words that tell you something about the motion of the system. For example:
    - 'At rest' and 'stationary' mean there is no movement and hence all the forces are balanced.
    - 'Accelerate', 'speeding up' or 'slowing down' mean at least one unbalanced force is at work.
    - 'Constant speed' means that an object is moving, but that there is no change in its velocity over time. This means there are no unbalanced forces acting on the system.
2. **Identify the forces acting on the object or system.** Which non-contact forces are at work? Which contact forces are at work?

    Note

    Note
    Look back to Unit 1 to revise how to identify different types of forces.
3. **Determine in which direction the forces are acting.** Which forces are vertical, and which are horizontal? Which are perpendicular to a surface and which are parallel to a surface? What are the directions of the forces in relation to one another? Remember to always show the coordinate system to define the positive directions.
4. **Determine the relative sizes of the forces acting on the object.** Which forces are balanced, and which are unbalanced?

You will see how to use this strategy in the following examples.

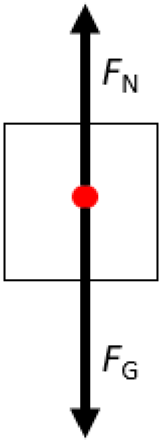
Example 2.1

Draw a force diagram for a cup of coffee on a table.

Solution

1. *Analyse the situation:* The object of interest is the cup. We regard the cup, with its contents, as the system (object) of interest. The object is at rest on a flat surface.
2. *Identify the forces acting on the object:* We know that gravity acts on the object. Because the object rests on a surface there must also be a normal force. The situation does not suggest any other forces at work.
3. *Determine the direction of each force:* We know that gravity acts downwards. The normal force is exerted by the surface on the object and therefore acts upwards, perpendicular to the surface.
4. *Determine the relative size of each force:* The object is at rest. That means the resultant force is zero, and so the two forces must be balanced.

We can now proceed to draw the diagram. We use a box or large dot to represent the object, rather than drawing the actual cup of coffee. We then add arrows to represent the individual forces, with the arrowheads pointing in the direction of the force and the length of an arrow representing the relative size of the force.



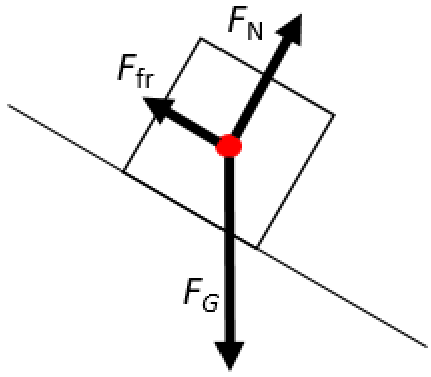
Example 2.2

Draw a force diagram for a car sliding down a slope.

Solution

1. *Analyse the situation:* The car is the system. It is moving and the movement is at an angle.
2. *Identify the forces acting on the object:* We know that gravity acts on the system. Because the system is in contact with a solid surface, we know there is also a normal force acting on the system. We also know that the system is moving over the surface, which tells us a frictional force will be acting on the system. The movement is not due to an applied force.
3. *Determine the direction of each force:* Gravity acts directly downwards. The normal force is exerted by the surface and is therefore upwards. However, remember that the normal force is always perpendicular to the surface, and therefore it is not in a directly opposite direction to the gravitational force. The car moves down the slope, and because friction is a force that opposes the motion, we therefore know that friction must act in the direction opposite to the motion.
4. *Determine the relative size of each force:* The car moves parallel to the surface and down the slope. That means forces in the vertical direction are not balanced; the gravitational force must be bigger than the opposing normal force. The force of friction is the only force acting parallel to the surface; there is no applied force.

We can now draw the completed force diagram:



Example 2.3

A woman is pushing her mother in a wheelchair. Which diagram correctly represents the forces acting on the person in the wheelchair?

Diagram A

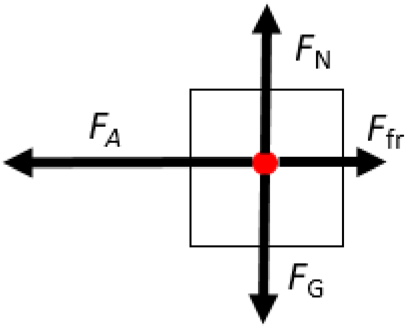
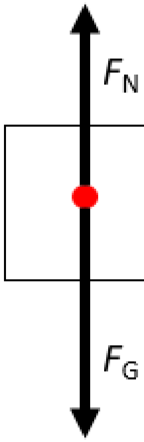


Diagram B



Solution

The object of interest is the person sitting in the wheelchair, not the combination of the wheelchair and the person. The person is stationary; it is only the wheelchair that is moving. This means that there are no horizontal forces acting on the person. Diagram A is therefore incorrect. Diagram B shows that only two vertical forces act on the object and that they are balanced, which correctly describes the situation of a stationary person in a moving wheelchair.

Example 2.4

Three potted plants sit on a hanging shelf, which is not moving. Which is the correct force diagram for the shelf?

Diagram A

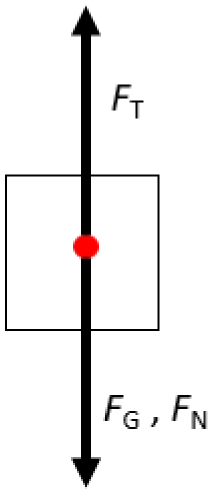
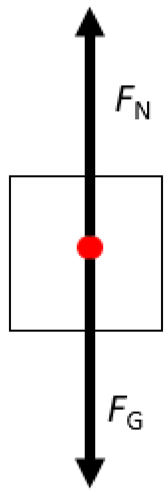
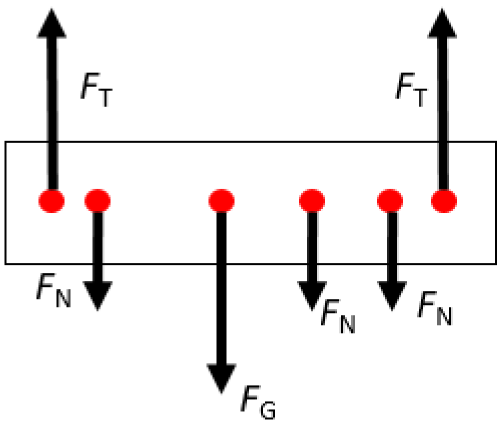


Diagram B



Solution

The object of interest is the shelf. Because the shelf is hanging but not moving, we know that the resultant force in both the vertical and the horizontal direction must be zero. There are no horizontal forces at work, only vertical forces. Gravity acts downwards on the shelf. However, the three pots also exert a downward force on the shelf. All the downward forces are balanced by two upward-acting tension forces, one in each cable. If we were to draw these forces separately, it would look like this:



However, it is preferable to draw the forces all relative to one point, so the combined diagram would look as shown in Diagram A, showing that all the downward forces are balanced by the upward forces.

Diagram B is not correct, because the normal forces are acting downward – they represent the pots pushing down on the shelf. The diagram as shown in B would have been correct if we were asked to draw a force diagram for the pots.

The best way to become confident at drawing force diagrams is to practise. Try this exercise on your own.

Exercise 2.1

1. Draw force diagrams for the following situations:
   a. A crate being pulled up a ramp using a rope
   b. A light bulb hanging from the ceiling
   c. A car skidding across the road after the brakes have locked.
2. Match each of the following situations with the correct force diagram.
   a. A ball being dropped from the top of a 10-storey building
   b. A baby pram being pushed at a constant speed
   c. A ball as it is being kicked from a stationary position to a goal post

Diagram A

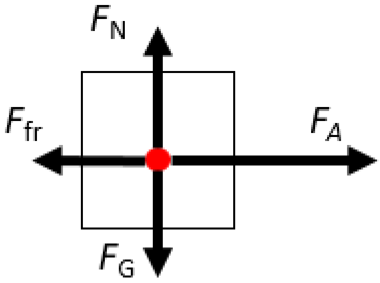


Diagram B

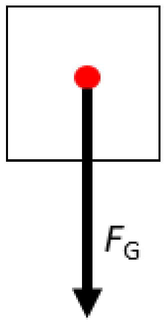


Diagram C

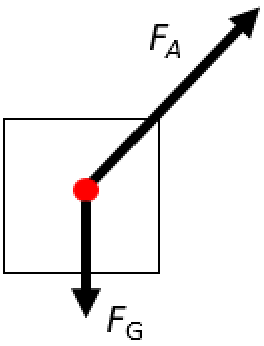
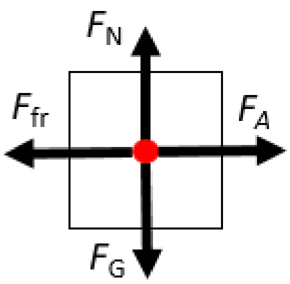


Diagram D



The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- A force diagram shows the forces acting on an object or a system of interest.
- Forces are represented by arrows that point in the direction of the force. The length of an arrow represents the relative size of the force.
- Force diagrams are conventionally labelled to show the type of force. The size of the force can also be included.

Unit 2: Assessment

Suggested time to complete: 15 minutes

1. A car is towing another car, which has broken down, using a tow rope. They have to travel through a hilly landscape to get to the garage. Draw a force diagram for the car being towed at each of the following stages of their journey.
    a. Early on in their journey they travel up a hill.
    b. The car in front loses speed the further it goes up the hill.
    c. After they reach the top of the hill, they have to travel down a gentle slope again. The driver of the second car has to apply the brakes to keep the rope taut.
2. Draw a force diagram to represent a lift in a tall building:
    a. when it is stationary at the fifth floor of the building, just after three people stepped inside
    b. when it is moving towards the first floor, slowing down as it approaches its stop.
3. Katlego is practising her tennis backhand shots at the practice wall near the tennis court. Which force diagram represents:
    a. the ball just after Katlego hits it with the racket?
    b. the ball when it hits the wall?

Diagram A

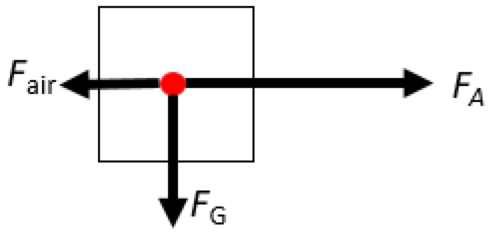


Diagram B

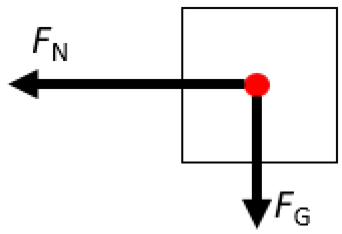


Diagram C

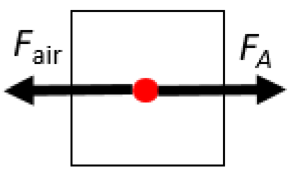
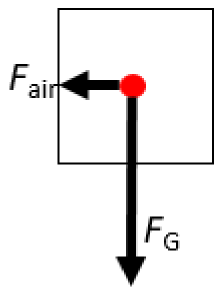


Diagram D

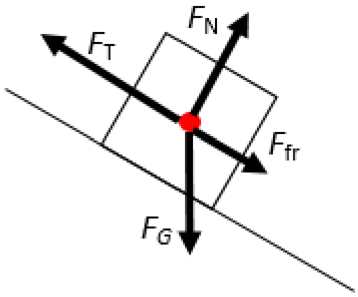


The full solutions are at the end of the unit.

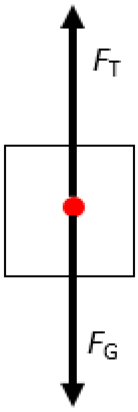
Unit 2: Solutions

Exercise 2.1

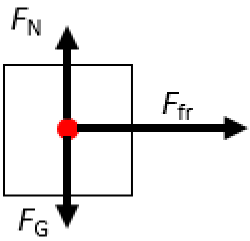
1.
    a.



b.

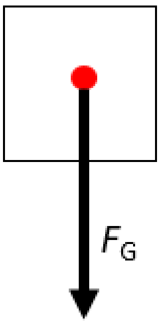


c.

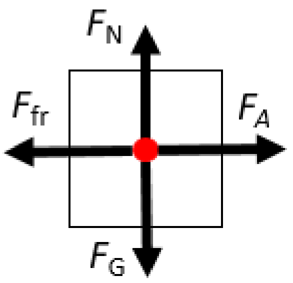


2.

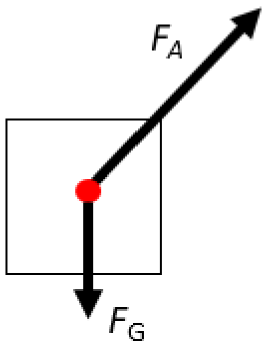
a.



b.



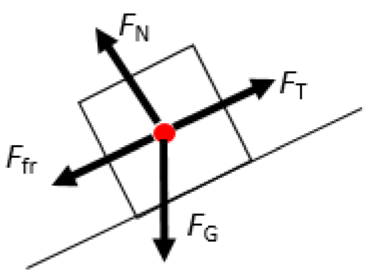
c.



Back to Exercise 2.1

Unit 2: Assessment

1.
   a.



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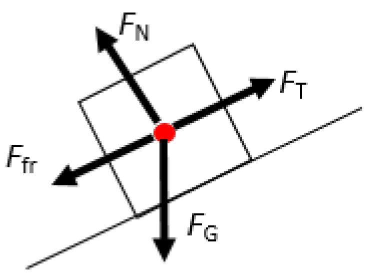
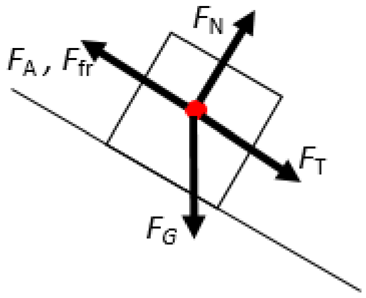
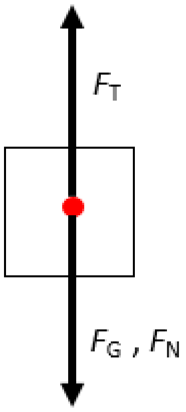


   c.

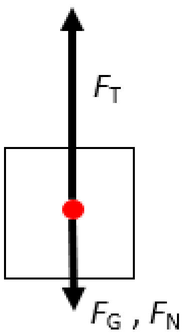


2.

a.

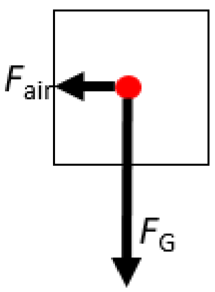


b.

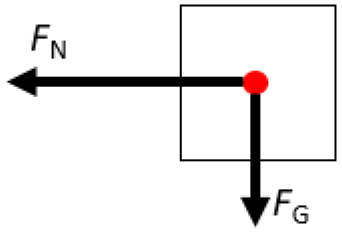


3.

a.



b.



Back to Unit 2: Assessment

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Unit 3: Mass and weight

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Unit outcomes

By the end of this unit you will be able to:

- Define gravitational acceleration: *g*
- Describe weight.
- Differentiate between mass (m) and weight ($F_{gravitation}$).
- Calculate weight.

What you should know

Before you start this unit, make sure you can:

- Distinguish between a vector and a scalar. Subject Outcome 2.1, Unit 3.
- Define a force. Subject Outcome 2.2, Unit 1.
- Say how gravity acts on an object. Subject Outcome 2.2, Unit 1.
- Define acceleration. Subject Outcome 2.1, Unit 1.
- Use equations of motion to determine acceleration. Subject Outcome 2.1, Unit 2.

Introduction

In this unit[1] you will learn that in physics there is a difference between mass and weight. Your understanding of forces so far will help you to think of weight in terms of gravity, and you will learn how to calculate weight depending on what the gravitational acceleration is where you are.

Gravity

Gravity is quite an intuitive concept. We realise from a young age that things fall to the ground when we drop them from a height. In the two previous units, you have defined gravity more formally as a non-contact force and included it in your force diagrams as a downward force.

Gravity is the force that arises between objects because of their mass. It is always an attractive force and acts at a distance. We experience the effect of the Earth's gravity as notable, because the Earth's mass is so much bigger than any other object on Earth.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 11 Learner's Book, p. 109, released under a CC-BY licence at https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-04.

Newton's universal law of gravitation

Sir Isaac Newton was the first scientist to define the gravitational force, and to show that it affects all bodies with mass. Newton's universal law of gravitation states that every particle in the universe attracts every other particle. The force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them. The magnitude of the gravitational force between two objects is shown by this formula:

$$F = \mathrm{G}\frac{m_1 m_2}{d^2}$$

With:

F = the magnitude of the gravitational force in newtons (N)
G = the gravitational constant $6.67 \times 10^{-11}\ \mathrm{N \cdot m^2 \cdot kg^{-2}}$
m_1 = the mass of the first object in kilograms (kg)
m_2 = the mass of the second object in kilograms (kg)
d = the distance between the objects in metres (m).

For large objects, we use the distance from the centre of the object(s) to do the calculation. This is especially important when dealing with very large objects such as planets. The distance from the centre of the planet and from the surface of the planet can differ by a large amount.

Note

When doing calculations involving planets, check carefully whether the diameter or radius is given as an indication of distance.

Let's look at an example of using Newton's universal law of gravitation in a calculation.

- Consider a person with a mass of $80\ \mathrm{kg}$ standing $10\ \mathrm{m}$ from someone else with a mass of $65\ \mathrm{kg}$. The attractive gravitational force between them would be:

$$\begin{aligned} F &= \mathrm{G}\frac{m_1 m_2}{d^2} \\ &= (6.67 \times 10^{-11})\left(\frac{(80)(65)}{(10)^2}\right) \\ &= 3.47 \times 10^{-9}\ \mathrm{N} \end{aligned}$$

- If the two people were only $1\ \mathrm{m}$ apart, then the force is:

$$\begin{aligned} F &= \mathrm{G}\frac{m_1 m_2}{d^2} \\ &= (6.67 \times 10^{-11})\left(\frac{(80)(65)}{(1)^2}\right) \\ &= 3.47 \times 10^{-7}\ \mathrm{N} \end{aligned}$$

- Now consider the gravitational force between the Earth and the Moon. The mass of the Earth is $5.98 \times 10^{24}\ \mathrm{kg}$, the mass of the Moon is $7.35 \times 10^{22}\ \mathrm{kg}$ and the Earth and Moon are apart. The gravitational force between the Earth and Moon is:

$$\begin{aligned} F &= \mathrm{G}\frac{m_1 m_2}{d^2} \\ &= (6.67 \times 10^{-11})\left(\frac{(5.98 \times 10^{24})(7.35 \times 10^{22})}{(0.38 \times 10^{9})^2}\right) \\ &= 2.03 \times 10^{20}\ \mathrm{N} \end{aligned}$$

The equation mathematically confirms what we see through observation:

- The greater the distance between the two interacting objects, the smaller the gravitational force between them.
- The bigger the masses of the two interacting objects, the bigger the gravitational force will be.

Note

Gravitational force is a vector. We use Newton's law of universal gravitation to determine the magnitude of the force and then analyse the problem to determine the direction.

Note

If you want to explore how the masses of two interacting objects and the distance between them affect their gravitational force, use this simulation:

Gravitational acceleration

You already know that a non-zero resultant force can change the speed or direction in which an object moves. You also know from your study of motion in one dimension that a change to an object's speed or direction is called acceleration. Therefore, force can cause an acceleration of an object.

The acceleration caused by the force of gravity on a free-falling object is called gravitational acceleration. It is represented by the symbol *g*, and has a constant value of $9.8\ \mathrm{m \cdot s^{-2}}$ on Earth.

gravitational acceleration (*g*) on Earth = $9.8\ \mathrm{m \cdot s^{-2}}$.

In Activity 3.1 you will investigate the value of gravitational acceleration experimentally.

Activity 3.1: Determine *g* by experiment

Time required: 10 minutes

What you need:

- a smartphone with a QR scanner
- software to view video files frame by frame (e.g. Windows Media Player)
- calculator, pen and notebook

What to do:

1. Use this QR code to download the video file.
2. Watch the video once.
3. Find the point in the video shortly before the ball is released. Then scroll forward frame by frame to the point where the ball is released. You can do this in Windows Media Player by holding down Ctrl and pressing the play button repeatedly.
4. Count the number of frames from the exact point when the ball is released to where it hits the ground. You may have to do this a few times to make sure you have counted accurately.
5. Calculate the time it took for the ball to reach the ground. The video was recorded at 30 frames per second.
6. Use the result and the equation $s = ut + \frac{1}{2}at^2$ to determine *g*. The ball was released from a height of $2.1\ \text{m}$.
7. Discuss the accuracy of the result and how the experiment could be improved.

What did you find?

It takes 20 frames from when the ball is released to when it hits the ground. So, at 30 frames per second, it took $\frac{20}{30} = 0.67$ seconds for the ball to reach the ground.

In the equation $s = ut + \frac{1}{2}at^2$, the term $ut = 0$, because the ball falls from rest; in other words, the initial velocity is zero. Acceleration, *a*, can be represented by the symbol *g* for gravitational acceleration. The equation can then be rearranged as follows to calculate *g*:

$$\begin{aligned} s &= ut + \frac{1}{2}at^2 \\ g &= \frac{2s}{t^2} \\ &= \frac{2(2.1)}{(0.67)^2} \\ &= 9.4\ \mathrm{m\cdot s^{-2}} \end{aligned}$$

This is only an approximation of the value of *g*, but is fairly close to the actual value of $9.8\ \mathrm{m\cdot s^{-2}}$. The margin of uncertainty in the time measurement is $0.03\ \mathrm{s}$, which contributes to the value not being exactly $9.8\ \mathrm{m\cdot s^{-2}}$. Accuracy could have been improved if the recording were made at a higher frame rate (e.g. 60 frames per second), if the height had been controlled more precisely and if there was no air resistance. However, despite these limitations, the experiment yields a reasonable approximation of *g*. Why not try the experiment yourself?

Note

For an alternative approach to this experiment, using more refined laboratory equipment, watch the video called 'Experiment to determine *g*' (duration: 10:37).

Although the magnitude of *g* is different on different planets, it is always constant on a particular planet. That means all free-falling objects experience the same gravitational acceleration ($9.8\ \mathrm{m\cdot s^{-2}}$ on Earth), regardless of their mass. A crate of gold will experience the same gravitational acceleration as a crate of cotton wool.

Did you know?

The Italian scientist and mathematician Galileo Galilei had already predicted the constant gravitational acceleration of free-falling bodies in the late 16th century. To see this yourself, watch the videos of this experiment on Earth (duration: 04:41 minutes) and on the Moon (duration: 00:51 minutes):

- Earth Video

- Moon Video

Activity 3.2: Research the value of g on the Moon and Mars

Time required: 10 minutes

What you need:

- a phone with a QR scanner
- an internet connection
- calculator, pen and notebook

What to do:

1. Scan the QR code and download the fact sheet:
2. Find the gravitational acceleration (g) on Mars and the Moon.
3. Give the values relative to that of the Earth's gravitational acceleration.
4. Challenge question: How do you think you can check whether NASA's measurements are correct?
   Hint:
   Newton's second law (which you will learn about in Level 3) is given by: $F = ma$.

You also know that Newton's universal law of gravitation is given by: $F = \mathrm{G}\frac{m_1 m_2}{d^2}$

What did you find?

- Gravitational acceleration on Mars is $3.7\ \mathrm{m \cdot s^{-2}}$. It is 0.38 times of that on Earth.
- Gravitational acceleration on the Moon is $1.6\ \mathrm{m \cdot s^{-2}}$. It is 0.16 times of that on Earth.
- Newton's second law of motion states that the force experienced by an object is equal to the product of the object's mass and its acceleration. We can therefore replace the term *F* in the equation of the universal law of gravitation:
  $m_{\mathrm{Earth}}\, a = \mathrm{G}\frac{m_{\mathrm{moon}} m_{\mathrm{Earth}}}{{d_{\mathrm{moon}}}^2}$
  The mass of the Earth cancels out on either side of the equation and we can write the acceleration as *g* (for gravitational acceleration), rather than *a*. We know from the information sheet that the mass (m) of the Moon is $0.073 \times 10^{24}\ \mathrm{kg}$ and that its radius (*d*) is $3.475 \times 10^{6}\ \mathrm{m}\ \div 2 = 1.737 \times 10^{6}\ \mathrm{m}$.

  The equation then becomes:

  $$g = \mathrm{G}\frac{m_{\mathrm{moon}}}{d^2{}_{\mathrm{moon}}}$$
  $$= \frac{(6.67 \times 10^{-11})(0.073 \times 10^{24})}{(1.737 \times 10^{6})^2}$$
  $$= 1.6\ \mathrm{m \cdot s^{-2}}$$

  We can do the same calculation with the information about Mars, and find that $g_{\mathrm{Mars}} = 3.7\ \mathrm{m \cdot s^{-2}}$

Weight and mass

Weight and mass are not the same, although we tend to use the terms to mean the same thing in everyday language.

- Mass is a measurement of how much matter an object consists of; it is a scalar quantity. Mass is measured in kilograms (kg).
- Weight is a measurement of how hard gravity is pulling on that object; it is a vector quantity. Weight is therefore simply $F_{\text{gravitation}}$ and is measured in newtons (N).

Your **mass** is the same wherever you are – on Earth, on the Moon, on Mars or floating in space – because the amount of matter you are made of does not change. However, your **weight** depends on how strong the gravitational force is that is acting on you at a particular moment. So, you would weigh less on the Moon and on Mars than on Earth, and in space you would weigh almost nothing at all.

Take note!

When you stand on a scale, you are trying measure how much of you there is. People who are trying to reduce their mass hope to see the reading on the scale get smaller, despite talking about losing weight.

If they are successful, their weight will decrease, yes, but it is because their mass is decreasing. A scale therefore uses the person's weight to determine their mass.

Calculating weight

We use either one of the following two equations to calculate weight, depending on what information we have available.

$$W = F_{\text{gravitation}} = mg$$
$$F_{\text{gravitation}} = \mathrm{G}\frac{m_1 m_2}{d^2}$$

Example 3.1

Calculate the weight of a hammer with a mass of $675\ \text{g}$ on Jupiter. Jupiter has a mass of $1.898 \times 10^{27}\ \text{kg}$ and a diameter of $142\ 984\ \text{km}$.

Solution

First analyse the given information:

- The gravitational acceleration of Jupiter is not given, only the masses of objects and the size of Jupiter. It would therefore be best to use the equation $F_{\text{gravitation}} = \mathrm{G}\frac{m_1 m_2}{d^2}$.
- The diameter of Jupiter is given. However, we know that we have to use the distance between the centres of the objects to do the calculation and therefore the radius has to be used: $\frac{142\ 982}{2} = 71\ 491\ \text{km}$. Remember that this has to be expressed in metres, so $71\ 492\ \text{km} = 7.1492\ \times 10^7\ \text{m}$
- All masses should be expressed in kilograms, so the mass of the hammer has to be converted: $675\ \text{g} = 0.675\ \text{kg}$.

Now do the calculation:

$$\begin{aligned} W = F_{\text{gravitation}} &= \mathrm{G}\frac{m_1 m_2}{d^2} \\ &= (6.67 \times 10^{-11})\left(\frac{(0.675)(1.898 \times 10^{27})}{(7.1492 \times 10^7)^2}\right) \\ &= 16.7\ \text{N} \end{aligned}$$

Example 3.2

Calculate the weight of a hammer with a mass of 675 g on Jupiter. The gravitational acceleration on Jupiter is $24.8 \text{ m} \cdot \text{s}^{-2}$.

Solution

As the gravitational acceleration is given, we can use the equation $W = F_{\text{gravitation}} = mg$. Remember to convert the mass of the hammer to kilograms.

$$
\begin{aligned}
W &= F_{\text{gravitation}} = mg \\
&= 0.675 \times 24.8 \\
&= 16.7 \text{ N}
\end{aligned}
$$

The weight is the same as determined using the equation for the universal law of gravitation.

Exercise 3.1

Questions 1, 2 and 4 were sourced from or based on questions in Siyavula Physical Science Gr 11 Learner's Book, pp. 114–118 and 133 released under a CC-BY licence at https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-04 and https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-06, respectively.

1. Jojo has a mass of 87.5 kg. What is his weight on Mercury, which has a gravitational acceleration of $3.70 \text{ m} \cdot \text{s}^{-2}$?
2. If object 1 has a weight of $1.78 \times 10^{3} \text{ N}$ on Neptune and object 2 has a weight of $3.63 \times 10^{5} \text{ N}$ on Mars, which has the greater mass? The gravitational acceleration on Neptune is $11.15 \text{ m} \cdot \text{s}^{-2}$, while it is $3.71 \text{ m} \cdot \text{s}^{-2}$ on Mars.
3. The gravitational acceleration on the Moon is about a sixth of that on Earth. What would the approximate weight be of a 2.5 kg packet of sugar on the Moon?
4. A satellite circles around the Earth at a height where the gravitational force is a factor 4 less than at the surface of the Earth. If the Earth's radius is R, what would the height of the satellite be above the surface?
   A. R
   B. $2R$
   C. $4R$
   D. $16R$
5. Challenge question: Your mass is 60 kg in Paris at ground level. How much less would you weigh after taking a lift to the top of the Eiffel Tower, which is 405 m high? Assume the Earth's mass is $6 \times 10^{24} \text{ kg}$ and the Earth's radius is 6400 km.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- Gravity is a force that arises between objects because of their mass.

- Gravity acts at a distance and is always an attractive force.
- Newton's universal law of gravity states that every particle in the universe attracts every other particle:
  - the greater the distance between the two interacting objects, the smaller the gravitational force between them
  - the bigger the masses of the two interacting objects, the bigger the gravitational force will be.
- The magnitude of the gravitational force between two objects is given by $F = \mathrm{G}\dfrac{m_1 m_2}{d^2}$.
- The gravitational constant is $6.67 \times 10^{-11}\ \mathrm{N \cdot m^2 \cdot kg^{-2}}$.
- The acceleration caused by the force of gravity on a free-falling object is called gravitational acceleration, *g*.
- The gravitational acceleration on Earth is $9.8\ \mathrm{m \cdot s^{-2}}$. It is constant for all objects, independent of mass.
- Although the magnitude of *g* is different on different planets, it is always constant on a particular planet.
- Mass is a measurement of how much matter is in an object. It is measured in kilograms (kg).
- Weight is a measurement of how hard gravity is pulling on an object. Weight is measured in newtons (N).
- Weight (Fgravitation) is the product of an object's mass and gravitational acceleration: $W = F_{\text{gravitation}} = mg$

Unit 3: Assessment

Suggested time to complete: 25 minutes

Questions 1 and 2 were sourced from Siyavula Physical Science Gr 11 Learner's Book, pp. 117–119 and pp. 132–133, released under a CC-BY licence at https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-04 and https://www.siyavula.com/read/science/grade-11/newtons-laws/02-newtons-laws-06, respectively.

For questions 1–3, choose the correct answer.

1. Two objects of mass $2X$ and $3X$ respectively, where X is an unknown quantity, exert a force F on each other when they are a certain distance apart. What will be the force between two objects situated the same distance apart but having a mass of $5X$ and $6X$, respectively?

   A. $0.2F$

   B. $1.2F$

   C. $2.2F$

   D. $5F$

2. As the distance of an object above the surface of the Earth is greatly increased, the weight of the object would:

   A. increase.

   B. decrease.

   C. increase and then suddenly decrease.

   D. remain the same.

3. A satellite experiences a force F when at the surface of the Earth. What will be the force on the satellite if it orbits at a height equal to the diameter of the Earth?

   A. $\dfrac{1}{F}$

   B. $\dfrac{1}{2}F$

C. $\frac{1}{3}F$

D. $\frac{1}{9}F$

4. Read each of the following statements and say whether you agree or disagree. Give reasons for your answers and rewrite the statement if necessary:
   a. The gravitational acceleration g is a universal constant.
   b. The weight of an object is independent of its mass.
   c. G is dependent on the mass of the object that is being accelerated.
5. Halley's comet, of approximate mass $1 \times 10^{15}\ \text{kg}$, was $1.3 \times 10^{8}\ \text{km}$ from the Earth at its point of closest approach during its last sighting in 1986.
   a. Name the force through which the Earth and the comet interact.
   b. Does the acceleration of the comet increase, decrease or remain the same as it moves closer to the Earth? Explain.
   c. If the mass of the Earth is $6 \times 10^{24}\ \text{kg}$, calculate the magnitude of the force exerted by the Earth on Halley's comet at its point of closest approach.
6. A man has a mass of $70\ \text{kg}$ on Earth. He is walking on a new planet that has a mass four times that of the Earth and the radius is the same as that of the Earth ($m_{\text{E}} = 6 \times 10^{24}\ \text{kg}$; $r_{\text{E}} = 6 \times 10^{6}\ \text{m}$).
   a. Calculate the force between the man and the Earth.
   b. Would his weight be bigger or smaller on the new planet? Explain your reasoning.
   c. Calculate the man's weight on the new planet.
7. An astronaut weighs $750\ \text{N}$ on the surface of the Earth. What will his mass be on Saturn, which is 100 times more massive than Earth and has a radius 5 times that of Earth?

The full solutions are at the end of the unit.

Unit 3: Solutions

Exercise 3.1

1.
$$\begin{aligned} F_{\text{gravitation}} &= W = mg \\ &= (87.5)(3.70) \\ &= 323.75\ \text{N} \end{aligned}$$

2. The mass of object 1, which is on Neptune, can be calculated as follows:
$$\begin{aligned} W_1 &= m_1 g \\ \therefore m_1 &= \frac{W_1}{g} \\ &= \frac{1.78 \times 10^{3}}{11.15} \\ &= 159.6\ \text{kg} \end{aligned}$$

   The mass of object 2, which is on Mars, can be calculated as follows:

$$\begin{aligned} W_2 &= m_2 g \\ \therefore m_2 &= \frac{W_2}{g} \\ &= \frac{3.63 \times 10^5}{3.71} \\ &= 9.78 \times 10^4 \text{ kg} \end{aligned}$$

Object 2 therefore has a greater mass.

3. We know that weight is directly proportional to gravitational acceleration. Therefore, if the gravitational acceleration on the Moon is about a sixth of that on Earth, we know the weight of the packet of sugar would be reduced by the same factor.
We can calculate the weight of the packet on Earth as:
$$\begin{aligned} W &= mg \\ &= (2.5)(9.8) \\ &= 24.5 \text{ N} \end{aligned}$$
The weight on the Moon would then be approximately $\frac{24.5}{6} = 4.1 \text{ N}$.
4. The correct answer is option A: *R*.
We know that gravitational force is inversely proportional to the square of the distance between the **centres of two objects**. If the gravitational force is $\frac{1}{4}$ at the height where the satellite is orbiting, it means the distance between the centres of the object must be 2 times that of the radius of the Earth. However, the question asks us to calculate the height at which the satellite is orbiting relative to the **surface** of the Earth. Therefore: $2R - R = R$.
5. We start with your weight on the surface of the Earth. The gravitational acceleration at the surface of the Earth is $9.8 \text{ m} \cdot \text{s}^{-2}$, and so your weight is:
$$\begin{aligned} F_{\text{gravitation}} &= W = mg \\ &= (60)(9.8) \\ &= 588 \text{ N} \end{aligned}$$
We know that $F_{\text{gravitation}} = \text{G}\frac{m_1 m_2}{d^2}$ and that $F_{\text{gravitation}} = W = mg$.
Let's define your mass as m_1 and the mass of the Earth as m_2. Then we can write:
$m_1 g = \text{G}\frac{m_1 m_2}{d^2}$. The value of m_1 cancels out on either side of the equation, to give the acceleration at the top of the Eiffel Tower as $g_{\text{Eiffel}} = \text{G}\frac{m_2}{d^2}$:
$$\begin{aligned} g_{\text{Eiffel}} &= \text{G}\frac{m_2}{d^2} \\ &= \frac{(6.67 \times 10^{-11})(6.0 \times 10^{24})}{(6400 \times 10^3 + 405)^2} \\ &= 9.77 \text{ m} \cdot \text{s}^{-2} \end{aligned}$$
Your weight at the top of the Eiffel Tower would then be:
$$\begin{aligned} W_{\text{Eiffel}} &= m g_{\text{Eiffel}} \\ &= (60)(9.77) \\ &= 586.2 \text{ N} \end{aligned}$$
You would therefore weigh 1.8 N less at the top of the Eiffel Tower than on the ground.

[Back to Exercise 3.1]

Unit 3: Assessment

1. D
   We can write an expression for the force in each case in terms of the distance.
   So, for force 1:
   $$F_1 = \mathrm{G}\frac{m_1 m_2}{d^2}$$
   $$d^2 = \mathrm{G}\frac{(2X)(3X)}{F_1}$$

   For force 2:
   $$F_2 = \mathrm{G}\frac{m_1 m_2}{d^2}$$
   $$d^2 = \mathrm{G}\frac{(5X)(6X)}{F_2}$$

   Since the distance is equal, the square of the distance is also equal and so we can equate these two and find the force.
   $$\mathrm{G}\frac{(2X)(3X)}{F_1} = \mathrm{G}\frac{(5X)(6X)}{F_2}$$
   $$\frac{6X^2}{F_1} = \frac{30X^2}{F_2}$$
   $$\therefore F_2 = 5F_1$$

   An alternative approach would be to look at the proportional increase in mass. The mass of object 1 increases 2.5 times, and the mass of object 2 increases 2 times. That means that the total mass has increased 5 times. Because we know force is directly proportional to the product of the masses, it follows that the force should also increase by a factor 5.
2. B. The weight would decrease.
   The distance is inversely proportional to the weight (or force of gravity) and so, as the distance increases, the weight decreases.
3. D: $\frac{1}{9}F$
   The diameter of the Earth is twice the radius. This means that the distance to the satellite would be the radius of the Earth plus twice the radius of the Earth, a factor 3 increase. Therefore, $\frac{1}{9}$.
4.
   a. Disagree. The value of *g* is constant on a specific planet (e.g. Earth), but it is not the same throughout the universe.
   b. Disagree. Weight is related to mass via the gravitational acceleration.
   c. Disagree. *G* is a universal constant: it is the same value throughout the universe.
5.
   a. Newton's law of universal gravitation
   b. The gravitational force the comet experiences increases because it is inversely proportional to the square of the distance. Because $F_{\mathrm{G}} = W$ and we know that $W = mg$, it follows that if W increases, so will *g*.
   c.
   $$\begin{aligned} F &= \mathrm{G}\frac{m_1 m_2}{d^2} \\ &= \left(6.67 \times 10^{-11}\right)\left(\frac{(6 \times 10^{24})(1 \times 10^{15})}{\left(1.3 \times 10^{11}\right)^2}\right) \\ &= 2.37 \times 10^{7}\ \mathrm{N} \end{aligned}$$

6.

a.

$$
\begin{aligned}
F_{\mathrm{E}} &= \mathrm{G}\frac{m_1 m_2}{d^2} \\
&= \left(6.67\times10^{-11}\right)\left(\frac{(70)(6\times10^{24})}{\left(6.4\times10^{6}\right)^2}\right) \\
&= 683.7\ \mathrm{N}
\end{aligned}
$$

b. His weight would be bigger on the new planet. The new planet has the same radius as the Earth, but a larger mass. Since the mass of the planet is proportional to the force of gravity (or the weight), the man's weight must be larger.

c.

$$
\begin{aligned}
F_{\mathrm{E}} &= \mathrm{G}\frac{m_1 4m_2}{d^2} \\
&= 4F_{\mathrm{E}} \\
&= (683.7)(4) \\
&= 2734.8\ \mathrm{N}
\end{aligned}
$$

7. Remember that mass is a measure of the amount of matter something consists of. The astronaut's mass would therefore be the same on Earth and on Saturn, regardless of the size of Saturn relative to the Earth. So, we can calculate the astronaut's mass using the gravitational acceleration as on Earth:

$$
\begin{aligned}
&W_{\mathrm{Earth}} = mg_{\mathrm{Earth}} \\
&\therefore m = \frac{W}{g} \\
&= \frac{750}{9.8} \\
&= 76.5\ \mathrm{kg}
\end{aligned}
$$

Back to Unit 3: Assessment

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SUBJECT OUTCOME III

MECHANICS: IDENTIFY, DESCRIBE AND APPLY PRINCIPLES OF MECHANICAL ENERGY

Subject outcome

Subject outcome 2.3: Identify, describe and apply principles of mechanical energy.

Learning outcomes

- Define mechanical energy, kinetic energy and gravitational potential energy.
- Calculate kinetic energy ($E_K = \frac{1}{2}mv^2$) and gravitational potential energy ($E_P = mgh$).
- Define the law of conservation of mechanical energy.
- Solve problems using the conservation of mechanical energy ($E_M = E_K + E_P$).

Unit 1 outcomes

By the end of this unit you will be able to:

- Define mechanical energy.
- Define kinetic energy.
- Define gravitational potential energy.
- Calculate kinetic energy ($E_K = \frac{1}{2}mv^2$).
- Calculate gravitational potential energy ($E_P = mgh$).

Unit 2 outcomes

By the end of this unit you will be able to:

- Define the law of conservation of mechanical energy.

- Solve problems using the conservation of mechanical energy ($E_{\text{mechanical}} = E_{\text{K}} + E_{\text{P}}$).

Unit 1: Introduction to mechanical energy

LINDA PRETORIUS

Unit outcomes

By the end of this unit you will be able to:

- Define mechanical energy.
- Define kinetic energy.
- Define gravitational potential energy.
- Calculate kinetic energy ($E_{\mathrm{K}} = \frac{1}{2}mv^2$).
- Calculate gravitational potential energy ($E_{\mathrm{P}} = mgh$).

Introduction

In this unit[1] you will learn about two forms of mechanical energy, in other words energy an object has due to its position or movement. You will also understand how to calculate the amount of energy an object has at different times due to its position or movement.

The concept of mechanical energy

All objects have energy. Energy is the ability of an object to do work. Energy is a scalar quantity and is measured in joules (J).

In physics, work is the term used to describe what is achieved when a force is applied to an object to make it move through some distance. In other words, the force applied to the object leads to a change in either the velocity or the position of the object.

When work is done on an object, energy is transferred. A moving object has the ability to do work on another object it comes into contact with. The energy – in other words, the ability to do work – associated with a moving object is called kinetic energy. An object can also have the ability to do work because of its position or state relative to another object. This type of energy is called potential energy.

It follows from these two definitions that mechanical energy is the sum of an object's kinetic energy and its potential energy: $E_{\mathrm{M}} = E_{\mathrm{K}} + E_{\mathrm{P}}$.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, p. 443–453, released under a CC-BY licence.

Activity 1.1: Think about energy

Time required: 5 minutes

What you need:

- You do not need any additional resources for this activity. However, if you want to watch a swinging action, you will need:
- an internet connection
- a phone with a QR scanner

What to do:

Think about someone on a swing.

- How can the person start the swinging action?
- What happens when the swing reaches the top of its path?
- At what point along the path is the swing moving fastest?
- What keeps the swing moving forward and back?

What did you find?

When someone sits or stands on a swing and wants to set it in motion, a force has to be applied. For example, someone has to push the person on the swing forward (or pull the swing back) or the person has to push off against the ground themselves. When the force is applied, work is being done on the person on the swing. This means energy is being transferred to the person on the swing. The amount of energy transferred to the person on the swing determines how far the swing will rise and how fast it will go.

When the swing reaches its highest point in a cycle, it swings back through the starting position and moves upwards again in the opposite direction. The swing's height changes during the motion: it is at its highest point at the end of each forward and backward motion, and at its lowest point at the starting position. If no further work is done on the swing, it will lose some of the transferred energy during each swing and reach progressively lower heights.

The swing's velocity also changes during the motion. The higher it goes, the faster it swings back again. The motion speeds up as the swing comes down from its highest point and slows down as it rises again. But the maximum speed decreases with every swing, just as the maximum height also decreases. The swing will keep on going forward and back until it loses all its energy (or an opposing force is applied) and will eventually come to rest.

The swinging action illustrates two types of energy being used. The moving swing has kinetic energy. At the top of its path, it has gravitational potential energy because of the change in its position. As it swings in the opposite direction it gains kinetic energy, which allows it to rise again. At the highest point on this leg, it has gravitational potential energy again.

Kinetic energy

Kinetic energy is the type of energy an object has because of its motion. In Activity 1.1, the swing had kinetic energy due to its motion.

Figure 1: This train has kinetic energy because of its motion

Mathematically, kinetic energy is defined as:

$$E_K = \frac{1}{2}mv^2$$

where:
E_K = kinetic energy (in joules, J)
m = mass of the object (in kilograms, kg)
v = velocity of the object (measured in metres per second, $\mathrm{m \cdot s^{-1}}$)

Note

You may sometimes see kinetic energy written as KE. This is simply another way to write kinetic energy.

The equation tells us that the kinetic energy (E_K) of a moving object depends on its mass and velocity. The faster the object moves and the more massive it is, the more its kinetic energy. A truck of $2\ 000\ \mathrm{kg}$, moving at $100\ \mathrm{km \cdot h^{-1}}$ will have more kinetic energy than a car of $500\ \mathrm{kg}$, also moving at $100\ \mathrm{km \cdot h^{-1}}$.

It is also important to note the mathematical relationship between kinetic energy and velocity. We can see from the equation that the kinetic energy of a moving object depends on the square of its velocity. Consider the amount of kinetic energy an object, for example a car, has moving at $60\ \mathrm{km \cdot h^{-1}}$. If that car doubles it velocity and moves at $120\ \mathrm{km \cdot h^{-1}}$, its kinetic energy will increase fourfold (2^2). If you consider that the energy of an object reflects its ability to do work, you can understand why the effect of a car travelling at $120\ \mathrm{km \cdot h^{-1}}$ and crashing into a brick wall is so much bigger than for a car travelling at $60\ \mathrm{km \cdot h^{-1}}$.

Calculating kinetic energy

By calculating the amount of kinetic energy a moving object has, we can quantify how much work it is able to do. When doing such calculations, remember to always check that the quantities you are working with are in the correct units: mass has to be in kilograms and velocity has to be in metres per second. If the quantities are not in the correct units, you have to convert them.

Let's look at some examples.

Example 1.1

A bullet with a mass of $150\ \mathrm{g}$ is shot with a muzzle velocity of $960\ \mathrm{m.s^{-1}}$. Calculate its kinetic energy.

Solution

We are asked to calculate the kinetic energy of the bullet. We are given its mass and velocity. The mass is given in grams, so we have to convert it to kilograms first: $150\ \mathrm{g} = 0.150\ \mathrm{kg}$. Velocity is given in the correct unit (metres per second).

Now we can use the equation for calculating kinetic energy:

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(0.150)(960)^2 \\ &= 69\ 120 \\ &= 69.1\ \text{kJ} \end{aligned}$$

Example 1.2

A brick with a mass of $1\ \text{kg}$ is dropped from a roof, $4\ \text{m}$ above the ground. The brick reaches the ground with a velocity of $8.85\ \text{m} \cdot \text{s}^{-1}$.

1. What is the kinetic energy of the brick just before it starts to fall?
2. What is the kinetic energy of the brick when it reaches the ground?

Solutions

1. Just before the brick starts to fall, it is stationary. Therefore, its velocity is zero, and so its kinetic energy is also zero.
2. At the bottom of the fall, just before the brick hits the ground, it is moving at $8.85\ \text{m} \cdot \text{s}^{-1}$. We can therefore calculate its kinetic energy at that moment:

$$\begin{aligned} E_K &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(1)(8.85)^2 \\ &= 39.2\ \text{J} \end{aligned}$$

The example shows that:

- the kinetic energy of an object falling from a height is 0 before it starts to fall, and at its maximum just before it hits the ground.
- the height above the ground does not affect the object's kinetic energy.

Exercise 1.1

1. Describe the relationship between an object's kinetic energy and its:
   a. mass
   b. velocity.
2. A stone with a mass of $100\ \text{g}$ is thrown up into the air. It has an initial velocity of $3\ \text{m} \cdot \text{s}^{-1}$. Calculate its kinetic energy:
   a. as it leaves the thrower's hand.

b. when it reaches its turning point.

3. A car with a mass of $700\ \text{kg}$ is travelling at a constant velocity of $100\ \text{km} \cdot \text{h}^{-1}$. Calculate the kinetic energy of the car.

The full solutions are at the end of the unit.

Gravitational potential energy

There are different kinds of potential energy, one of which is gravitational potential energy. Remember that energy is the ability of an object to do work. Gravitational potential energy is therefore the potential of an object to do work because of its relative position in a gravitational field. In the case of Earth, this position is the relative height above the surface of the Earth.

Figure 2: These shoes have gravitational potential energy because of their position

We can define gravitational potential energy as:

$$E = mgh$$

where:
E_P = potential energy (measured in joules, J)
m = mass of the object (measured in kilograms, kg)
g = gravitational acceleration ($9.8\ \text{m} \cdot \text{s}^{-2}$ on Earth)
h = perpendicular height from the reference point (measured in metres, m)

From the equation, we can see that the gravitational potential energy of an object depends on its mass and its height above a reference point. The object's gravitational potential energy is directly proportional to both its height and its mass. That means:

- the higher the object is relative to the chosen reference point, the more gravitational potential energy it will have
- the more mass the object has, the more gravitational potential energy it will have.

Note

You will often find that the term potential energy is used when gravitational potential energy is meant. You may sometimes see potential energy written as PE or U_g.

Calculating gravitational potential energy

By calculating the amount of gravitational potential energy an object has, we can quantify how much work it is able to do due to its height. When doing these calculations, remember to always check that the quantities you are working with are in the correct units: mass must be in kilograms and height has to be in metres. If the quantities are not in the correct units, you must convert them.

Example 1.3

A netball player, who is $1.7\ \text{m}$ tall, holds a $0.5\ \text{kg}$ netball $0.5\ \text{m}$ above her head and shoots for the goal net, which is $2.5\ \text{m}$ above the ground.

1. What is the gravitational potential energy of the ball when the netball player is about to shoot it into the net?
2. What is the gravitational potential energy of the ball when it gets into the net?

Solutions

1. We know that the netball player is $1.7\ \text{m}$ tall and holds the ball $0.5\ \text{m}$ above her head. So, the ball is $1.7 + 0.5 = 2.2\ \text{m}$ above the ground before being thrown towards the net. The mass is known, and given in kilograms, and we know that gravitational acceleration is $9.8\ \text{m} \cdot \text{s}^{-2}$. To calculate the ball's gravitational potential energy at this point, we use:
$$\begin{aligned} E_P &= mgh \\ &= (0.5)(9.8)(2.2) \\ &= 10.8\ \text{J} \end{aligned}$$
2. When the ball reaches the net, it is at a height of $2.5\ \text{m}$ above the ground. Its gravitational potential energy has increased because it is higher above the ground than before. Our calculation con-

firms this:

$$\begin{aligned} E_P &= mgh \\ &= (0.5)(9.8)(2.5) \\ &= 12.3 \text{ J} \end{aligned}$$

The example shows that the higher the object is from the reference point (the ground in this case), the more gravitational potential energy it has.

Example 1.4

A can filled with water has a total mass of 25 kg. It is hoisted up using a pulley and rope. The rope breaks when the can is 4 m above the ground, and the can falls down.

1. Calculate the gravitational potential energy of the can at its highest point.
2. Calculate the gravitational potential energy of the can halfway down its fall.
3. Calculate the gravitational potential energy of the can on the ground after it has fallen.

Solutions

1. By lifting the can of water against the force of gravity, it was given gravitational potential energy. We know that the can reaches a height of 4 m before the rope breaks, so $h = 4 \text{ m}$. The mass of the filled can is 25 kg, and we know that gravitational acceleration is $9.8 \text{ m} \cdot \text{s}^{-2}$. The quantities are given in the correct units already, so we can calculate its gravitational potential energy as follows:
$$\begin{aligned} E_P &= mgh \\ &= (25)(9.8)(4) \\ &= 980 \text{ J} \end{aligned}$$
2. When the can has fallen halfway down, it is 2 m above the ground. Its mass has not changed. Its gravitational potential energy at the point is therefore:
$$\begin{aligned} E_P &= mgh \\ &= (25)(9.8)(2) \\ &= 490 \text{ J} \end{aligned}$$
3. On the ground, the can is at the same level as the ground, so its height relative to the reference point is 0 m. That means it has no gravitational potential energy.

This example shows us that objects have maximum potential energy at their maximum height and will lose their potential energy as they fall.

Exercise 1.2

1. Describe the relationship between an object's gravitational potential energy and its:
   a. mass
   b. height above a reference point.

2. A boy of mass $30\ \mathrm{kg}$ climbs onto the roof of a garage. The roof is $2.5\ \mathrm{m}$ from the ground.
    a. How much potential energy did the boy gain by climbing onto the roof?
    b. The boy now jumps down. What is the potential energy of the boy when he is $1\ \mathrm{m}$ from the ground?
    c. What is the potential energy of the boy when he lands on the ground?
3. A hiker, with a mass of $70\ \mathrm{kg}$, walks up a mountain, $800\ \mathrm{m}$ above sea level, to spend the night at the top in the first overnight hut. The second day she walks to the second overnight hut, $500\ \mathrm{m}$ above sea level. The third day she returns to her starting point, $200\ \mathrm{m}$ above sea level. Give all your answers in kilojoules (kJ).
    a. What is the potential energy of the hiker at the first hut (relative to sea level)?
    b. How much potential energy has the hiker lost during the second day?
    c. How much potential energy did the hiker have when she started her journey (relative to sea level)?
    d. How much potential energy did the hiker have at the end of her journey when she reached her original starting position?

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- Energy is the ability to do work.
- Energy is a scalar quantity. It is measured in joules (J).
- Kinetic energy is the ability of an object to do work because of its motion: $E_{\mathrm{K}} = \frac{1}{2}mv^2$.
- Gravitational potential energy is the potential of an object to do work because of its relative position in a gravitational field: $E_{\mathrm{P}} = mgh$.

Unit 1: Assessment

Suggested time to complete: 15 minutes

Questions 1 and 2 were sourced from exercises and examples in Siyavula Physical Science Gr 10 Learner's Book, p. 443–469, released under a CC-BY licence.
Questions 3 and 4 were sourced from College Physics, pp. 281–282, released under a CC-BY 4.0 licence.

1. Consider the situation where an apple falls from the top branch of a tree. Indicate whether the following statements regarding this situation are **true** or **false**. If the statement is false, also write down the correct statement.
    a. The potential energy of the apple is at a maximum when the apple lands on the ground.
    b. The kinetic energy remains constant throughout the motion.
    c. To calculate the gravitational potential energy of the apple we need the mass of the apple and the height of the tree.
    d. The apple falls at an acceleration of $9.8\ \mathrm{m \cdot s^{-2}}$.

2. A herder is herding his sheep into the kraal. A mother sheep and her lamb are both running at $1.4\ \text{m}\cdot\text{s}^{-1}$ towards the kraal. The mother sheep has a mass of $80\ \text{kg}$ and the lamb has a mass of $25\ \text{kg}$. Calculate the kinetic energy for both the sheep and the lamb.
3. Compare the kinetic energy of a $20\ 000\ \text{kg}$ truck moving at $110\ \ \text{km}\cdot\text{h}^{-1}$ with that of an $80\ \text{kg}$ astronaut in orbit moving at $27\,500\ \ \text{km}\cdot\text{h}^{-1}$.
4. A hydroelectric power facility converts the gravitational potential energy of water behind a dam to electric energy. What is the gravitational potential energy relative to the generators of a lake of volume $50.0\ \text{km}^3$ (mass = $5.00\times10^{13}\ \text{kg}$), given that the lake has an average height of $40.0\ \text{m}$ above the generators?
5. A skateboarder (mass = $70\ \text{kg}$) is moving at $3\ \text{m}\cdot\text{s}^{-1}$ before he jumps to reach a maximum height of $80\ \text{cm}$.

   a. Does he have more energy as he prepares for the jump or at the top of the jump?
   b. What do you think is the reason for the difference?

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1.
   a. An object's kinetic energy is directly proportional to its mass.
   b. An object's kinetic energy is directly proportional to the square of its velocity.
2. Remember that mass has to be in kilograms, so we have to convert the mass given in grams to kilograms before we do the calculation.

   a.
$$\begin{aligned}E_{\text{K}} &= \frac{1}{2}mv^2\\ &= \frac{1}{2}(0.1)(3)^2\\ &= 0.5\ \text{J}\end{aligned}$$

   b. When the stone reaches its turning point, it is momentarily stationary. It has velocity at that point, and therefore its kinetic energy is zero.
3. We have to work with velocity in metres per second and so have to covert kilometres per hour:
   $100\ \text{km}\cdot\text{h}^{-1} = \dfrac{100000}{3600}\ \text{m}\cdot\text{s}^{-1} = 27.78\ \text{m}\cdot\text{s}^{-1}$
   To calculate the kinetic energy:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(700)(27.78)^2 \\ &= 2.70 \times 10^5 \text{ J} \\ &= 270 \text{ kJ} \end{aligned}$$

Back to Exercise 1.1

Exercise 1.2

1.
   a. An object's gravitational potential energy is directly proportional to its mass.
   b. An object's gravitational potential energy is directly proportional to its height above a reference point.
2.
   a. All the information is given in the correct units. We can therefore proceed to calculate the boy's gravitational potential at the top of the roof as follows:
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (30)(9.8)(2.5) \\ &= 735 \text{ J} \end{aligned}$$
   b. He loses gravitational potential energy once he jumps off the roof. At 1 m from the ground, his gravitational potential energy is:
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (30)(9.8)(1) \\ &= 294 \text{ J} \end{aligned}$$
   c. When he lands on the ground, he is back to his reference position. Because $h = 0 \text{ m}$, his gravitational potential energy is 0 J.
3.
   a. The hiker starts at an altitude of 200 m above sea level. However, the question asks us to calculate her gravitational potential energy relative to sea level. Therefore, we have to use $h = 800 \text{ m}$:
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (70)(9.8)(800) \\ &= 548.8 \text{ kJ} \end{aligned}$$
   b. At the end of the second day the hiker is 500 m above sea level, which is 300 m lower than at the end of the first day.
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (70)(9.8)(500) \\ &= 343 \text{ kJ} \end{aligned}$$
   She has therefore lost $548.8 - 343 = 205.8 \text{ kJ}$ during the second day's hike.
   c. At the start of her journey, her gravitation potential energy was:
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (70)(9.8)(200) \\ &= 137.2 \text{ kJ} \end{aligned}$$
   d. She had the same amount of gravitational potential energy at the end of her journey as at the beginning: 137.2 kJ

Back to Exercise 1.2

Unit 1: Assessment

1.
   a. False. The apple's gravitational potential energy is at a maximum just before it drops from the branch.
   b. False. Kinetic energy increases as the apple falls. It is at a maximum just before the apple hits the ground.
   c. True
   d. True
2. For the mother sheep:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(80)(1.4)^2 \\ &= 78.4\ \mathrm{J} \end{aligned}$$

   For the lamb:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(25)(1.4)^2 \\ &= 24.5\ \mathrm{J} \end{aligned}$$

3. Remember to check that all the information is in the correct units and convert any that is not. We have to convert kilometres per hour to metres per second:

$$110\ \mathrm{km \cdot h^{-1}} = \frac{110\ 000}{3600} = 30.55\ \ \mathrm{m \cdot s^{-1}}$$

$$27\ 500\ \mathrm{km \cdot h^{-1}} = \frac{2.75 \times 10^7}{3600} = 7.64 \times 10^3\ \ \mathrm{m \cdot s^{-1}}$$

   For the truck:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(2.0 \times 10^4)(30.55)^2 \\ &= 9.33 \times 10^6\ \mathrm{J} \end{aligned}$$

   For the astronaut:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(80)(7.64 \times 10^3)^2 \\ &= 2.33 \times 10^9\ \mathrm{J} \end{aligned}$$

   The astronaut has approximately 250 times more kinetic energy than the truck.
4.

$$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (5.0 \times 10^{13})(9.8)(40) \\ &= 1.96 \times 10^{16}\ \mathrm{J} \end{aligned}$$

5.
   a. As he prepares to jump, the skateboarder has kinetic energy:

$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ &= \frac{1}{2}(70)(3)^2 \\ &= 315\ \mathrm{J} \end{aligned}$$

He gains gravitational potential energy as he jumps. At his maximum height ($0.8\ \mathrm{m}$), he has:

$$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (70)(9.8)(0.8) \\ &= 548.8\ \mathrm{J} \end{aligned}$$

He therefore has more energy at the top of the jump than when he prepared for it.

b. To allow him to jump, he pushes down on the board. He therefore does work on the board and transfers energy to it, which allows him to jump up.

Back to Unit 1: Assessment

Media Attributions

Unit 2: Conservation of mechanical energy

LINDA PRETORIUS

Unit outcomes

By the end of this unit you will be able to:

- Define the law of conservation of mechanical energy.
- Solve problems using the conservation of mechanical energy ($E_{\text{mechanical}} = E_{\text{K}} + E_{\text{P}}$).

What you should know

Before you start this unit, make sure you can:

- Define and calculate kinetic energy, as covered in Subject outcome 2.3, Unit 1.
- Define and calculate gravitational potential energy, as covered in Subject outcome 2.3, Unit 1.

Introduction

In this unit[1] you will learn about the relationship between gravitational potential energy and kinetic energy in a closed system. This will help you to understand what the conservation of mechanical energy means. By drawing on what you already know about gravitational potential energy and kinetic energy, you will be able to calculate the total amount of mechanical energy of a system.

Mechanical energy

Mechanical energy, E_{M}, is simply the sum of gravitational potential energy (E_{P}) and kinetic energy (E_{K}). Mechanical energy is defined as:

$$E_{\text{M}} = E_{\text{K}} + E_{\text{P}}$$
$$\therefore E_{\text{M}} = \frac{1}{2}mv^2 + mgh$$

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, p. 454–466, released under a CC-BY licence.

Example 2.1

Calculate the total mechanical energy for a ball of mass $0.15\ \text{kg}$, which has a kinetic energy of $20\ \text{J}$ and is $2\ \text{m}$ above the ground.

Solution

We have to find the total mechanical energy of the ball. All the given information is in the correct units.

$$\begin{aligned} E_\text{M} &= E_\text{K} + E_\text{P} \\ &= \frac{1}{2}mv^2 + mgh \\ &= 20\ \text{J} + (0.15)(9.8)(2) \\ &= 20\ \text{J} + 2.94\ \text{J} \\ &= 22.94\ \text{J} \end{aligned}$$

Conservation of energy

Energy is a conserved quantity. That means that the amount of energy in a system does not change over time. In other words, the amount of energy in a system before and after an event is constant. This may seem strange, because you can say that you have less energy after a strenuous workout than before you started exercising. However, the energy you had at the start of your workout did not 'disappear' or get 'used up' – your body simply converted one form of energy to another: the total amount of energy in the workout system – consisting of your body and the immediate space and objects you interacted with – remained constant.

This is formally defined by the law of the conservation of energy.

Law of conservation of energy

Energy cannot be created or destroyed, but is merely changed from one form to another.

Activity 2.1: Observe energy conversion

Time required: 5 minutes

What you need:

- an internet connection
- a phone with a QR scanner

What to do:

Scan the QR code to watch the video called Carnival track. The full duration is 03:35 minutes, but you need to watch only from 02:50. Describe to a friend, someone at home or just for yourself what you see happening.

What did you find?

In the video, we see a force being applied to a marble to start it rolling along a track. After an initial unsuccessful try, we see that the marble has enough energy to roll up the hill. It then rolls down the hill and climbs up against the steep rise, but then rolls back again.

We can see two types of energy being used here. The rolling marble has kinetic energy. As it rolls up the hill, it loses kinetic energy but gains potential energy. At the top of the hill it has maximum gravitational potential energy, because of the change in its position. As it rolls down the hill it gains kinetic energy again, and has enough to roll up against the steep rise. At its highest point it has gravitational potential energy again. The marble eventually comes to rest.

In the video in Activity 2.1 you observed the conservation of energy. A force applied to the marble transferred energy to it. Some of the kinetic energy was converted into heat and sound, and the rest was converted to gravitational potential energy as it rolled up the hill. As it rolled down the hill, the marble's gravitational potential energy was converted to kinetic energy and also some heat and sound. So the total amount of energy in that system remained constant throughout: the ball lost speed and eventually came to rest not because its energy had been 'used up', but because the kinetic energy was converted to other forms.

Take note!

The system is the collection of objects that together act as one in the described situation.

The law of conservation of mechanical energy

We know that mechanical energy is the sum of the kinetic energy and the gravitational potential energy in a system. In a closed system – that is, one in which only conservative forces apply – the mechanical energy will remain constant. This is called the law of conservation of mechanical energy.

Law of conservation of mechanical energy

The total amount of mechanical energy in a closed system remains constant.

A conservative force is one that transfers energy in such a way that it can be fully recovered each time the state or position of the system changes. This means that the work done on an object by a conservative force depends only on the initial and final position of the object, not on the path it took in between. Gravity and spring force are conservative forces. Friction and air resistance are non-conservative forces.

Note

Scan the QR code to watch a video on conservative and non-conservative forces to help you understand the concept (Duration: 04.00).

Using the law of the conservation of mechanical energy

The law of conservation of mechanical energy tells us that kinetic energy in a closed system can become potential energy, and vice versa. Energy cannot 'disappear'. For example, in the absence of air resistance, the mechanical energy of an object moving through the air in the Earth's gravitational field remains constant (is conserved).

So, the mechanical energy (E_M) at one moment in an object's motion must be equal to its mechanical energy at any other moment: $E_{\mathrm{M}1} = E_{\mathrm{M}2}$.

Because mechanical energy is the sum of kinetic and potential energy, it follows then that the sum of the kinetic energy (E_K) and the potential energy (E_P) at one moment in an object's motion must be equal to the sum of the kinetic energy and the potential energy at any other moment during the object's motion: $E_{\mathrm{K}1} + E_{\mathrm{P}1} = E_{\mathrm{K}2} + E_{\mathrm{P}2}$.

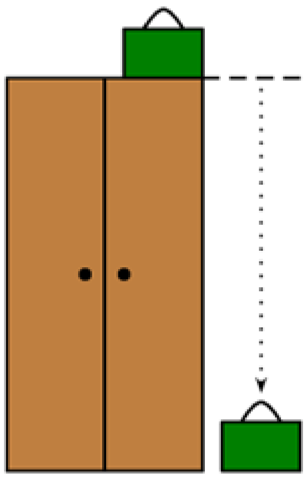
We can expand this to $\frac{1}{2}m{v_1}^2 + mgh_1 = \frac{1}{2}m{v_2}^2 + mgh_2$, and so calculate values for velocity, displacement or other parameters on which the energy depends more easily than with equations of motion. Let's explore this using an example.

Example 2.2

A suitcase with a mass of $1\ \mathrm{kg}$ falls from the top of a cupboard, which is $2\ \mathrm{m}$ high.

1. What is the gravitational potential energy of the suitcase at the top of the cupboard?
2. What is the velocity at which the suitcase will hit the ground?

Solutions



Mechanical energy at the top: $E_{\text{M1}} = E_{\text{K1}} + E_{\text{P1}}$

The mechanical energy will remain constant throughout the motion.

Mechanical energy at the bottom: $E_{\text{M2}} = E_{\text{K2}} + E_{\text{P2}}$

1. The suitcase is at rest at the top of the cupboard, so its kinetic energy is zero ($v_1 = 0\ \text{m} \cdot \text{s}^{-1}$). It has only gravitational potential energy:
$$\begin{aligned} E_{\text{P}} &= mgh_1 = (1)(9.8)(2) \\ &= 19.6\ \text{J} \end{aligned}$$
2. When the suitcase hits the ground, its potential energy is zero ($h = 0\ \text{m}$).
From here we can calculate the velocity at which the suitcase will hit the ground:
$$\begin{aligned} E_{\text{M1}} &= E_{\text{M2}} \\ E_{\text{K1}} + E_{\text{P1}} &= E_{\text{K2}} + E_{\text{P2}} \\ \frac{1}{2}m(v_1)^2 + mgh_1 &= \frac{1}{2}m(v_2)^2 + mgh_2 \\ \frac{1}{2}(1)(0)^2 + (1)(9.8)(2) &= \frac{1}{2}(1){v_2}^2 + (1)(9.8)(0) \\ \frac{1}{2}{v_2}^2 &= 19.6 \\ {v_2}^2 &= 39.2 \\ \therefore v = 6.26\ \text{m} \cdot \text{s}^{-2} \end{aligned}$$

From this example we can see that when an object is lifted, like the suitcase, it gains potential energy. As it falls back to the ground, it will lose this potential energy, but gain kinetic energy. We know that energy cannot be created or destroyed, but only be changed from one form into another. So in Example 2.2, the potential energy that the suitcase loses is changed to kinetic energy.

The suitcase will have maximum potential energy at the top of the cupboard and maximum kinetic energy at the bottom of the cupboard. Halfway down it will have half kinetic energy and half potential energy. As it moves down, the potential energy will be converted (changed) into kinetic energy. At the bottom, the potential energy will have been fully converted to kinetic energy. The $19.6\ \text{J}$ of potential energy at the top will become $19.6\ \text{J}$ of kinetic energy at the bottom.

Let's look at some more examples.

Take note!

In problems involving the use of conservation of energy, we work only with conservative forces and so the path taken by the object can be ignored. The only important quantities are the object's velocity (which gives it kinetic energy) and height above the reference point (which gives it gravitational potential energy). Air resistance or friction are usually stated to be negligible and can be ignored.

Example 2.3

During a flood, a rock of mass $100\ \mathrm{kg}$ is dislodged from a riverbank and falls down a waterfall. The waterfall is $5\ \mathrm{m}$ high. You can ignore air resistance and any other non-conservative force.

1. Calculate the potential energy of the rock at the top of the waterfall.
2. Calculate the kinetic energy of the rock at the bottom of the waterfall.
3. Calculate the magnitude of the velocity of the rock at the bottom of the waterfall.

Solutions

All the given information is in the correct units.

1.
$$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (100)(9.8)(5) \\ &= 4900\ \mathrm{J} \end{aligned}$$

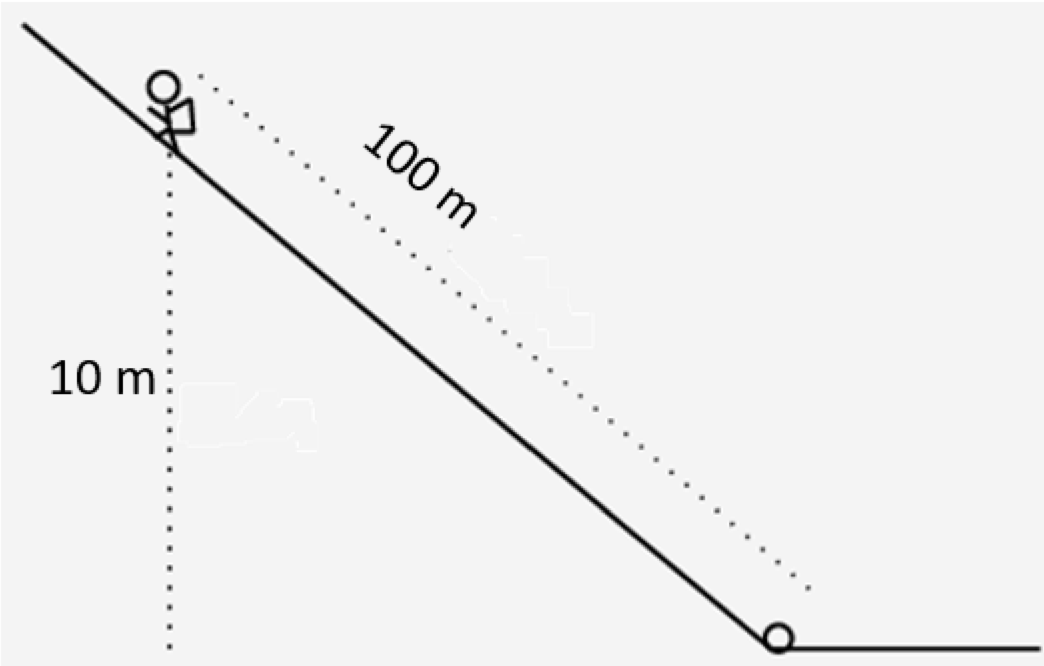
2. We know that the total mechanical energy must be conserved. Therefore the total energy of the rock at the top must be equal to the total energy at the bottom. The rock has no kinetic energy at the top, and at the bottom of the waterfall it has lost all its potential energy. Therefore:
$$\begin{aligned} E_{\mathrm{K}_{\mathrm{top}}} + E_{\mathrm{P}_{\mathrm{top}}} &= E_{\mathrm{K}_{\mathrm{bottom}}} + E_{\mathrm{P}_{\mathrm{bottom}}} \\ 0 + E_{\mathrm{P}_{\mathrm{top}}} &= E_{\mathrm{K}_{\mathrm{bottom}}} + 0 \\ E_{\mathrm{P}_{\mathrm{top}}} &= E_{\mathrm{K}_{\mathrm{bottom}}} \\ \therefore E_{\mathrm{K}_{\mathrm{bottom}}} &= 4900\ \mathrm{J} \end{aligned}$$

3.
$$\begin{aligned} E_{\mathrm{K}} &= \frac{1}{2}mv^2 \\ 4900 &= \frac{1}{2}(100)v^2 \\ v^2 &= 98 \\ &= 9.90\ \ \mathrm{m\cdot s^{-1}} \end{aligned}$$

Example 2.4

A mountain climber in the Drakensberg during winter drops her water bottle. The water bottle slides

$100\ \mathrm{m}$ down the side of a steep icy slope to a point $10\ \mathrm{m}$ lower than the climber's position. The mass of the climber is $60\ \mathrm{kg}$ and her water bottle has a mass of $500\ \mathrm{g}$.



1. If the bottle starts from rest, how fast is it travelling by the time it reaches the bottom of the slope? (Ignore friction.)
2. What is the total change in the climber's potential energy as she climbs down the mountain to fetch her water bottle?

Solutions

1. We have to calculate the velocity of the bottle as it reaches the bottom of the slope, and we know that it starts with a velocity of $0\ \mathrm{m \cdot s^{-1}}$ at the top of the slope. The mass of the bottle is $500\ \mathrm{g} = 0.5\ \mathrm{kg}$.

   We can calculate the velocity at the bottom using the conservation of mechanical energy, as the energy at the top has to be equal to the energy at the bottom. The distance that the bottle has fallen has no effect on the change in its energy, only the change in its height.

   Define the top of the slope as position 1 and at the bottom as position 2.

$$\begin{aligned}
E_{\mathrm{M1}} &= E_{\mathrm{M2}} \\
E_{\mathrm{K1}} + E_{\mathrm{P1}} &= E_{\mathrm{K2}} + E_{\mathrm{P2}} \\
0 + mgh_1 &= \frac{1}{2}m(v_2)^2 + 0 \\
(v_2)^2 &= \frac{2mgh}{m} \\
(v_2)^2 &= 2gh \\
(v_2)^2 &= 2(9.8)(10) \\
v_2 &= 14\ \mathrm{m \cdot s^{-1}}
\end{aligned}$$

2. We have to calculate the difference between the climber's potential energy at the top of the slope and the bottom of the slope. We know that her potential energy at the bottom of the slope is $0\ \mathrm{J}$.

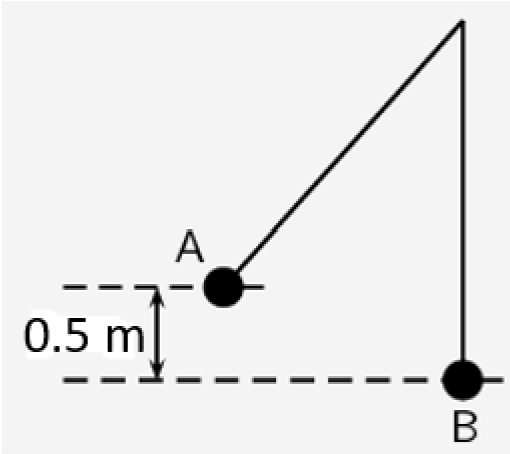
So, to calculate the difference between her potential energy at the top and the bottom, we simply have to calculate what the potential energy was at the top:

$$\begin{aligned} E_P &= mgh \\ &= (60)(9.8)(10) \\ &= 5880 \text{ J} \end{aligned}$$

Exercise 2.1

Questions were sourced from exercises and examples in [Siyavula Physical Science Gr 10 Learner's Book, p. 443–469](), released under a CC-BY licence.

1. A tennis ball with a mass of 120 g is dropped from a height of 5 m. Ignore air resistance.
   a. What is the potential energy of the ball when it has fallen 3 m?
   b. What is the velocity of the ball when it hits the ground?
2. A 2 kg metal ball is suspended from a rope as a pendulum. If it is released from point A and swings down to point B (the bottom of its arc), calculate the velocity of the ball at point B.



3. A roller coaster ride at an amusement park starts from rest at a height of 50 m above the ground and rapidly drops down along its track. At some point, the track does a full $360°$ loop, which has a height of 20 m, before finishing off at ground level. The roller coaster train with a full load of people on it has a mass of 850 kg. If the roller coaster and its track are frictionless, calculate:
   a. the velocity of the roller coaster when it reaches the top of the loop
   b. the velocity of the roller coaster at the bottom of the loop (i.e. ground level).

4. A skier, with a mass of 50 kg, is at the top of a ski slope 6.4 m high.
   a. Determine the maximum velocity that she can reach when she skis to the bottom of the slope.
   b. Do you think that she will reach this velocity? Give a reason for your answer.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- The mechanical energy of an object is the sum of the potential energy and kinetic energy of the object.

- The law of conservation of energy states that energy cannot be created or destroyed, but can only be changed from one form to another.
- The law of conservation of mechanical energy states that the total mechanical energy of a closed system (i.e. where friction or air resistance does not apply) remains constant: $E_{\text{M1}} = E_{\text{M2}}$.
- We can use the conservation of mechanical energy to calculate parameters that determine the amount of energy in a system:

$$\begin{aligned} E_{\text{M1}} &= E_{\text{M2}} \\ E_{\text{K1}} + E_{\text{P1}} &= E_{\text{K2}} + E_{\text{P2}} \\ \frac{1}{2}m(v_1)^2 + mgh_1 &= \frac{1}{2}m(v_2)^2 + mgh_2 \end{aligned}$$

Unit 2: Assessment

Suggested time to complete: 15 minutes

Questions 1, 3 and 4 were sourced from exercises and examples in [Siyavula Physical Science Gr 10 Learner's Book, p. 443–469](), released under a CC-BY licence.

1. A stone is dropped from a window $6\ \text{m}$ above the ground. The mass of the stone is $25\ \text{g}$. Use the principle of conservation of energy to determine the speed with which the stone strikes the ground.
2. A child swings on a playground swing. The combined mass of the child and the swing is $25\ \text{kg}$. Her maximum velocity at the lowest point of her motion is $5.5\ \text{m} \cdot \text{s}^{-1}$. Calculate the maximum height she achieves during the motion. Friction and air resistance is negligible.

3. A truck of mass 1.2 tons is parked at the top of a hill, $150\ \mathrm{m}$ high. The truck driver lets the truck run freely down the hill to the bottom.
   a. What is the maximum velocity that the truck can achieve at the bottom of the hill?
   b. Will the truck achieve this velocity? Give a reason for your answer.
4. Prove that the velocity of an object, in free fall, in a closed system, is independent of its mass.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1.
   a. We are asked to calculate the potential energy when the ball has fallen $3\ \mathrm{m}$ already, and therefore when it is $2\ \mathrm{m}$ above the ground.
   $$\begin{aligned} E_{\mathrm{P}} &= mgh \\ &= (0.12)(9.8)(2) \\ &= 2.35\ \mathrm{J} \end{aligned}$$
   b. Define top as position 1, and bottom as position 2.
   $$\begin{aligned} E_{\mathrm{M}_1} &= E_{\mathrm{M}_2} \\ E_{\mathrm{P}_1} + E_{\mathrm{K}_1} &= E_{\mathrm{P}_2} + E_{\mathrm{K}_2} \\ mgh_1 + 0 &= 0 + \frac{1}{2}m(v_2)^2 \\ (0.12)(9.8)(5) &= \frac{1}{2}(0.12)(v_2)^2 \\ (v_2)^2 &= 98 \\ v_2 &= 9.9\ \mathrm{m \cdot s^{-1}} \end{aligned}$$
2. We know that potential energy at point A must be equal to the kinetic energy at point B. The potential energy at the bottom (B) is 0, and the kinetic energy at the top (A) is also 0. Therefore we can write:
   $mgh_{\mathrm{A}} = \frac{1}{2}m(v_{\mathrm{B}})^2$.
   The masses cancel out on each side of the equation and we can simplify the equation to the following:
   $$\begin{aligned} v_{\mathrm{B}} &= \sqrt{2gh}_{\mathrm{A}} \\ &= \sqrt{2(9.8)(0.5)} \\ &= \sqrt{9.8} \\ &= 3.13\ \mathrm{m \cdot s^{-1}} \end{aligned}$$
3. From the conservation of mechanical energy, we know that at any two points in the system, the total mechanical energy must be the same. Define the start as position 1, the top of the loop as position 2 and the bottom of the loop as position 3.
   a. The situation at the start of the roller coaster compared with that at the top of the loop can be given as:
   $$\begin{aligned} E_{\mathrm{M}_1} &= E_{\mathrm{M}_2} \\ E_{\mathrm{P}_1} + E_{\mathrm{K}_1} &= E_{\mathrm{P}_2} + E_{\mathrm{K}_2} \\ mgh_1 + 0 &= mgh_2 + \frac{1}{2}m(v_2)^2 \end{aligned}$$
   We can eliminate the mass, *m*, from the equation by dividing both sides by *m*.

$$
\begin{aligned}
gh_1 &= \frac{1}{2}(v_2)^2 + gh_2 \\
(v_2)^2 &= 2g(h_1 - h_2) \\
(v_2)^2 &= 2(9.8)(50 - 20) \\
v_2 &= 24.25\ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

b. From the conservation of mechanical energy, we know that the total mechanical energy at the bottom of the loop should be the same as the total mechanical energy of the system at any other position. Therefore, the situation at the starting position and at the bottom of the loop can be given as:

$$
\begin{aligned}
E_{\text{M}_1} &= E_{\text{M}_3} \\
E_{\text{P}_1} + E_{\text{K}_1} &= E_{\text{P}_3} + E_{\text{K}_3} \\
mgh_1 + 0 &= 0 + \frac{1}{2}m(v_3)^2 \\
(v_3)^2 &= 2gh_1 \\
(v_3)^2 &= 2(9.8)(50) \\
v_3 &= 31.30\ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

4. Define the top of the slope as position 1 and the bottom as position 2.
   a. The skier starts from rest so her kinetic energy at the top of the slope is 0. At the bottom of the slope she would have lost all her potential energy. Therefore:

$$
\begin{aligned}
E_{\text{M}_1} &= E_{\text{M}_2} \\
E_{\text{P}_1} + E_{\text{K}_1} &= E_{\text{P}_2} + E_{\text{K}_2} \\
mgh_1 + 0 &= 0 + \frac{1}{2}m(v_2)^2 \\
(v_2)^2 &= 2gh_1 \\
(v_2)^2 &= 2(9.8)(6.4) \\
v_2 &= 11.2\ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

   b. She will likely come close to the velocity but not attain it exactly owing to her experiencing some (although little) air resistance. Friction will probably be almost negligible owing to the snow creating a smooth surface down the slope.

Back to Exercise 2.1

Unit 2: Assessment

1. Define the top of the motion as position 1 and the ground as position 2.

$$
\begin{aligned}
E_{\text{M}_1} &= E_{\text{M}_2} \\
E_{\text{P}_1} + E_{\text{K}_1} &= E_{\text{P}_2} + E_{\text{K}_2} \\
mgh_1 + 0 &= 0 + \frac{1}{2}m(v_2)^2 \\
(0.025)(9.8)(6) &= \frac{1}{2}(0.025)(v_2)^2 \\
(v_2)^2 &= 117.6\ \text{m}^2\cdot\text{s}^{-2} \\
v_2 &= 10.84\ \text{m}\cdot\text{s}^{-1}
\end{aligned}
$$

2.

$$
\begin{aligned}
E_{\text{K}_{\text{bottom}}} &= \frac{1}{2}mv^2 \\
&= \frac{1}{2}(25)(5.5)^2 \\
&= 378.13\ \text{J}
\end{aligned}
$$

We know that the mechanical energy is conserved. Therefore:

$$
\begin{aligned}
E_{P_{top}} + E_{K_{top}} &= E_{P_{bottom}} + E_{K_{bottom}} \\
mgh_{top} + 0 &= 0 + 378.13 \text{ J} \\
(25)(9.8)(h) &= 378.13 \text{ J} \\
h_{top} &= 1.54 \text{ m}
\end{aligned}
$$

3.

a.

$$
\begin{aligned}
E_{P_{top}} &= mgh \\
&= (1200)(9.8)(150) \\
&= 1.76 \times 10^6 \text{ J}
\end{aligned}
$$

Because mechanical energy is conserved:

$$
\begin{aligned}
E_{P_{top}} + E_{K_{top}} &= E_{P_{bottom}} + E_{K_{bottom}} \\
1.76 \times 10^6 \text{ J} + 0 &= 0 + \frac{1}{2}m(v_{bottom})^2 \\
1.76 \times 10^6 \text{ J} &= \frac{1}{2}(1200)(v_{bottom})^2 \\
v_{bottom} &= 54.16 \text{ m} \cdot \text{s}^{-1}
\end{aligned}
$$

b. No, the truck will experience air resistance and friction, and will not reach the maximum velocity possible.

4. In a closed system mechanical energy is conserved:

$$
\begin{aligned}
E_{M_1} &= E_{M_2} \\
E_{P_1} + E_{K_1} &= E_{P_2} + E_{K_2} \\
mgh_1 + \frac{1}{2}m(v_1)^2 &= mgh_2 + \frac{1}{2}m(v_2)^2
\end{aligned}
$$

The mass of the ball m appears in each term, so it can be eliminated. The equation then becomes:

$$
\begin{aligned}
g(h_1 - h_2) &= \frac{1}{2}((v_2)^2 - (v_1)^2) \\
2g(h_1 - h_2) &= (v_2)^2 - (v_1)^2
\end{aligned}
$$

This proves that the velocity of the object is independent of its mass. It does not matter what its mass is, it will always have the same velocity when it falls through this height.

Back to Unit 2: Assessment

Media Attributions

SUBJECT OUTCOME IV

MECHANICS: IDENTIFY, DESCRIBE, AND APPLY PRINCIPLES OF SIMPLE MACHINES AND MECHANICAL ADVANTAGE IN EVERYDAY CONTEXTS

Subject outcome

Subject outcome 2.4: Identify, describe, and apply principles of simple machines and mechanical advantage in everyday contexts.

Learning outcomes

- Describe and identify the functions of simple machines.
- State and identify examples of the six basic machines:
  - lever
  - wheel and axle
  - pulley
  - inclined plane
  - screw
  - wedge.
- State and use the law of simple machines in calculations.
- Define mechanical advantage as:
  - ideal mechanical advantage (IMA) = distance effort F moves ÷ distance resistance F moves
  - actual mechanical advantage (AMA) = resistance force ÷ effort force.
- Calculate % efficiency of machine: $\text{Efficiency } (\%) = (AMA \div IMA) \times 100$.
- Draw diagrams and calculate mechanical advantage of levers.

Unit 1 outcomes

By the end of this unit you will be able to:

- Describe simple machines.
- Describe the functions of simple machines.
- State the law of simple machines.
- State and identify examples of six basic machines:
  - lever

- wheel and axle
- pulley
- inclined plane
- screw
- wedge.

Unit 2 outcomes

By the end of this unit you will be able to:

- Define ideal mechanical advantage (IMA) as the ratio between the distance through which the effort force moves an object and the distance through which the resistance force moves an object: IMA = distance effort F moves÷ effort resistance F moves.
- Use the law of simple machines in calculations.
- Draw diagrams of a lever where:
  - the fulcrum is between the resistance force and the effort force
  - the resistance force is between the fulcrum and the effort force
  - the effort force is between the fulcrum and the resistance force.
- Calculate mechanical advantage of levers.

Unit 3 outcomes

By the end of this unit you will be able to:

- Define ideal mechanical advantage (IMA) as the ratio between the distance through which the effort force moves an object and the distance through which the resistance force moves an object: IMA = distance effort force ÷ distance resistance force.
- Define actual mechanical advantage (AMA) as the ratio between the resistance force and the effort force: AMA = resistance force ÷ effort force.
- Calculate the relative efficiency of a simple machine: efficiency (%) = (AMA ÷ IMA) x 100.

Unit 1: Simple machines

LEIGH KLEYNHANS

Unit 1 outcomes

By the end of this unit you will be able to:

- Describe simple machines.
- Describe the functions of simple machines.
- State the law of simple machines.
- State and identify examples of six basic machines:
  - lever
  - wheel and axle
  - pulley
  - inclined plane
  - screw
  - wedge.

What you should know

Before you start this unit, make sure you can:

- Identify and apply principles of force. See Subject outcome 2.2 to revise this.
- Identify, describe and apply principles of mechanical energy. See Subject outcome 2.3 to revise this.

Introduction

In this unit you will learn what a simple machine is and about the different ways in which simple machines are used to make work easier. Once you understand the principle of a simple machine, you will learn about six different types of simple machines used in everyday applications.

Basic functioning of simple machines

What are simple machines? Simple machines are tools that make work easier. They have few or no moving parts. These machines use energy to do work with one movement. They make our work easier by letting us use less mechanical effort to move an object.

So, we can say that the function of simple machines is to transfer energy by means of doing work. The amount of energy transferred remains constant. However, the machine can change the ratio of the force and distance involved in the energy transfer.

Formula for work or energy transfer: $Work\ or\ Energy = Force \text{ x } distance$

Simple machines make work easier for us by allowing us to push or pull over increased distances, using the idea of spreading force over distance: if you push further, you can use less force. You are doing the same amount of work — it just seems easier. You move an object a greater distance to accomplish the same amount of work with less force. Simple machines give us an advantage by changing the amount, speed, or direction of forces. They allow us to use a smaller force (the effort force) over a large distance to overcome a larger force (resistance force) acting over a smaller distance.

The law of simple machines

The law of simple machines states that the product of the effort force and the distance over which it is applied is equal to the resistance force and the distance over which it acts.

$F_e \text{ x } d_e = F_r \text{ x d}_r$

The equation shows how a simple machine can achieve the same amount of output work by reducing the amount of effort force and increasing the distance over which the effort force is applied.

Exercise 1.1

1. What is the advantage of using simple machines, if they do not reduce the amount of work required?
2. What is the difference between the effort force and the resistance force in a simple machine?
3. State the law of simple machines in words.
4. State the law of simple machines in an equation.

The full solutions are at the end of the unit.

Types of simple machines

There are six different types of simple machines that we use in everyday applications.

Levers

A lever is a board or bar that rests on a turning point. This turning point is called the fulcrum. The object that a lever moves, is called the load. The effort is the applied force you use to move the lever. By changing the position of the fulcrum, you can gain extra power with less effort. The closer the object is to the fulcrum, the easier it is to move. Depending on where the fulcrum is located, a lever can multiply either the force applied or the distance over which the force is applied.

There are three types of levers:

- 1st class levers
- 2nd class levers
- 3rd class levers.

1st class levers

1st class levers have the fulcrum between the load and the effort. The lever changes the direction of the force.

There are three scenarios for 1st class levers.

1. A lever with the fulcrum close to the load.

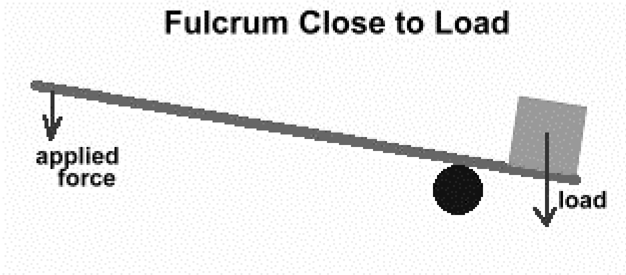


Figure 1: 1st class lever with the fulcrum close to load

   If the fulcrum is placed close to the load, the load can be moved with just a small applied force (effort). This type of lever system gives you a mechanical advantage, which means that the force you apply gets multiplied, so a large force acts on the load. The trade-off of using a lever like this is that you have to apply a force over a large distance, and the load itself will move only a short distance.

2. A lever with the fulcrum exactly halfway between the load and where you apply the force (effort).

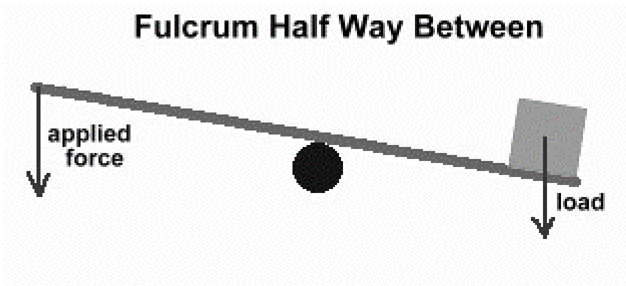


Figure 2: 1st class lever with fulcrum halfway between effort and load

   This lever system has no mechanical advantage. Whatever force is necessary to move the load is the force you must apply. This type of lever system takes advantage of another property of some levers: they reverse the direction of the force. You can push in one direction, and the load moves the other way.

3. A lever where the fulcrum is nearer the applied force (effort).

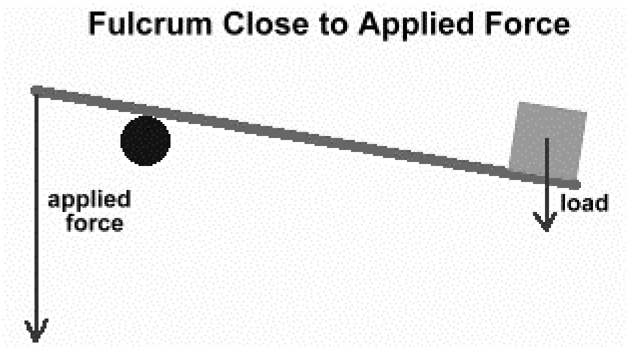


Figure 3: 1st class lever with fulcrum close to effort

In this scenario, much more force than the weight of the load itself must be applied. If you are lifting something, it will require much more force than would be needed if you were to just lift the load by yourself – this type of lever system makes the work harder. This type of lever system usually uses a motor to lift the load. The advantage is the load is far away, and it moves a long distance.

Examples of 1st class levers are:

- a see-saw
- scissors
- pliers.

2nd class levers

2nd class levers have the load in the centre; between the fulcrum and the applied force or effort.

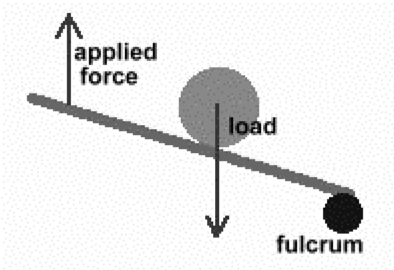


Figure 4: A 2nd class lever with the load in the centre

This lever causes the load to move in the same direction as the force applied. When the load is nearer to the fulcrum, the effort needed to lift the load will be less. If you want to move a very large load with a small effort, you must put the load very close to the fulcrum.

Examples of 2nd class levers are:

- a wheelbarrow
- nutcracker.

3rd class levers

In 3rd class levers, the applied force or effort is in the centre; between the load and fulcrum.

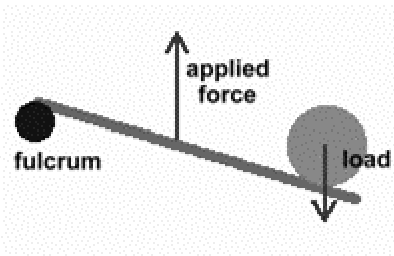


Figure 5: A 3rd class lever with the effort in the centre

This lever system does not give any mechanical advantage. No matter where you apply the force, the force you apply must always be greater than the force of the load. No matter how close or how far the load is from the fulcrum, the effort used to lift the load, has to be greater than the load. The load moves in the same direction as the force you apply. A motor is usually used with this lever system to lift loads at a distance.

Examples of 3rd class levers:

- a bent arm
- a fishing rod.

Wheels and axles

The second type of simple machine is the wheel and axle. A wheel with a rod through it, called an axle, can lift or move loads. The axle allows the wheel to turn. The wheel and axle system can be used as a tool to multiply the force you apply or to multiply the distance travelled. There is rotation through a complete circle (360^o). The circle turned by the wheel is much larger than the circle turned by the axle. The increased distance over which the force is applied as the wheel turns results in a more powerful force on the axle, which moves a shorter distance.

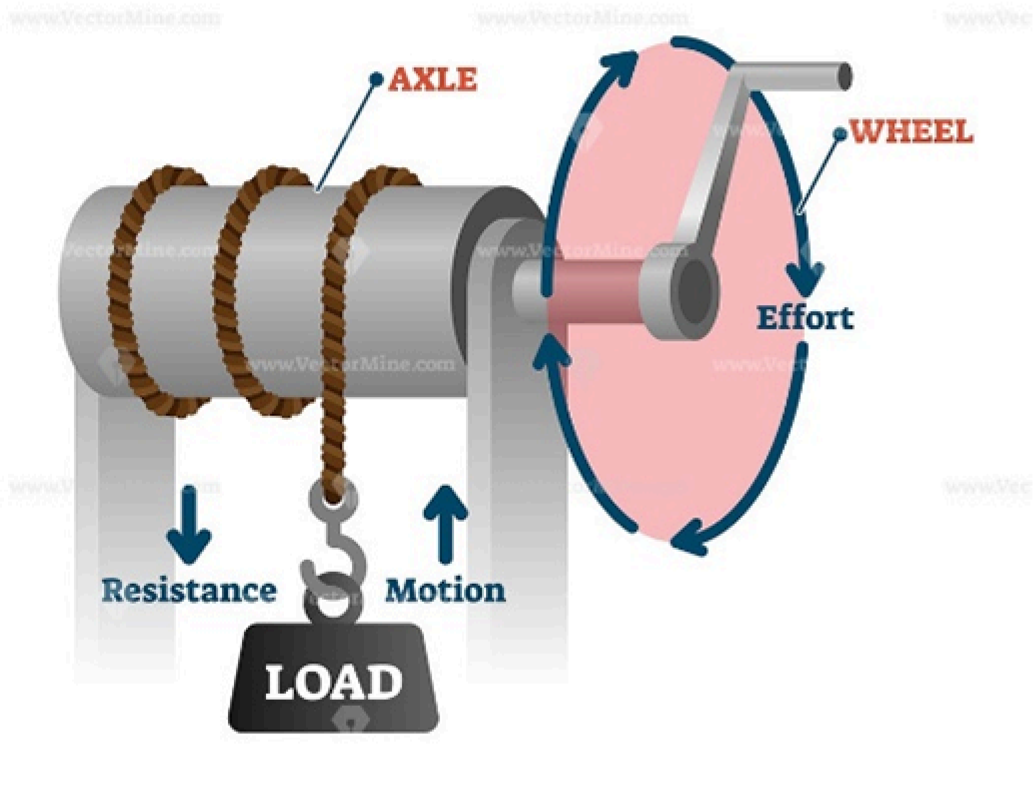


Figure 6: A wheel and axle system

Examples of wheels and axles:

- cars
- roller skates
- door handles
- gears.

Pulleys

A pulley is a variation of the wheel and axle. Instead of an axle, the wheel rotates on a rope or cord. In a pulley, a cord fits in a groove in the wheel. As the wheel rotates, the cord moves in either direction. When a hook is attached to the rope you can use the wheel's rotation to raise and lower objects. The rope is attached to the load and when you pull on one side of the pulley system, the wheel turns and the load will move. Pulleys allow you move loads up, down, or sideways. Pulleys are good for moving objects to hard-to-reach places. A pulley makes work seem easier because it changes the direction of motion to work with gravity. The force required to lift the load remains the same as lifting it without the pulley but pulleys have many advantages. For example, it is much easier to raise a flag from the ground, instead of climbing up the pole.

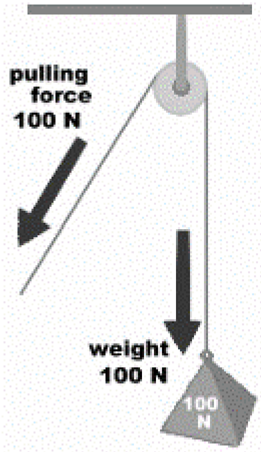


Figure 7: A simple pulley system

A pulley saves the most effort when you have more than one pulley working together. Two or more pulleys connected together allow a heavy load to be lifted with less force. The main advantage of this pulley combination is that the amount of effort is less than half of the load.

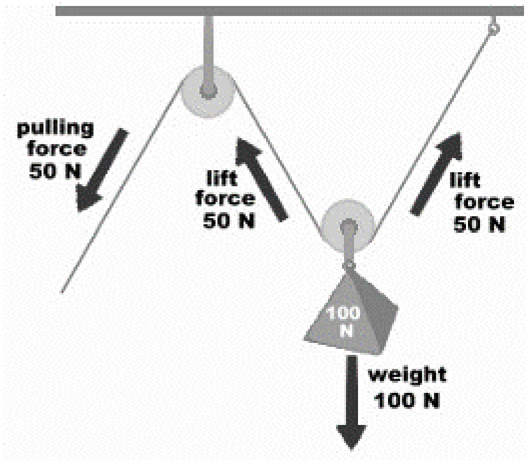


Figure 8: A combination pulley system

Examples of pulleys are:

- flag poles
- masts on sailboats
- window blinds
- building cranes.

Inclined planes or ramps

An inclined plane is a flat surface that is higher on one end and connects a lower level to a higher level.

Inclined planes or ramps make the work of moving things easier, as they allow an object to be raised with less effort than if lifted directly upward. You need less force to move objects to a higher lever using an inclined plane.

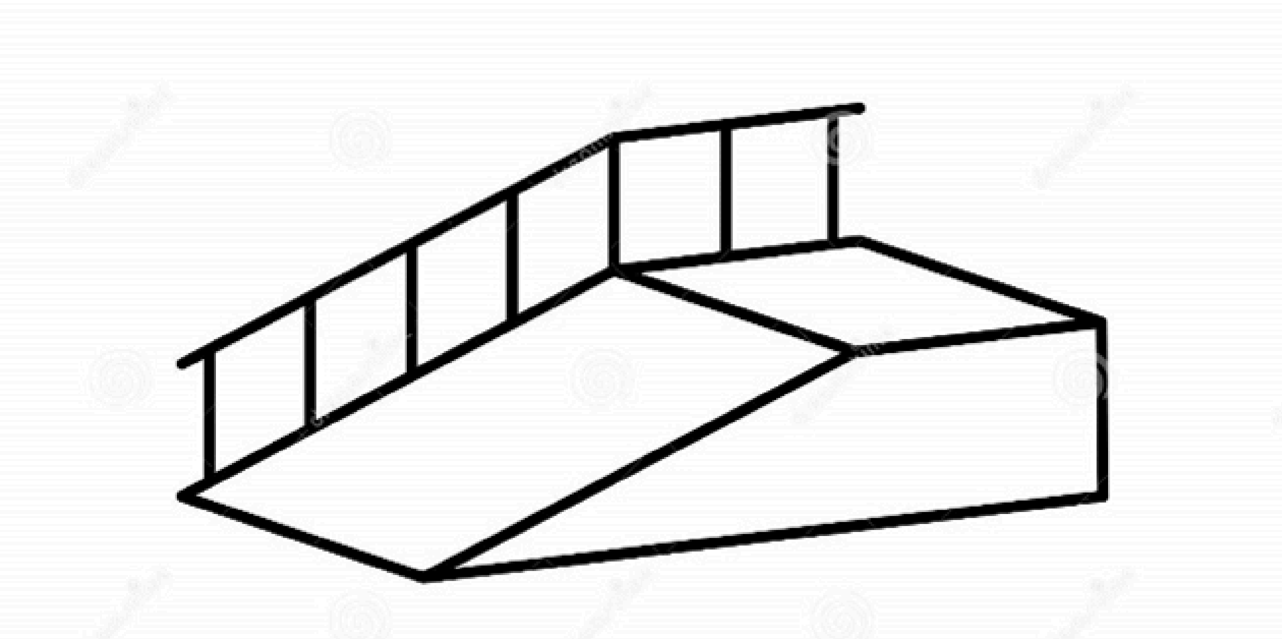


Figure 9: An inclined plane

An inclined plane works to reduce effort by increasing the distance over which the load must be moved. The longer the distance of the ramp, the easier it is to do the work. It will, however, take a longer time to do the work.

Examples of inclined planes are:

- ramps
- slanted roads
- paths up a hill
- slides.

Screws

A screw has ridges and is not smooth like a nail. Screws can be used to lower and raise things or to hold things together. A screw is like a long ramp as the thread is similar to a continuous inclined plane. The wider the thread of a screw, the harder it is to turn it. The distance between the threads determines the slope of the inclined plane; and the steeper the slope, the wider the thread. Screws with less distance between the threads are easier to turn.

Figure 10: An example of a screw mechanism

Examples of screws are:

- jar or bottle lids
- light bulbs
- clamps
- car jacks
- wrenches
- adjustable chairs and stools
- spiral staircases.

Wedges

A wedge is a simple machine used to push two objects apart. A wedge is usually made up of two inclined planes. These planes meet and form a sharp edge. This edge can split or push objects apart. A wedge can also be used as a lifting device, by forcing it under an object. Most wedges (but not all) are combinations of two inclined planes but they can also be round, like the tip of a nail. The narrower the wedge (or the sharper the point of a wedge), the easier it is drive it in and push things apart.

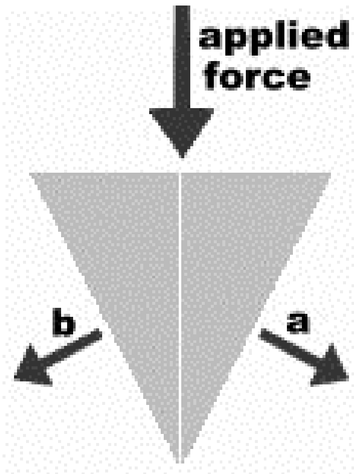


Figure 11: A wedge drives the force apart; the direction of output force is changed from one direction into two (a and b)

Examples of wedges are:

- knives
- axes
- teeth
- forks
- nails.

Note

Watch this video to find out more about the use of simple machines in everyday life (Duration: 03.00).

Summary

In this unit you have learnt the following:

- A simple machine is a device used to reduce the mechanical effort required to move objects.
- The principle of simple machines is based on the relationship between force and distance to do a fixed amount of work: the greater the distance, the less force required.
- Mechanical advantage is the amount of effort saved when using a machine.
- Simple machines use mechanical advantage to multiply force.
- There are six types of simple machines used in everyday life:
    - A lever – using a rod or board to increase or change the direction of the force on the load.
    - A wheel and axle – a rod fixed to the centre of a wheel to increase force on the load.
    - A pulley – a rope that passes over a grooved wheel to change direction of the force on the load, or when used in combinations to reduce the applied force required.
    - An inclined plane – increases the distance and thereby reduces the effort to raise a load from a low level to a higher level.
    - A screw – a spiral inclined plane, it can keep objects together or raise and lower a platform.
    - A wedge – two back-to-back inclined planes used to redirect the applied force and split something apart.

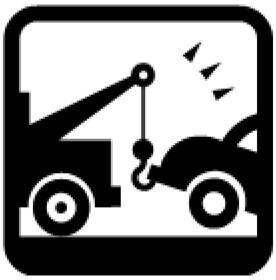
Unit 1: Assessment

Suggested time to complete: 10 minutes

1. Match the simple machine with its correct definition by writing the corresponding number in the answer column.

Simple machine	Advantage
a. Lever	1. Large rotation can increase force on a smaller rotation
b. Inclined plane	2. Reduces effort to raise or lower a load vertically
c. Wedge	3. Reduces the effort to raise an object from a low level to a high level by increasing the distance
d. Screw	4. Uses a rope to change the direction of the force
e. Wheel and axle	5. Increases the force on the load
f. Pulley	6. Can split an object apart

2. Identify the type of simple machine in each picture:

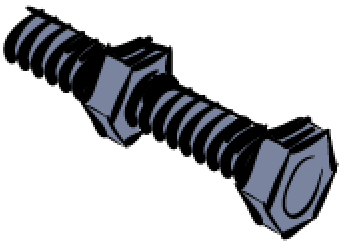


a.

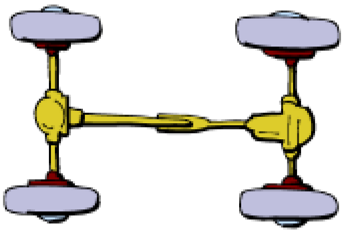
b.

c.

d.

e. 

f. 

g. 

h. 

i. 

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1. Simple machines make the work easier by changing the ratio of the force and the distance
2. The effort force is the input force applied to the machine and the resistance force is the weight of the

object that has to be moved.

3. Simple machines transfer energy but allow the use of a smaller force (the effort force) over a large distance to overcome a larger force (resistance force) acting over a smaller distance. In this way they make the work easier.

   The law of simple machines states that the product of the effort force and the distance over which it is applied is equal to the resistance force and the distance over which it is applied. F_e x $d_e = F_r$ x d_r 4.

Back to Exercise 1.1

Unit 1: Assessment

1.
   a. 5
   b. 3
   c. 6
   d. 2
   e. 1
   f. 4
2.
   a. lever
   b. wheel and axle
   c. lever, wheel and axle
   d. wedge
   e. screw
   f. inclined plane
   g. wheel and axle
   h. pulley
   i. lever

Back to Unit 1: Assessment

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Unit 2: The concept of mechanical advantage

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Define ideal mechanical advantage (IMA) as the ratio between the distance through which the effort force moves an object and the distance through which the resistance force moves an object: IMA = distance effort F moves ÷ distance resistance F moves.
- Use the law of simple machines in calculations.
- Draw diagrams of a lever where:
  - the fulcrum is between the resistance force and the effort force
  - the resistance force is between the fulcrum and the effort force
  - the effort force is between the fulcrum and the resistance force.
- Calculate mechanical advantage of levers.

What you should know

Before you start this unit, make sure you can:

- Identify and apply principles of force, specifically the calculation of weight (F_g) from mass, as covered in Subject outcome 2.2.
- Identify, describe and apply principles of mechanical energy, as covered in Subject outcome 2.3.
- Identify levers as simple machines, as covered in Subject outcome 2.4, Unit 1.

Introduction

The amount of effort saved when using machines is called mechanical advantage (MA). Simple machines use mechanical advantage as a key property to their functionality, helping humans perform tasks that would require more force than a person could produce. We will use the lever as an example of a simple machine to illustrate the concept of mechanical advantage.

Effort force and resistance force

When levers are used as simple machines, the input force that is applied to the lever is referred to as the effort force. The load that is being lifted has weight and the force required to move the object is referred to as the resistance force.

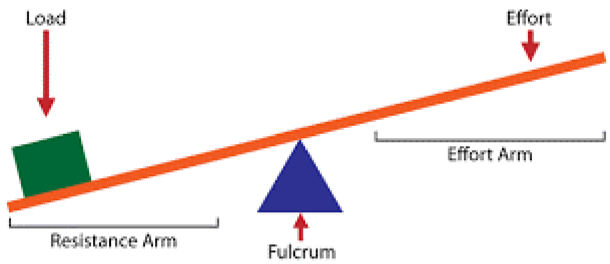


Figure 1: The effort and the resistance forces in a lever

Applying the law of simple machines to levers

The law of simple machines states that the product of the effort force and the distance over which it is applied is equal to the resistance force and the distance over which it is applied. F_e x $d_e = F_r$ x d_r

where:
F_e is the effort force
F_r is the resistance force
d_e is the distance the effort force moves
d_r is the distance the resistance force moves

Mass and weight force are directly proportional, therefore masses can be substituted into this formula instead of forces, depending on what is given in the question.

When this law is applied to levers, the distance the effort moves (d_e) and the distance the resistance force moves (d_r) are proportional to the distance the effort is from the fulcrum and the distance the load is from the fulcrum. This formula, therefore, allows us to calculate where to place a load relative to the position of the effort to balance a lever.

Example 2.1

An adult of 75 kg sits 0.5 m from the fulcrum of a seesaw. How far from the fulcrum should a child of 25 kg sit to keep the seesaw balanced? Draw a diagram to support your reasoning.

Solution

Step 1: Check the units; the units of F and d must be the same

Masses must both be in kg.

Answer for distance will be in m.

Step 2: Wite down the formula

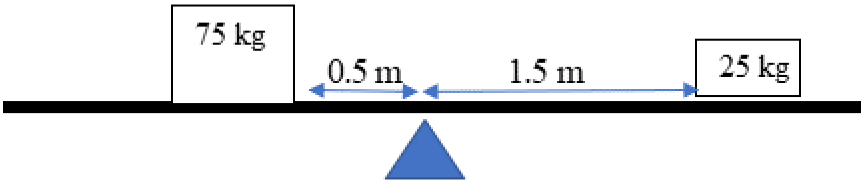
F_e x $d_e = F_r$ x d_r

Step 3: Substitute the values and calculate your answer

75 x $0.5 = 25$ x d_r
$d_r = 1.5$ m

Step 4: Draw a diagram to support your answer

A seesaw is a 1st class lever, so the fulcrum is between the effort and the load.



Activity 2.1: Practise using the law of simple machines

Time required: 10 minutes

What you need:

- internet access

What to do:

1. Go to the PhET Simulation '[Balancing Act]'.
2. Load the simulation and go to Balance Lab.
3. Check the rulers box. Move the slider to the right, as indicated in the screenshot below.

4. Place your 'load' of a $5\ \mathrm{kg}$ brick on the left side at $1.25\ \mathrm{m}$.
5. Place a $5\ \mathrm{kg}$brick on the right side until the lever is balanced.
6. Measure the effort arm's distance.
7. Remove each of the bricks.
8. Place your 'load' of a $20\ \mathrm{kg}$ brick on the left side at $1.25\ \mathrm{m}$.
9. Place a $5\ \mathrm{kg}$ brick on the right side until the lever is balanced.
10. Measure the effort arm's distance.
11. Think about the following:
    - Is the lever in the simulation a first, second, or third class lever? Explain how you know.

- Was the distance for a small weight in Step 9 greater than, less than, or equal to the distance for the large weight? Why?

12. When the lever was balanced, how did the force x distance of the effort compare to the force x distance of the resistance?
13. Now play the game to consolidate the concept.

What did you find?

- In order to balance a mass on a seesaw, an equal mass can be placed an equal distance from the fulcrum on the other side.
- If a smaller mass is used to balance a larger mass, it must be placed further from the fulcrum.
- If a larger mass is used to balance a smaller mass, it must be placed closer to the fulcrum.
- These results support the law of machines: F_e x $d_e = F_r$ x d_r.
- The lever in the simulation is a 1st class lever because the fulcrum is between the effort and the load.

Drawing diagrams of levers

The law of simple machines can be applied to all three classes of levers. Always draw a diagram to assist you with the calculations:

1st class lever – fulcrum is between the effort and the load e.g. a seesaw:

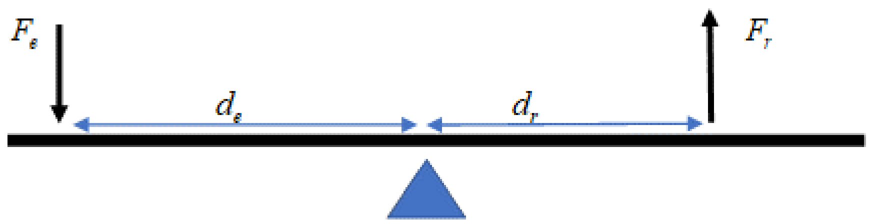


Figure 2: A 1st class lever

2nd class lever – the load is between the effort and fulcrum e.g. wheelbarrow:

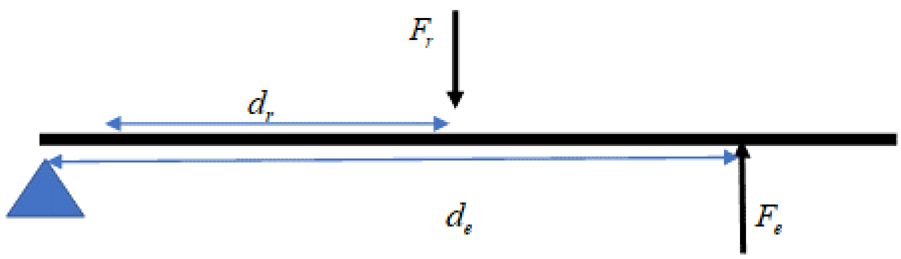


Figure 3: A 2nd class lever

3rd class lever – the effort is between the fulcrum and the load e.g. tweezers:

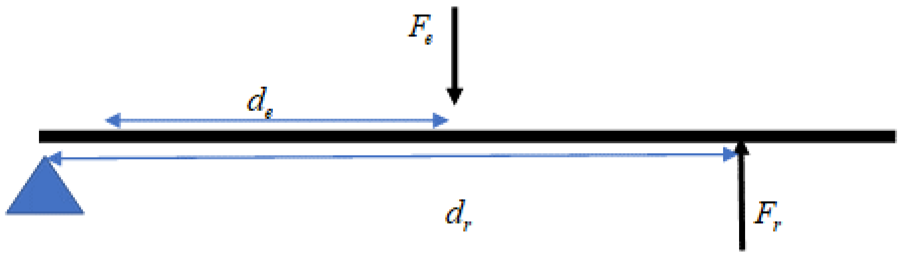


Figure 4: A 3rd class lever

Exercise 2.1

1. A $60\ \text{kg}$ block is $2\ \text{m}$ from the fulcrum of a lever. What mass can be placed at $1.5\ \text{m}$ from the fulcrum to balance it?
2. How far should a $1\ \text{kg}$ object be placed from the fulcrum of a lever to balance a $3.5\ \text{kg}$ object that is $90\ \text{cm}$ from the fulcrum?
3. What force should be applied at the end of a lever of total length $5\ \text{m}$ with a fulcrum at the midpoint to balance a mass of $30\ \text{kg}$ that is placed $2\ \text{m}$ from the other end? Draw a diagram to assist you.
4. You have a strong rigid iron rod of $1\ \text{m}$ in length. If you want to use the rod as a lever to lift a rock of $40\ \text{kg}$, where should you position the fulcrum if you push down on the opposite end of the rod with a force of $100\ \text{N}$? Draw a diagram to support your answer.

The full solutions are at the end of the unit.

Mechanical advantage

The mechanical advantage is a number that tells us how many times greater the output force is compared to the input force. Mechanical advantage is a measure of the ratio of output force (resistance force) in a system to the input force (effort force). It can also be determined using the ratio of the distance over which the resistance force moves to the distance over which the effort force acts. The formula can be derived by manipulating the formula for the law of simple machines.

$MA = \frac{F_r}{F_e} = \frac{d_e}{d_r}$ where:

MA is the mechanical advantage (no units, as it is a ratio)
F_e is the effort force (in N)
F_r is the resistance force (in N)
d_e is the distance the effort force moves (or distance of effort from the fulcrum)
d_r is the distance the resistance force moves (or distance of the load from the fulcrum).

Example 2.2

1. Calculate the mechanical advantage of a lever where the effort is $60\ \text{cm}$ from the fulcrum and the load is $20\ \text{cm}$ from the fulcrum.
2. If the input force on this lever is $100\ \text{N}$, what will the output force be?

Solutions

1. Step 1: Write down the given information
   $d_e = 60\ \text{cm}$
   $d_r = 20\ \text{cm}$

   Step 2: Write down the formula
   $$MA = \frac{d_e}{d_r}$$

   Step 3: Substitute values and calculate answer
   $$MA = \frac{60}{20} = 3$$
2. If the MA is 3, this means the output force is 3x the effort force. Therefore, the output force will be $3\ \text{x}\ 100 = 300\ \text{N}$

Exercise 2.2

1. Calculate the mechanical advantage of a lever if the input force is $25\ \text{N}$ and the output force is $125\ \text{N}$.
2. If the MA of a lever is 6 and the weight of the load is $300\ \text{N}$, calculate the effort force.
3. If the MA of a lever is 4, calculate the effort force to lift a mass of $10\ \text{kg}$.
4. What distance should the load be from the fulcrum to create a mechanical advantage of 2.5 on a lever when the effort force is $6\ \text{m}$?

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

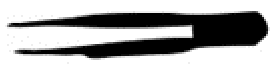
- In levers, the effort force is the force applied to move the load and the resistance force is the weight force of the load.
- The law of simple machines ($F_e\ \text{x}\ d_e = F_r\ \text{x}\ d_r$) can be used to calculate the mass/force required to balance a load or the position from the fulcrum where a force/mass should be placed to balance the load.
- In a 1st class lever, the fulcrum is in the middle.
- In a 2nd class lever, the load (resistance force) is in the middle.
- In a 3rd class lever, the effort (effort force) is in the middle.

- Mechanical advantage is how many times greater the output force in a simple machine is compared to the input force.
- Mechanical advantage can be calculated using the formula: $MA = \frac{F_r}{F_e} = \frac{d_e}{d_r}$.

Unit 2: Assessment

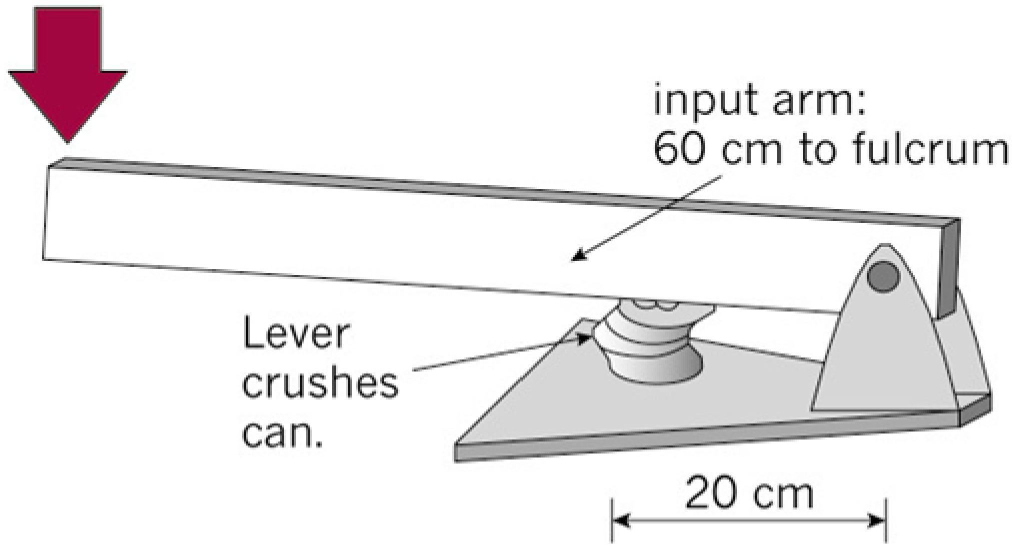
Suggested time to complete: 30 minutes

1. A wheelbarrow is used to lift a load of $50\ \mathrm{kg}$. The length from the wheel axis to the centre of the load is $1\ \mathrm{m}$ and the length from the wheel axis to the handle is $1.25\ \mathrm{m}$.
    a. Draw a diagram of this situation and identify the class of lever.
    b. Find the mechanical advantage of the system.
    c. Calculate the minimum effort force to lift the wheelbarrow.
2. One child of mass $30\ \mathrm{kg}$ sits $2\ \mathrm{m}$ from the fulcrum of a seesaw. Determine if the seesaw will be balanced if another child of mass $22\ \mathrm{kg}$ sits $2.5\ \mathrm{m}$ from the fulcrum on the other side. Draw a diagram of the system to support your answer.
3. Some tweezers (a 3rd class lever) are being used to remove a splinter. The length of the tweezers is $9\ \mathrm{cm}$.



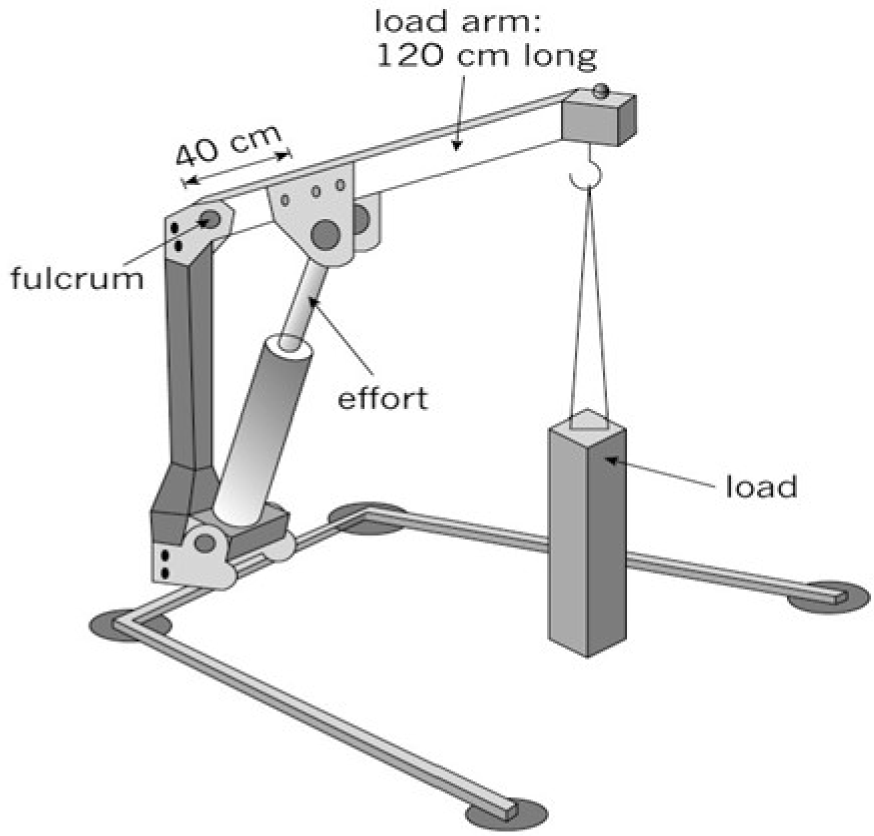
The splinter will break if the force on it is greater than $10\ \mathrm{N}$. If the fingers are placed $3\ \mathrm{cm}$ from the tip of the tweezers, what is the maximum, squeezing force that should be applied to remove the splinter? Draw a diagram to assist you with your answer.

4. Look at the lever below. The lever is pushed down to crush a can. The lengths of the input arm (d_e) and the output arm (d_r) are indicated.



    a. With the can in the position shown, calculate the mechanical advantage this lever will give.
    b. How do you know that this lever will crush a can more easily than by hand?
    c. The designer decides to make it even easier to crush the can. She moves the can closer to the fulcrum. This reduces the output arm to $15\ \mathrm{cm}$. Recalculate the mechanical advantage of the lever.
5. Look at the lifting system illustrated below. It uses a hydraulic cylinder for the input force. It is a system

that could be used for lifting an engine out of a motorcar. The lifting lever at the top is a 3rd class lever, because the input is between the fulcrum and the output. A 3rd class lever always gives a distance advantage. It never gives a mechanical advantage.



a. How long is the input arm on this lever?

b. How long is the output arm?

c. Calculate the mechanical advantage that this lever gives.

d. Explain what this MA value indicates about the output force (F_r) compared to the input force (F_e).

e. A person wants to use this system to lift an engine out of a car. He needs the engine to be lifted by $90\ \text{cm}$. How far will the hydraulic cylinder at the input need to move for the engine to be lifted $90\ \text{cm}$ at the output?

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

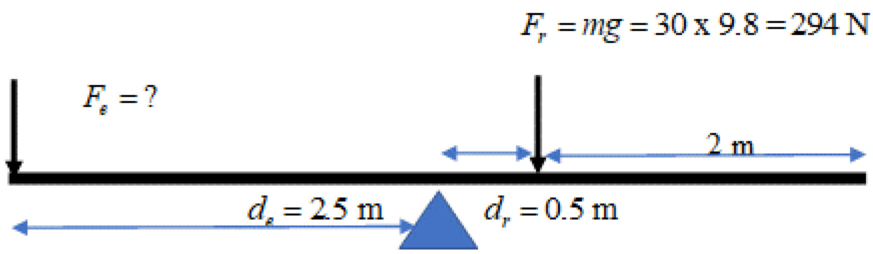
1.

$$F_e \text{ x } d_e = F_r \text{ x } d_r$$
$$F_e \text{ x } 1.5 = 60 \text{ x } 2$$
$$F_e = 80 \text{ kg}$$

2.

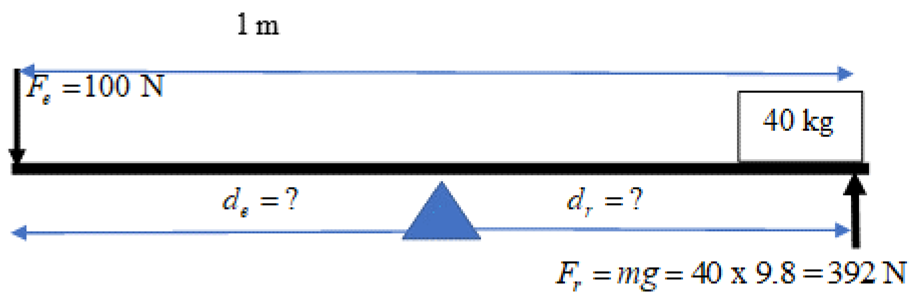
$$F_e \text{ x } d_e = F_r \text{ x } d_r$$
$$3.5 \text{ x } 90 = 1 \text{ x } d_r$$
$$d_r = 315 \text{ cm}$$

3.



$$F_e \text{ x } d_e = F_r \text{ x } d_r$$
$$F_e \text{ x } 2.5 = 294 \text{ x } 0.5$$
$$F_e = 58.8 \text{ N}$$

4.



$$F_e \text{ x } d_e = F_r \text{ x } d_r$$
$$100 \text{ x } d_e = 392 \text{ x } d_r$$
$$\text{but } d_e + d_r = 1 \text{ m, so } d_e = 1 - d_r$$
$$100 \text{ x } (1 - d_r) = 392 \text{ x } d_r$$
$$100 - 100d_r = 392d_r$$
$$100 = 492d_r$$
$$d_r = 0.203 \text{ m}$$

The fulcrum must be placed 0.203 m from the rock.

Back to Exercise 2.1

Exercise 2.2

1.

$$MA = \frac{F_r}{F_e} = \frac{125}{25} = 4$$

2.

$$MA = \frac{F_r}{F_e}$$
$$6 = \frac{300}{F_e}$$
$$F_e = 50 \text{ N}$$

3.

$F_g = mg = 10 \text{ x } 9.8 = 98 \text{ N}$

$MA = \frac{F_r}{F_e}$

$4 \ = \frac{98}{F_e}$

$F_e = \frac{98}{4}$

$= 24.5 \text{ N}$

4.

$MA = \frac{d_e}{d_r}$

$2.5 \ = \frac{6}{d_r}$

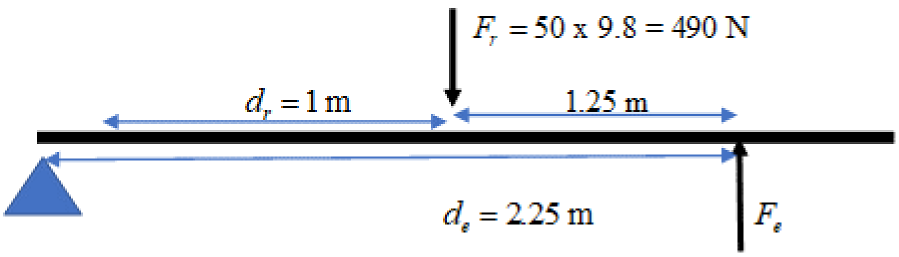
$d_r = 2.4 \text{ m}$

Back to Exercise 2.2

Unit 2: Assessment

1.

a.



b.

$MA = \frac{d_e}{d_r} = \frac{2.25}{1} = 2.25$

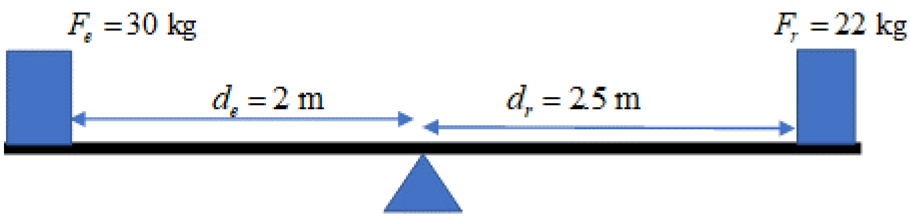
c.

$F_e \text{ x } d_e = F_r \text{ x } d_r$

$F_e \text{ x } 2.25 = 490 \text{ x } 1$

$F_e = 392 \text{ N}$

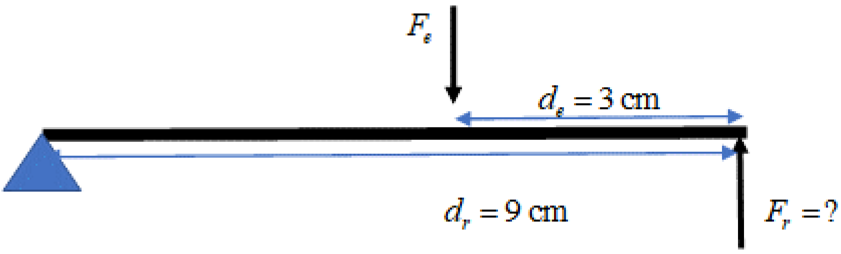
2.



F_e x d_e = 30 x 2 = 60
F_r x d_r = 22 x 2.5 = 55
F_e x $d_e \neq F_r$ x d_r

The seesaw will not be balanced.

3.



F_e x d_e = F_r x d_r
F_e x 3 = 10 x 9
F_e = 30 N

4.

a. $MA = \frac{d_e}{d_r} = \frac{60}{20} = 3$

b. MA indicates that the output force of the lever is 3 times that of the input force (force of the hand). Less force is required from the hand therefore it will be easier with the lever.

c. $MA = \frac{d_e}{d_r} = \frac{60}{15} = 4$

5.

a. 40 cm

b. 120 cm

c. $MA = \frac{d_e}{d_r} = \frac{40}{120} = 0.33$

d. The output force is less than the input force.

e.

$$MA = \frac{d_e}{d_r}$$
$$0.33 = \frac{d_e}{90}$$
$$d_e = 30 \text{ cm}$$

Back to Unit 2: Assessment

Media Attributions

Unit 3: Mechanical advantage of simple machines

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Define ideal mechanical advantage (IMA) as the ratio between the distance through which the effort force moves an object and the distance through which the resistance force moves an object: IMA = distance effort force ÷ distance resistance force.
- Define actual mechanical advantage (AMA) as the ratio between the resistance force and the effort force: AMA = resistance force ÷ effort force.
- Calculate the relative efficiency of a simple machine: efficiency (%) = (AMA ÷ IMA) x 100.

What you should know

Before you start this unit, make sure you can:

- Identify levers as simple machines, as covered in Subject outcome 2.4, Unit 1.
- Calculate mechanical advantage, as covered in Subject outcome 2.4, Unit 2.

Introduction

In the previous unit, you learnt to calculate the mechanical advantage of levers as simple machines. These calculations are theoretical and do not take friction, flexing or wear-and-tear into account. In this unit we will learn how these factors can affect the output of a simple machine. We will also learn about the difference between ideal mechanical advantage (IMA) and actual mechanical advantage (AMA), and how to apply your knowledge to calculate the efficiency of various simple machines.

Ideal mechanical advantage

The ideal mechanical advantage (IMA) is the mechanical advantage of a device with the assumption that its components do not flex, there is no friction, and there is no wear-and-tear. It is calculated using the physical dimensions of the device and defines the maximum performance the device can achieve. It is a theoretical value calculated using the formula:

$$IMA = \frac{d_e}{d_r}$$

where:
d_e is the distance of the effort force
d_r is the distance of the resistance force

In reality, a machine will dissipate energy to overcome friction as surfaces move over each other causing wear-and-tear, heat, and sound. This calculation will therefore not reflect the actual output of the machine.

Example 3.1

A box is lifted using a lever. The distance of the box from the fulcrum is $1.5\ \mathrm{m}$ and the effort force is applied at $2.5\ \mathrm{m}$ from the fulcrum. Calculate the ideal mechanical advantage of this simple machine.

Solution

Step 1: Write the formula for ideal mechanical advantage

$$IMA = \frac{d_e}{d_r}$$

Step 2: Substitute the given values

$$IMA = \frac{2.5}{1.5}$$

Step 3: Write the answer

$$IMA = 1.67$$

Actual mechanical advantage

Actual mechanical advantage (AMA) is calculated using actual measurements of the output of a machine. The actual mechanical advantage will always be less than the ideal mechanical advantage. The formula used for actual mechanical advantage is:

$$AMA = \frac{F_r}{F_e}$$

where:
F_r is the resistance force
F_e is the effort force

Example 3.2

A box of mass $500\ \mathrm{kg}$ is lifted using a lever. The applied force is $3\ 000\ \mathrm{N}$. Calculate the actual mechanical advantage of this simple machine.

Solution

Step 1: Calculate the resistance force

This is the weight of the box

$F_g = mg$

$= 500 \text{ x } 9.8$

$= 4\ 900 \text{ N}$

Step 2: Write the formula for actual mechanical advantage

$$AMA = \frac{F_r}{F_e}$$

Step 3: Substitute the given values

$$AMA = \frac{4\ 900}{3\ 000}$$

Step 4: Write the answer

$AMA = 1.63$

Efficiency of simple machines

Efficiency is a measure of how well a machine can perform. To calculate the efficiency of a machine, we look at the ratio of the actual mechanical advantage to the ideal mechanical advantage and then convert it to a percentage:

$$\text{efficiency} = \frac{AMA}{IMA} \text{ x } 100$$

A high percentage efficiency indicates a machine with a high output and little energy 'lost' to heat or sound. Whereas a machine with a low percentage efficiency will have a low output with much energy transformed into heat or sound.

Example 3.3

A box with a weight of $2\ 500 \text{ N}$ is placed at a distance of 1.25 m from the fulcrum of a lever. It is lifted using an applied force of $1\ 300 \text{ N}$ acting at 2.75 m from the fulcrum at the other end of the lever. Calculate the efficiency of this simple machine.

Solution

Step 1: Calculate the actual mechanical advantage

$AMA = \frac{F_r}{F_e}$

$= \frac{2\ 500}{1\ 300}$

$= 1.92$

Step 2: Calculate the ideal mechanical advantage

$$IMA = \frac{d_e}{d_r}$$
$$= \frac{2.75}{1.25}$$
$$= 2.2$$

Step 3: Write formula for efficiency of simple machines

$$\text{efficiency} = \frac{AMA}{IMA} \text{ x } 100$$

Step 4: Substitute values

$$\text{efficiency} = \frac{1.92}{2.2} \text{ x } 100$$

Step 5: Write the answer

87.27%

Summary

In this unit you have learnt the following:

- Machines do not produce a theoretical output because not all energy is transformed into useful work during their operation.
- Ideal mechanical advantage (IMA) is the theoretical calculation of the maximum possible output of a machine.
- Actual mechanical advantage (AMA) is the measurement of the actual output of the machine.
- Actual mechanical advantage will always be less than ideal mechanical advantage because some work is done to overcome friction and is transformed into heat and sound.
- Efficiency is an indication (in a percentage) of the ratio between the IMA and the AMA.

Unit 3: Assessment

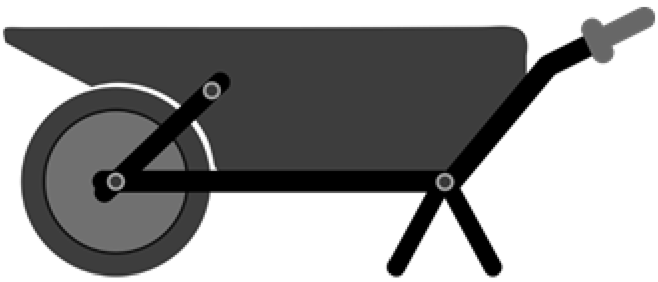
Suggested time to complete: 15 minutes

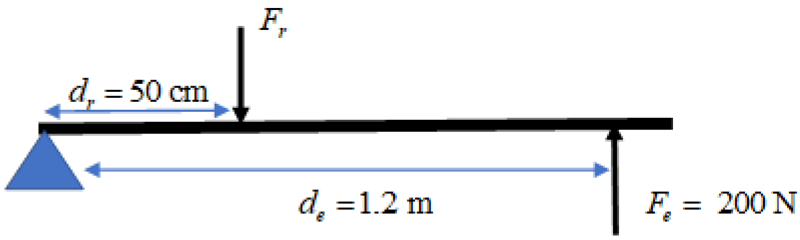
1. In an acrobatic demonstration, one person jumps onto the end of a plank (lever). This creates a large effort force of magnitude $9.2 \text{ x } 10^2 \text{ N}$ at the end of the board at a distance of 1.7 m from the fulcrum. A smaller person (with a load force of $4.6 \text{ x } 10^2 \text{ N}$) located 3.1 m away from the fulcrum) moves a larger distance and high enough to perform acrobatic moves.

   Calculate:
   a. the AMA of the board
   b. the IMA of the board
   c. the efficiency of the system.
2. The input force of 15 N acting on the effort arm of a lever moves 0.4 m. This lifts a 40 N weight, resting on the resistance arm, a distance of 0.1 m
   a. Explain why the AMA of a machine is generally less than its IMA.

b. What is the efficiency of the machine?

3. A wheelbarrow is 75 efficient. Use the information in the diagram to calculate the mass of the load in the wheelbarrow.





The full solutions are at the end of the unit.

Unit 3: Solutions

Unit 3: Assessment

1.
$F_e = 9.2 \text{ x } 10^2 \text{ N}$
$d_e = 1.7 \text{ m}$
$F_r = 4.6 \text{ x } 10^2 \text{ m}$
$d_r = 3.1 \text{ m}$

a. $AMA = \frac{F_r}{F_e} = \frac{4.6 \text{ x } 10^2}{9,2 \text{ x } 10^2} = 0.5$

b. $IMA = \frac{d_e}{d_r} = \frac{1.7}{3.1} = 0.55$

c. $Efficiency = \frac{AMA}{IMA} \text{ x } 100 = \frac{0.5}{0.55} \text{ x } 100 = 91\%$

2.
$F_e = 15 \text{ N}$
$d_e = 0.4 \text{ m}$
$F_r = 40 \text{ N}$
$d_r = 0.1 \text{ m}$

a. Not all the input energy is converted to output energy. Some energy is transformed to heat and sound because of friction.

b. $AMA = \frac{F_r}{F_e} = \frac{40}{15} = 2.67$

$IMA = \frac{d_e}{d_r} = \frac{0.4}{0.1} = 4$

$Efficiency = \frac{AMA}{IMA}$ x $100 = \frac{2.67}{4}$ x $100 = 67\%$

3. $IMA = \frac{d_e}{d_r} = \frac{1.2}{0.5} = 2.4$

$Efficiency = \frac{AMA}{IMA}$ x 100

$75 = \frac{AMA}{2.4}$ x 100

$AMA = 1.8$

$AMA = \frac{F_r}{F_e}$

$1.8 = \frac{F_r}{200}$

$F_r = 360$ N

$F_g = mg$

$360 = m$ x 9.8

$m = 36.73$ kg

[Back to Unit 3: Assessment]

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SUBJECT OUTCOME V

WAVES, SOUND AND LIGHT: IDENTIFY, DESCRIBE AND APPLY PRINCIPLES OF WAVES

Subject outcome

Subject outcome 3.1: Identify, describe and apply principles of waves.

Learning outcomes

- Identify and describe vibration and oscillation as a periodic motion.
- Define period, frequency and amplitude.
- Define a wave and identify different examples.
- Describe the nature of waves. (A disturbance that travels and not the medium or energy that is carried or transferred.)
- Distinguish between the two categories of waves, longitudinal and transverse, and identify examples.
- Identify particle position on graphs showing displacement to illustrate difference between longitudinal and transverse waves.
- Draw, label and interpret a displacement-position graph of a simple harmonic wave showing wavelength and amplitude.
- Calculate frequency, period and wave speed and wavelength of a transverse wave.
- Describe the effect of medium on wave speed.
- Distinguish between standing and moving waves.
- Identify and describe superposition in standing waves.

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify and describe vibration and oscillation as a periodic motion.
- Describe the nature of waves.
- Define and identify a wave.
- Define the concepts period, frequency and amplitude.

Unit 2 outcomes

By the end of this unit you will be able to:

- Distinguish between the two categories of waves, namely longitudinal and transverse.
- Identify examples of longitudinal and transverse waves.
- Identify particle position on graphs showing displacement to illustrate the difference between longitudinal and transverse waves.
- Draw, label and interpret a displacement-position graph of a simple harmonic wave showing wavelength and amplitude.

Unit 3 outcomes

By the end of this unit you will be able to:

- Calculate frequency, period, wave speed and wavelength of a transverse wave.
- Describe the effect of the medium on wave speed.

Unit 4 outcomes

By the end of this unit you will be able to:

- Distinguish between standing and moving waves.
- Identify and describe superposition in standing waves.

Unit 1: Properties of waves

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Unit outcomes

By the end of this unit you will be able to:

- Identify and describe vibration and oscillation as a periodic motion.
- Describe the nature of waves.
- Define and identify a wave.
- Define the concepts period, frequency and amplitude.

Introduction

In this unit[1] you will learn what a wave is and about the basic concepts that describe wave motion. Understanding these concepts forms the foundation of all the work you will do on waves in later units.

What is a wave?

Waves occur frequently in nature. The most obvious examples are waves in water, on a dam, in the ocean, or in a bucket. But waves do not only occur in water. For example, during an earthquake energy travels as a wave through rock. When your friend speaks to you, sound waves are produced that travel through the air to your ears.

In physics, we are interested in the properties of waves. All waves have the same properties. Activity 1.1 will help you to start thinking about how we can define a wave.

Activity 1.1: Observe waves

Time required: 5 minutes

What you need:

- an internet connection
- a phone with a QR scanner

1. Parts of the text in this unit were sourced from [Siyavula Physical Science Gr 10 Learner's Book, p. 139–156](), released under a CC-BY licence.

- a notebook and a pen

What to do:

1. Watch these three video clips showing wave motion.
   - Video clip 1
   - Video clip 2
   - Video clip 3
2. Note down what you observe about the wave motion in each clip to help you describe what a wave is. You may have to watch the clips a few times.

What did you find?

- Video clip 1 shows that a wave travels. However, we can see that it is not the water itself that travels forward, but rather that consecutive sections of the water are displaced and then fall back down again. This suggests that what we see as a wave form is energy travelling through the water. You can see this easily by watching the motion of one of the surfers lying on their boards, not riding the wave.
- Video clip 2 shows that waves form at regular intervals and that their crests are displaced at the same height above the still water level in each one. The continuous movement is also shown here.

- Video clip 3 shows waves forming when the surface of the water is disturbed.

A good working definition of a wave, based on our observations from the three video clips in Activity 1.1, is that a wave is a regular disturbance that takes place in a medium, resulting in a transfer of energy through the medium.

There are four important things to remember:

- A wave forms as the result of a *medium* being disturbed.
- In a wave, *energy* is transferred, not the medium itself.
- A wave is a regular disturbance, unlike a pulse, which is a single disturbance.
- Because the disturbance occurs repeatedly at regular intervals, a wave is described as a continuous, periodic motion.

Formally, a wave is therefore defined as follows:

A wave is a periodic, continuous disturbance that consists of a train of pulses.

Waves can be described as being either transverse or longitudinal, depending on the direction of the disturbance of the medium relative to the direction in which the wave travels. You will learn more about the two types of waves in Unit 2.

Properties of wave motion

All waves, regardless of the type of wave, have characteristic properties that describe their motion. It is useful to know what these properties are to understand how waves behave. Activity 1.2 will help you to visualise the basic properties of a wave.

Activity 1.2: Create a wave

Time required: 5 minutes

What you need:

- a piece of rope (approx. $2\ \text{m}$ long)
- a piece of coloured ribbon
- a notebook and a pencil

What to do:

1. Put the rope on an even surface, for example a floor or a long work bench.
2. Tie the one end of the rope to a fixed point slightly above the floor or even surface. Alternatively, ask a friend or someone at home to hold the other end of the rope. Make sure that the rope is

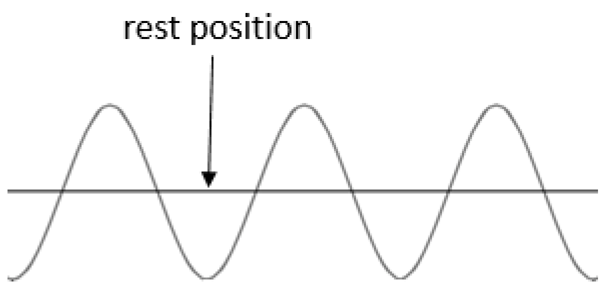
quite loose and free to move on the other end.

3. Hold the rope loosely (in other words, do not pull it tight), and then flick the rope up once. What do you observe? Draw a diagram in your notebook.
4. Return the rope to the starting position (as in step 3). Flick the rope up and down continuously, trying to achieve a regular rhythm. Describe what you observe now.
5. Trace the movement of the wave in your notebook.
6. Repeat step 4 a few times, trying to alter the speed at which the wave moves or the height of the disturbance. Note down your observations.
7. Now tie the ribbon along the middle of the rope.
8. Create a wave along the rope again. Watch the ribbon carefully as the pulses travel through the rope. Describe what happens to the ribbon.

If you cannot do this activity yourself, watch the video called Making waves (Duration: 00.12).

What did you find?

As your hand moved up and down, a wave formed along the rope. The rope rose above its rest position and then dipped down below the rest position. Each pulse had the same shape and height and formed repeatedly along the length of the rope. The trace in your notebook probably looks something like this:



The wave would have reached the end of the rope faster if your initial disturbance was fast rather than slow. The height of the peaks and dips would have changed depending on how hard you shook the rope. The ribbon represented the (particles of the) medium in which the wave travels. You would have noticed that the wave travelled from one side to the other, but that the particles (the ribbon) moved only up and down. This shows that energy is transferred in a wave, but not the medium itself.

The characteristic properties of waves are easily observed in a transverse wave, as you formed in Activity 1.2.

In a wave, the particles of the medium form alternating sections of maximum displacement from the rest position. In a transverse wave (as you formed in Activity 1.2), these sections are called **crests** and **troughs**. A crest is the highest point the medium rises to and a trough is the lowest point the medium sinks to, relative to the rest position.

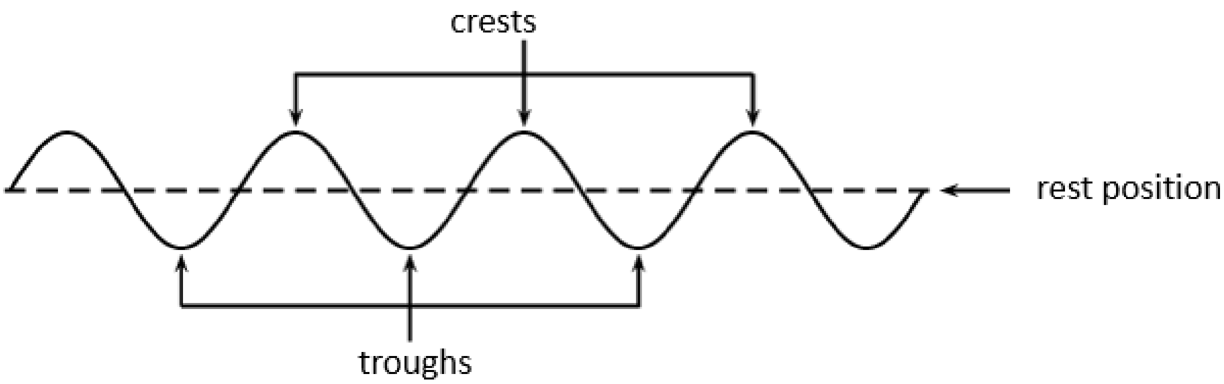


Figure 1: Crests and troughs in a wave

The **rest position** is the position where the particles of a medium would be if there was no disturbance. The rest position can also be called the equilibrium position. The **amplitude** of the wave is the distance between the point of the medium's maximum displacement and the rest position. The amplitude is equal on either side of the rest position.

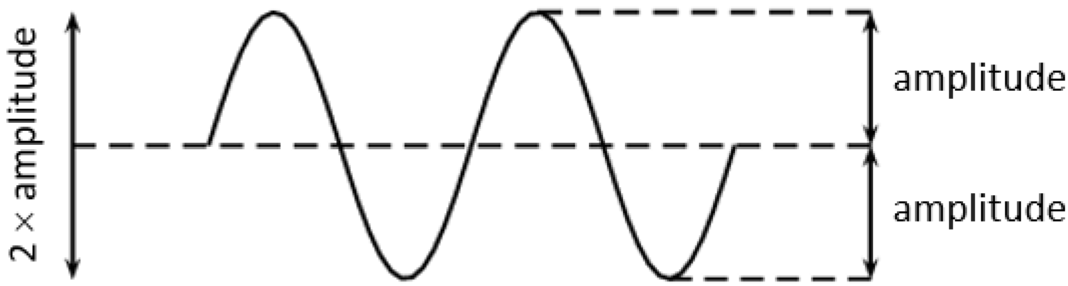


Figure 2: Amplitude in a wave

The **wavelength** is the distance between any two consecutive points on a wave that are in phase. For example, in a transverse wave the wavelength is the horizontal distance between two consecutive troughs or two consecutive peaks. We use the symbol λ (the Greek letter *lambda*) to denote wavelength. Wavelength is measured in metres (m).

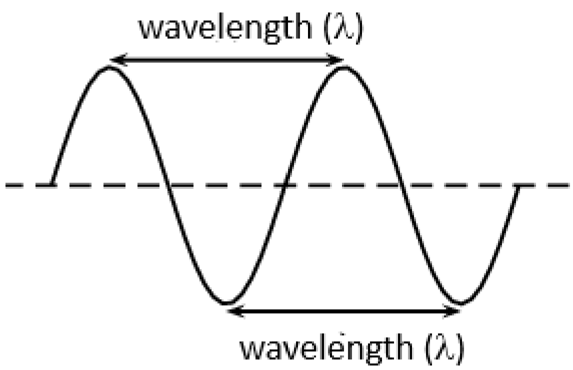


Figure 3: Wavelengths in a wave

Positions on a wave that have a whole number of wavelengths between them are **in phase** with each other. For example, all the points shown by the dots of the same colour are in phase.

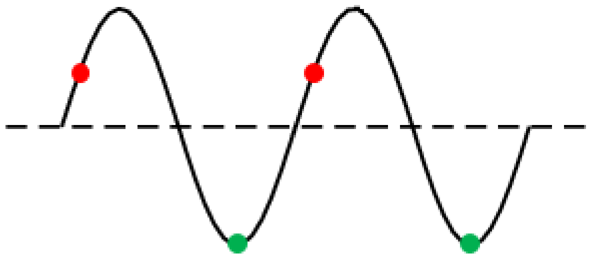


Figure 4: Positions on a wave that are in phase

In a wave, the particles of the medium vibrate (from side to side, or up and down). They do not move forward with the wave; it is the energy that moves forward through the medium. We say the wave propagates through the medium as it travels.

Note

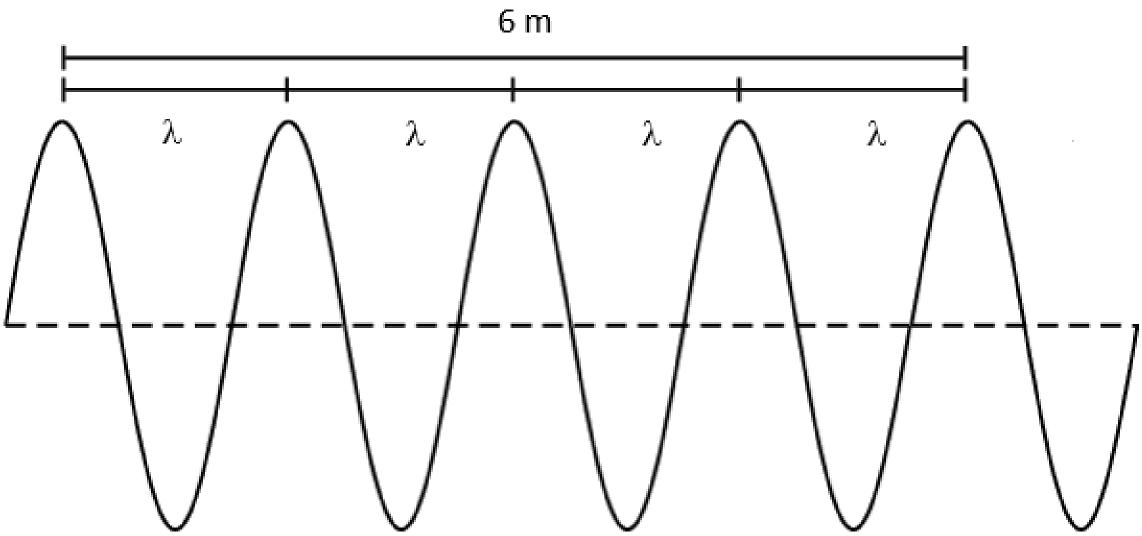
The properties described here also apply to longitudinal waves, as you will learn in Unit 2, although the terms crest and troughs do not apply.

Example 1.1

1. The total distance between 5 consecutive crests of an ocean wave is $6\ \text{m}$. What is the wavelength of the wave?
2. If the crest of a wave measures $2\ \text{m}$ above the still-water mark in the harbour, what is the amplitude of the wave?

Solutions

1. By drawing a rough sketch of the situation, we see that 5 consecutive crests represent 4 full wavelengths.



If the total distance for 4 wavelengths is $6\ \mathrm{m}$, it means that one wave is $\frac{6\ \mathrm{m}}{4} = 1.5\ \mathrm{m}$ long.

2. The still-water mark in the harbour represents the rest position. If a crest measures $2\ \mathrm{m}$ above that point, it means the amplitude is $2\ \mathrm{m}$.

Period and frequency

The **period** (*T*) of a wave is the time that it takes for a full wavelength to pass a fixed point, measured in seconds (s). The **frequency** (*f*) of a wave is the number of full wavelengths that pass a fixed point in one second. Frequency is measured in units per second (/s or s^{-1}), which is also called hertz (Hz).

The period is mathematically related to the frequency: $T = 1 \div f$. You can write this as $T = \frac{1}{f}$.

Frequency is the inverse of the period: $f = \frac{1}{T}$.

Example 1.2

What is the period of a wave of frequency $10\ \mathrm{Hz}$?

Solution

We know that period and frequency are inversely related to each other:

$$\begin{aligned} T &= \frac{1}{10\ \mathrm{s}^{-1}} \\ &= 0.1\ \mathrm{s} \end{aligned}$$

Summary

In this unit you have learnt the following:

- A wave is formed when continuous pulses are transmitted through a medium.
- The amplitude is the maximum displacement of a particle in a wave from its rest position.
- The wavelength (λ) is the distance between any two adjacent points on a wave that are in phase. It is measured in metres.
- The period (*T*) of a wave is the time it takes one wavelength to pass a fixed point. It is measured in seconds (s): $T = \frac{1}{f}$
- The frequency (*f*) of a wave is the number of waves that pass a point in a second. It is measured in hertz (Hz) or s^{-1}. It is the inverse of the period: $f = \frac{1}{T}$

Note

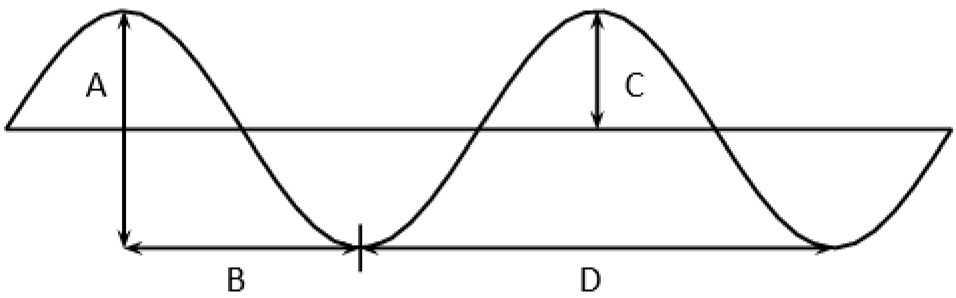
Watch the video called Wave motion for a quick recap of wave motion and the properties of waves (Duration: 03.38).

Unit 1: Assessment

Suggested time to complete: 20 minutes

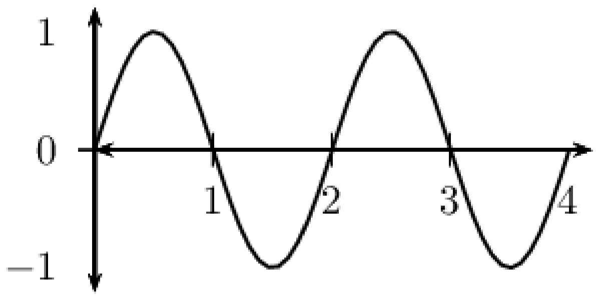
Questions were sourced from exercises and examples in Siyavula Physical Science Gr 10 Learner's Book, p. 139–155, released under a CC-BY licence.

1. Consider the diagram below and answer the questions that follow:

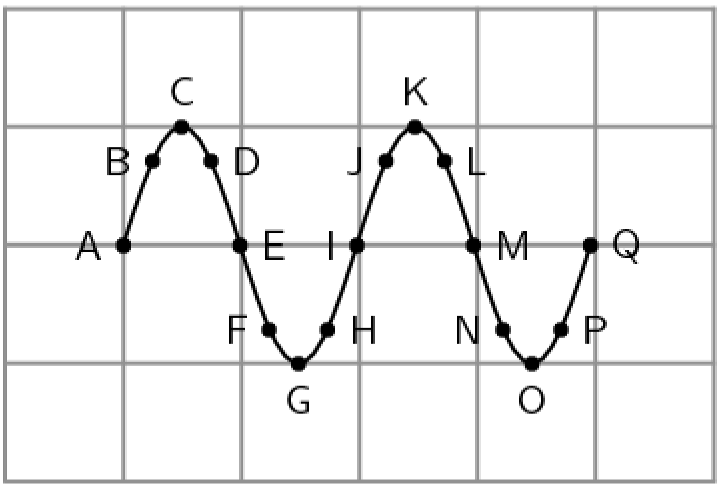


   a. Which letter represents the wavelength?
   b. Which letter represents the amplitude?

2. Consider the wave shown in the diagram:



   a. How long would a wavelength of a wave be if it is twice the length shown for this wave?
   b. What would the amplitude of a wave be if it is half of what is shown for this wave?
3. A fly flaps its wings back and forth 200 times each second. Calculate the period of a wing flap.
4. Choose the correct option to complete the sentence:
   As the period of a wave increases, the frequency increases/decreases/does not change.
5. A microwave oven produces radiation with a frequency of 2.45 gigahertz (GHz). A cell phone requires signals to be transmitted at 450 megahertz (MHz). Which device is associated with waves with a shorter period?
6. Study the following diagram and answer the questions:



   a. Identify two sets of points that are in phase.
   b. Identify two sets of points that are out of phase.
   c. Identify any two points that would indicate a wavelength.

The full solutions are at the end of the unit.

Unit 1: Solutions

Unit 1: Assessment

1.
   a. D
   b. C
2.

a. 4 units

b. 0.5 units

3. One back-and-forth movement represents one cycle (i.e. one wave). Therefore, 200 back-and-forth movements per second represent 200 waves per second. This is the frequency. To calculate the period:

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{200} \\ &= 0.005 \text{ s} \end{aligned}$$

It therefore takes the fly 0.005 seconds to complete one back-and-forth movement.

4. decreases

5. For the microwave oven:

$1 \text{ GHz} = 1 \times 10^9 \text{ Hz}$. Therefore, $2.45 \text{ GHz} = 2.45 \times 10^9 \text{ Hz}$.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{2.45 \times 10^9} \\ &= 4.08 \times 10^{-10} \text{ s} \end{aligned}$$

For the cell phone:

$1 \text{ MHz} = 1 \times 10^6 \text{ Hz}$. Therefore, $450 \text{ MHz} = 4.5 \times 10^8 \text{ Hz}$.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{4.5 \times 10^8} \\ &= 2 \times 10^{-9} \text{ s} \end{aligned}$$

The waves used in cell phone communication therefore have a longer period than those produced by a microwave oven.

6.

a. Any of two sets of the following: A and I; I and Q; C and K; E and M; D and L; H and P; G and O; F and N; B and J.

b. Any two pairs not listed in (a), for example: A and E; C and G; B and D, etc.

c. A wavelength is defined as the distance between any two points of a wave that are in phase. Therefore, any of the pairs listed in (a) will indicate a wavelength.

Back to Unit 1: Assessment

Media Attributions

Unit 2: Types of waves

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Unit outcomes

By the end of this unit you will be able to:

- Distinguish between the two categories of waves, namely longitudinal and transverse.
- Identify examples of longitudinal and transverse waves.
- Identify particle position on graphs showing displacement to illustrate the difference between longitudinal and transverse waves.
- Draw, label and interpret a displacement-position graph of a simple harmonic wave showing wavelength and amplitude.

What you should know

Before you start this unit, make sure you can:

- Describe the nature of a wave, as covered in Subject outcome 3.1, Unit 1.
- Describe the properties of a wave, especially the concepts period, frequency and amplitude, as covered in Subject outcome 3.1, Unit 1.

Introduction

In this unit[1] you will learn about the difference between two types of waves, namely transverse and longitudinal waves. You will apply your knowledge about general wave properties to draw and interpret graphical representations of these waves.

Different types of wave motion

You already know that a wave is defined as a periodic, continuous disturbance that consists of a train of pulses. From your observations in the activities in Unit 1, you will recall that a wave requires a medium in which to propagate. However, the wave motion is caused by *energy* travelling through the medium, not the particles of the medium themselves. So at any one position along the wave's path, the medium merely experiences a momentary disturbance from its original position.

We can describe the type of wave motion by considering the direction of the disturbance of the medium

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 8 and Chapter 9, p. 139–165, released under a CC-BY licence.

relative to the direction in which the wave travels. This is the fundamental difference between the two types of wave motion, namely transverse and longitudinal.

Transverse waves

In Activity 1.2 in Unit 1, you learnt about the general properties of wave motion by observing how a wave propagates along a rope that was fixed at one end while being flicked up and down at the free end. The resulting wave form is described as a transverse wave, because the disturbance of the medium was perpendicular to the direction in which the wave propagated. In other words, the displacement of the medium was in a vertical direction, but the wave travelled in a horizontal direction. Waves that form in water, like in a dam or in the ocean, are examples of transverse waves.

A transverse wave is a wave in which the movement of the particles of the medium is perpendicular to the direction of propagation of the wave.

Properties of a transverse wave

To understand wave behaviour, it is useful to revise the properties of waves. You can do this by, observing a transverse wave.

Activity 2.1: Observe a transverse wave

Time required: 10 minutes

What you need:

- an internet connection
- a phone with a QR scanner
- a notebook and a pencil

What to do:

1. Watch the video called Transverse wave (Duration: 00.09). Notice the three coloured ribbons on the string that represent three different particles in the medium.
2. Sketch the wave form seen in the video in your notebook.
3. Describe the motion of one of the particles (coloured ribbons) over the course of the motion.
4. Now watch the video again, but play it frame by frame from time stamp 00.03.

a. Pause the video after 10 frames. Compare the displacement of the three particles from the rest position at this time.

b. Play a few more frames and then pause the video again. Describe how each particle's displacement has changed from before.

c. At this point, also compare one particle's displacement to that of the other two.

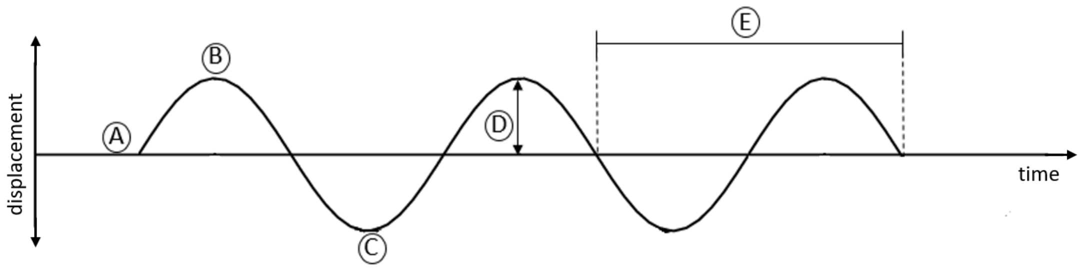
5. Keep playing the video frame by frame, but focus only on the displacement of the blue ribbon (in the middle). Describe its displacement over the course of approximately 30 frames.

Note

You can watch the video frame by frame in Windows Media Player by holding down the Ctrl key and then pressing the 'play' button repeatedly.

What did you find?

- The video shows that the particles are displaced in a vertical direction, while the wave moves in a horizontal direction. In other words, the displacement of the medium is perpendicular to the direction in which the wave travels. This is a transverse wave, and the sketch in your notebook should look similar to this diagram.



- If we consider this sketch to represent the motion of a single particle over time, it illustrates the following properties of a transverse wave.
    - A: The **rest position** is the position where the particles of a medium would be if there was no disturbance.
    - B: The **crest** is the highest point of displacement above the rest position.
    - C: The **trough** is the lowest point of displacement below the rest position, and is equal to the height of the crest.
    - D: The **amplitude** is the maximum height of the disturbance from the rest position.
    - E: The **wavelength** is the distance between any two consecutive points on a wave that are in phase.
- When you focused only on the blue ribbon, you would have seen that as the energy reaches a particle (the ribbon) at a specific position along the medium, the particle is displaced above its rest position. It continues in this upward direction until it reaches its maximum displacement above the rest position, and then incrementally starts moving downwards. It continues in this direction downward until it reaches a maximum displacement below the rest position. It then incrementally starts moving upwards again, back to the rest position, and the cycle continues. Although the particle's vertical position from the rest position changes, its horizontal position remains unchanged.
- You would also have seen that the particles are not all at the same displacement at a fixed time. This is because a different amount of energy has been transferred to them at that specific moment. Particles on either side of the one you are focussing on will be less displaced because the

energy of the wave has either moved past the earlier particle already or is yet to reach the particle further along the medium.

- This pattern of displacement continues as long as the wave propagates along the medium.

Note

Refer back to Unit 1 to revise these properties of wave motion.

To visualise a particle's position over time in a transverse wave, we can plot displacement against time on a graph. Watch this animation to see how a graph of transverse wave motion develops.

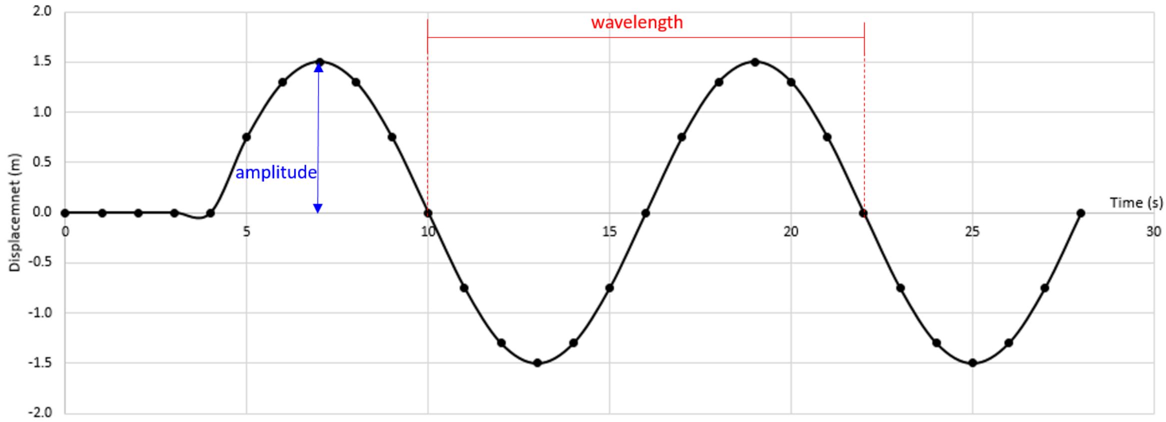
Run through the animation once at normal speed, and then run it stepwise using the 'forward step' button to see how the displacement time graph develops.

Example 2.1

1. Use the data in the table to draw a graph that shows how a *single* particle's position changes in a transverse wave as the wave moves through the medium.
   Remember: The particle does not move horizontally.
2. Indicate the wavelength on the graph.
3. Indicate the wave's amplitude on the graph.
4. Does the graph represent a particle at the start of the wave motion or one some distance from the starting position? Give the reason for your answer.
5. Describe the displacement of a particle that is half a wavelength to the right of the particle represented by this graph. Explain your reasoning.

Solutions

1. – 3. The wave form is shown below. The wavelength is shown in red. The amplitude is shown in blue.



4. The graph shows no displacement of particles for some time. This shows that the energy reached the particle only after some time, which means that the particle was some distance away from the start of the wave motion.
5. A particle that is half a wavelength to the right of the particle presented by this graph will be displaced later. That means its wave form will be shifted half a wavelength to the right.

Longitudinal waves

When we studied transverse waves, we looked at two different motions: the motion of the particles of the medium and the motion of the wave itself. We can follow the same approach to illustrate the properties of a longitudinal waves.

In a longitudinal wave, the particles of the medium move parallel to the motion of the wave – in other words, in the same direction as which the wave travels. An example of a longitudinal wave is a sound wave. It is difficult to observe a sound wave visually, though. A slinky spring is useful in illustrating the properties of a longitudinal wave, as you will see in Activity 2.2.

A longitudinal wave is a wave in which the movement of the particles of the medium is parallel to the direction of propagation of the wave.

Activity 2.2: Investigate longitudinal waves

Time required: 10 minutes

What you need:

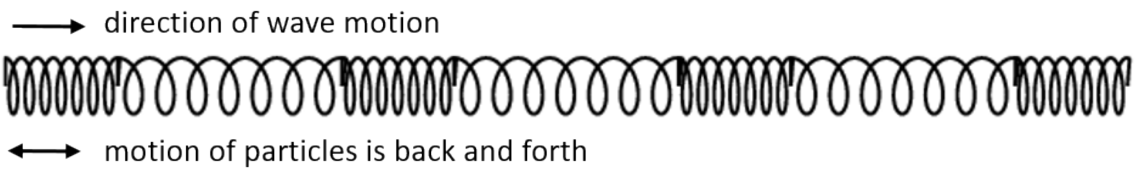
- a slinky spring
- a notebook and a pencil

What to do:

1. Take a slinky spring and lay it on a flat surface.
2. Hold one end and pull the free end of the spring and push it away from you and then pull it back towards you. Observe what happens.
3. Now tie a ribbon to one coil in the middle of the spring.
4. Pull the free end of the spring back and forth again and observe the motion of the ribbon.
5. Then pull the spring back and forth continuously to set up a train of pulses (in other words, a wave). In your notebook, draw the motion of the wave.

What did you find?

- When you pulled the slinky spring backwards and forwards, the disturbance of the individual coils occurred in the same direction as the direction of the pulling motion.
- The ribbon represented a particle of the medium. From the demonstration, you could see that the particles of the medium move in the same plane as the wave (the direction of the energy) in a longitudinal wave.
- The wave motion you observed should look similar to the diagram shown here. The diagram shows that, as the energy travels through the medium, the particles of the medium are squeezed together in some areas and spread out in other areas. This forms a periodic pattern.



Properties of a longitudinal wave

Activity 2.2 demonstrated that the properties of a longitudinal wave are similar to a transverse wave; a longitudinal wave also involves a repeating pattern of the medium being displaced from its rest position. However, instead of the medium being displaced vertically above or below the rest position, the particles of the medium are squeezed closer together or spread out further apart along the plane of the rest position in a longitudinal wave.

A region in a longitudinal wave where the particles of the medium are squeezed together is called a **compression**.

A region in a longitudinal wave where the particles of the medium are spread out is called a **rarefaction**.

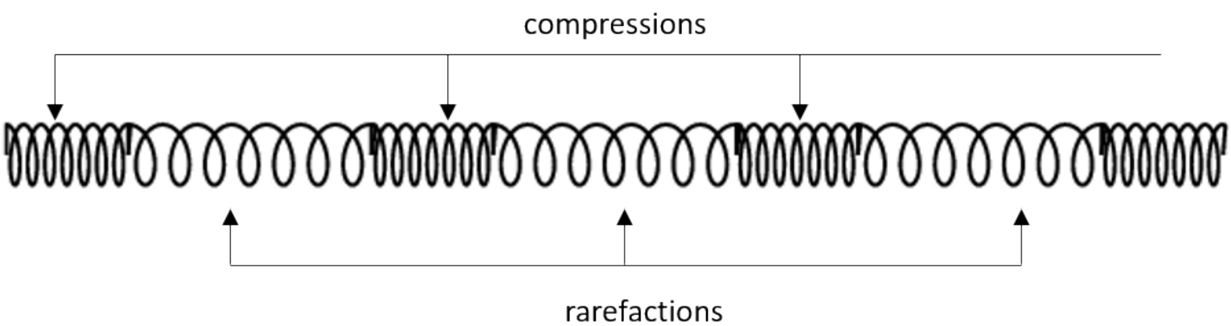


Figure 1: Compressions and rarefactions in a longitudinal wave

Other properties defined for transverse waves, such as wavelength, amplitude, period and frequency, also apply to longitudinal waves. The wavelength of a longitudinal wave is the distance between two consecutive compressions, or two consecutive rarefactions.

Note

Watch this simulation to see how the position of a particle changes in a longitudinal wave over time.

Summary

In this unit you have learnt the following:

- We can distinguish between two types of waves, namely transverse and longitudinal, based on the direction of the disturbance of the medium relative to the direction in which the wave travels.
- In a transverse wave the movement of the particles of the medium is perpendicular to the direction of propagation of the wave.
- In a longitudinal wave the movement of the particles of the medium is parallel to the direction of propagation of the wave.
- Amplitude is the maximum displacement of a particle from its rest position.
- In a transverse wave, the wavelength is the distance between any two consecutive points in phase, such as two peaks or two troughs.
- In a longitudinal wave, the wavelength is the distance between two consecutive compressions, or two consecutive rarefactions.

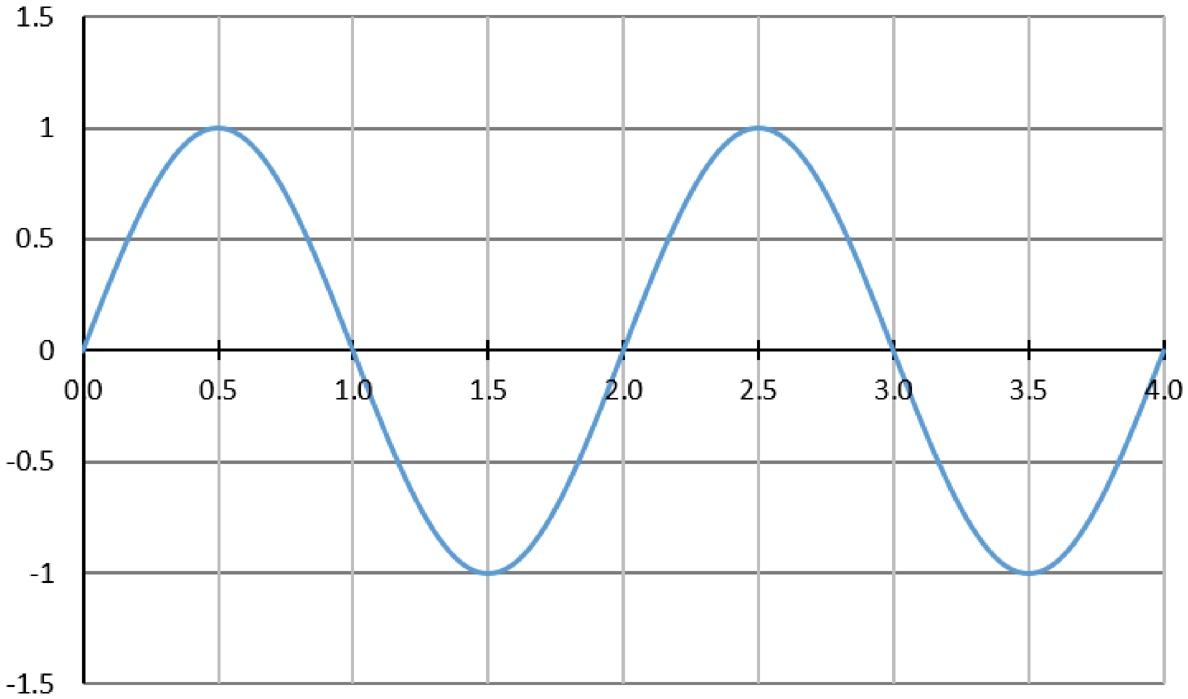
Unit 2: Assessment

Suggested time to complete: 15 minutes

1. Which of the following is not a longitudinal wave?
   A. light
   B. sound
   C. ultrasound
2. In which of the following can a longitudinal wave, such as sound, not travel?
   A. a solid
   B. a liquid
   C. gas

D. a vacuum

3. You are given the transverse wave below:



Draw the following:

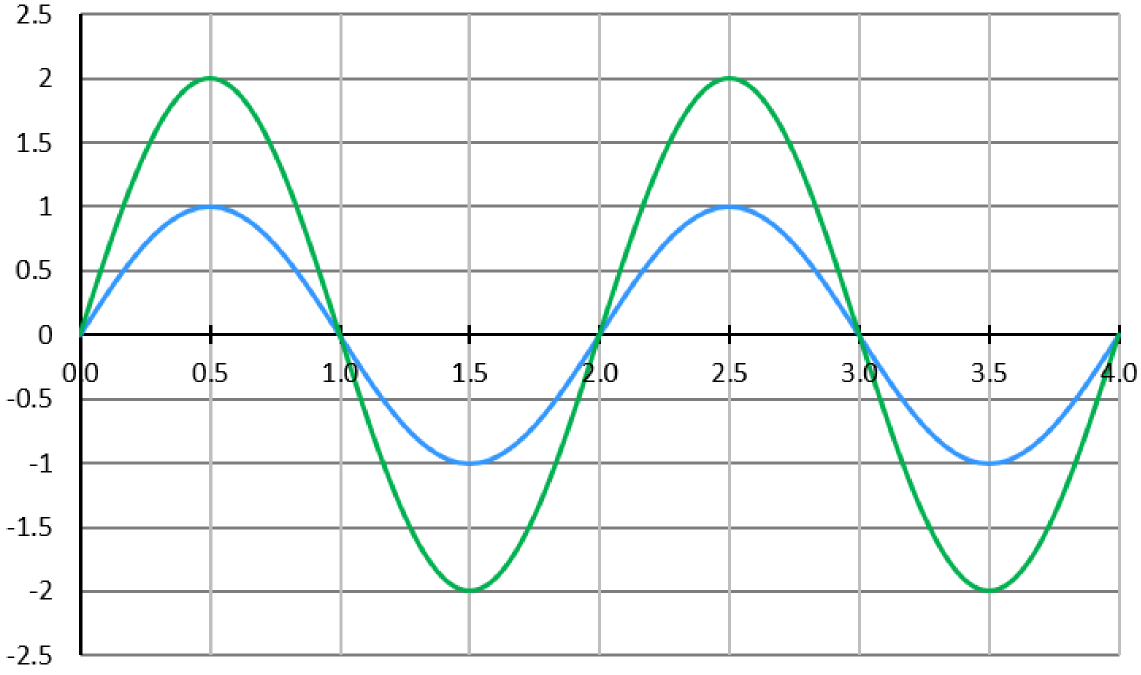
a. A wave with twice the amplitude of the given wave.
b. A wave with half the wavelength of the given wave.

The full solutions are at the end of the unit.

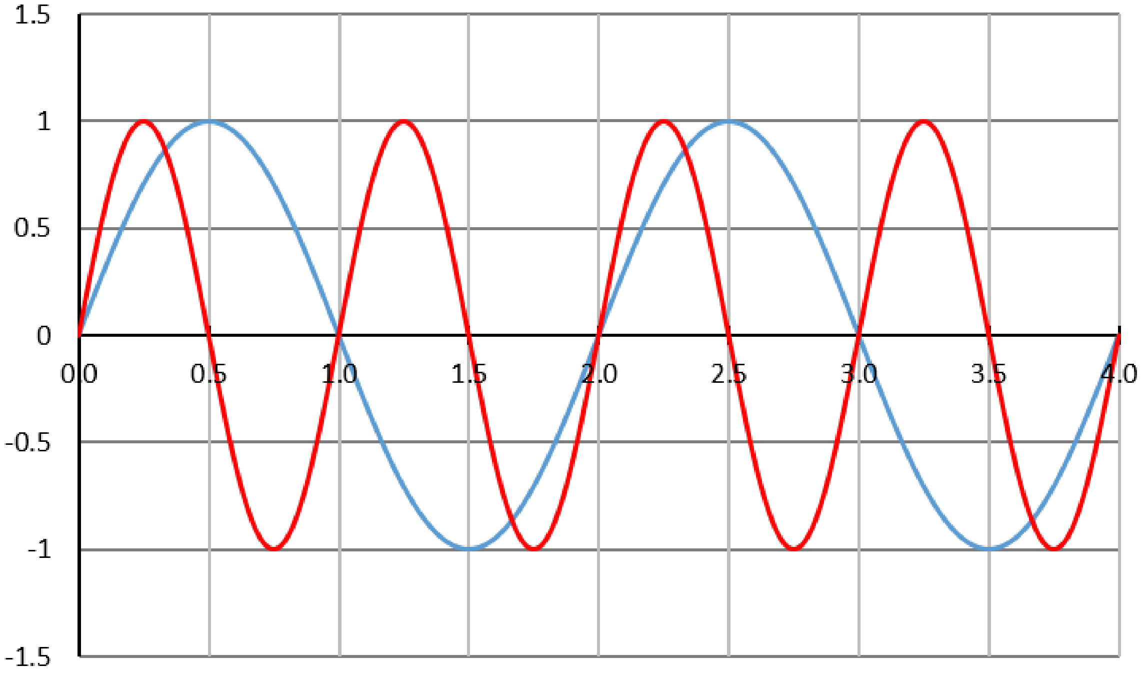
Unit 2: Solutions

Unit 2: Assessment

1. A: light
2. D: vacuum
3.
   a. The graph of the original wave is shown in blue. The graph of the wave with twice the amplitude is shown in green.



b. The graph of the original wave is shown in blue. The graph of the wave with half the wavelength is shown in red.



[Back to Unit 2: Assessment]

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- QR_Code_PSL2SO31U2_2
- QR_Code_PSL2SO31U2_4

Unit 3: Wave calculations

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Unit outcomes

By the end of this unit you will be able to:

- Calculate frequency, period, wave speed and wavelength of a transverse wave.
- Describe the effect of the medium on wave speed.

What you should know

Before you start this unit, make sure you can:

- Describe what a wave is, as covered in Subject outcome 3.1, Unit 1.
- Define frequency, period and wavelength of a transverse wave, as covered in Subject outcome 3.1, Unit 1.
- Describe the relationship between speed, distance and time, as covered in Subject outcome 2.1, Unit 1.

Introduction

In this unit[1] you will apply your knowledge about the basic properties of waves to understand how a transverse wave moves. You will also learn how to calculate the properties of a wave to describe its behaviour.

Calculating the properties of a wave

You know by now that energy travels in wave form. The speed at which a certain wave moves therefore tells us the speed at which a certain type of energy, such as light or sound, travels. Because speed is defined as the change in distance over time, we can use the speed of a wave to determine how far away the source of the energy is from a reference point. Calculating the speed of a wave has many useful applications in real life, such as in astronomy, navigation, medical imaging and even traffic law enforcement.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, p. 139–152, released under a CC-BY licence.

Figure 1: The properties of light waves are used in astronomy to calculate the distance or size of astronomical objects

Note

You may also see the term ‘wave velocity’ used to refer to wave speed (*v*).

The wave equation

Speed is defined as distance covered in a certain time. We can also apply this to wave behaviour. You already know from your work in Unit 1 that the period of a wave tells us how long it takes for one complete wave to move past a fixed point.

Applying the definition of speed to wave behaviour, we can say that the speed of a wave is the distance travelled (the wavelength) in one period:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{\lambda}{T}$$

But you also know that period (*T*) is inversely related to the frequency (*f*) of a wave: $f = \frac{1}{T}$.

In other words, for a wave with a period of 0.2 seconds, $\frac{1}{0.2} = 5$, so five complete wavelengths will move past a fixed point per second. The wave therefore has a frequency of $\frac{1}{T} = \frac{1}{0.2} = 5\ \text{Hz}$.

Combining these concepts, we can also write:

$$
\begin{aligned}
v &= \frac{\text{distance travelled}}{\text{time taken}} \\
&= \frac{\lambda}{T} \\
&= \lambda \cdot \frac{1}{T} \\
&= \lambda \cdot f
\end{aligned}
$$

We call this equation the wave equation:

$$v = \lambda \cdot f$$

where:
v = speed of the wave in metres per second (m.s^{-1})
λ= wavelength in metres (m)
f = frequency of the wave (Hz)

Take note!

The unit of frequency – hertz – is defined as 'per second: s^{-1}.

By manipulating the wave equation, we can calculate the characteristics of a given wave.

Example 3.1

1. When a particular string is vibrated at a frequency of $10\ \text{Hz}$, a transverse wave of wavelength $0.25\ \text{m}$ is produced. Determine the speed of the wave as it travels along the string.
2. A cork on the surface of a swimming pool bobs up and down once every second on some ripples. The ripples have a wavelength of $20\ \text{cm}$. If the cork is $2\ \text{m}$ from the edge of the pool, how long does it take a ripple passing the cork to reach the edge?

Solutions

1. We can use the wave equation to calculate the speed of the wave: $v = \lambda \cdot f$.
   We know that the wavelength is $0.25\ \text{m}$ and the frequency is $10\ \text{Hz}$. The quantities are already given in SI units, and therefore we can substitute them directly into the equation:

$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (0.25\ \text{m})(10\ \text{Hz}) \\
&= 2.5\ \text{m} \cdot \text{s}^{-1}
\end{aligned}
$$

The wave travels at $2.5\ \text{m} \cdot \text{s}^{-1}$ along the string.

2. From the information given, we know that the frequency of the wave is $1\ \text{Hz}$.
   We are required to determine the time it takes for a ripple to travel between the cork and the edge of the pool. The wavelength is not in SI units and should be converted.

   Let the distance between the cork and the edge of the pool be *D*.

   We know that speed (*v*) is distance (*D*) over time (*t*), so we can write: $v = \frac{D}{t}$.
   We can then manipulate the equation to make time the subject of the formula: $t = \frac{D}{v}$.

   We know that $v = \lambda \cdot f$, so we can write: $t = \frac{D}{\lambda \cdot f}$.

   Remember to convert the wavelength to SI units before substituting the values into the equation:
   $20\ \text{cm} = 0.2\ \text{m}$

   Therefore:
$$
\begin{aligned}
t &= \frac{D}{\lambda \cdot f} \\
&= \frac{(2\ \text{m})}{(0.2\ \text{m})(1\ \text{Hz})} \\
&= \frac{(2\ \text{m})}{(0.2\ \text{m})(1\ \text{s}^{-1})} \\
&= 10\ \text{s}
\end{aligned}
$$

   It therefore takes the ripple 10 seconds to reach the edge of the pool.

Exercise 3.1

Questions 1, 3 and 4 were sourced from or based on questions in Siyavula Physical Science Gr 10 Learner's Book, pp. 152–154, released under a CC-BY licence.

1. A transverse wave has a frequency of $15\ \text{Hz}$. The horizontal distance from a crest to the nearest trough is measured to be $2.5\ \text{cm}$. Find the:
   a. period of the wave
   b. speed of the wave.
2. Calculate the frequency of a wave that is travelling at a speed of $6.0\ \text{m.s}^{-1}$ and has a wavelength of $1.8\ \text{m}$.
3. Microwave ovens produce radiation with a frequency of $2\ 540\ \text{MHz}$ $(1\ \text{MHz} = 10^6\ \text{Hz})$ and a wavelength of $0.122\ \text{m}$. What is the wave speed of the radiation?

4. Tom is fishing from a pier and notices that four waves pass by in 8 s and he estimates the distance between two successive crests is 4 m. The timing starts with the first crest and ends with the fourth. Calculate the speed of the wave.

The full solutions are at the end of the unit.

The effect of the medium on wave speed

The speed of a wave depends on the properties of the medium in which it is travelling. This means that a wave of a fixed frequency will travel at different speeds through different mediums.

- The denser the medium, the faster a wave travels. Waves therefore travel faster through solids than through liquids, and faster through liquids than through gases.
- The higher the tension of a medium (in other words, the less elastic it is), the faster the wave will travel, because each section of the medium is in tighter contact with the adjacent section. A wave will therefore travel faster through a taut string than a loose one.
- Waves slow down when they move from deeper water into shallower water.

It is important to remember that once a wave has been generated, its frequency cannot change. From the wave equation $v = \lambda \cdot f$, it follows then that if the wave's speed changes, its wavelength must also change. Because speed is directly proportional to wavelength ($v \propto \lambda$) according to the wave equation, a decrease in speed will lead to a decrease in wavelength; similarly, an increase in speed will lead to an increase in wavelength. This is the reason why a tsunami produces shorter and higher waves near the shore.

Summary

In this unit you have learnt the following:

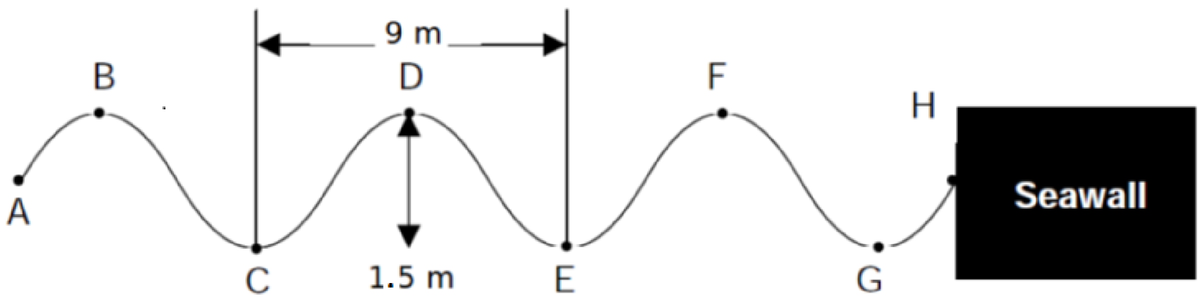
- The period of a wave is the inverse of its frequency: $T = \frac{1}{f}$.
- Wave speed is calculated according to the wave equation: $v = \lambda \cdot f$, where v is the speed, λ is the wavelength and f is the frequency.
- When working with the wave equation, all quantities have to be expressed in SI units:
  - Frequency must be expressed in hertz (Hz)
  - Wavelength must be expressed in metres (m).
  - Wave speed must be expressed in metres per second ($m.s^{-1}$).
- The speed of a wave depends on the properties of the medium:
  - The denser a medium, the faster a wave will travel.
  - The more tension in a medium, the faster a wave will travel.
  - The shallower the depth of the medium, the slower a wave will travel.
- The frequency of a wave does not change when it moves from one medium to another; only its speed and wavelength change.

Unit 3: Assessment

Suggested time to complete: 40 minutes

Questions 1–4 were sourced from or based on questions from [OpenStax College] released under a Creative Commons Attribution Licence 4.0 licence. Questions 5–6 were sourced from or based on questions in [Siyavula Physical Science Gr 10 Learner's Book, pp. 155–156] released under a CC-BY licence.

1. When is the wavelength directly proportional to the period of a wave?
   A. when the velocity of the wave is halved
   B. when the velocity of the wave is constant
   C. when the velocity of the wave is doubled
   D. when the velocity of the wave is tripled
2. If a seagull sitting in water bobs up and down once every 2 seconds and the distance between two crests of the water wave is 3 m, what is the speed of the wave?
   A. 1.5 m.s^{-1}
   B. 3 m.s^{-1}
   C. 6 m.s^{-1}
   D. 12 m.s^{-1}
3. A boat in the trough of a wave takes 3 seconds to reach the highest point of the wave. The speed of the wave is 5 m.s^{-1}. What is its wavelength?
   A. 0.83 m
   B. 15 m
   C. 30 m
   D. 180 m
4. A woman creates two waves every second by shaking a slinky spring up and down.
   a. What is the period of each wave?
   b. If each wave travels 0.9 metres after one complete wave cycle, what is the speed of wave propagation?
5. A wave travels along a string at a speed of 1.5 m.s^{-1}. If the frequency of the source of the wave is 7.5 Hz, calculate:
   a. the wavelength of the wave
   b. the period of the wave.
6. Ocean waves crash against a seawall around the harbour. Eight complete waves hit the seawall in 5 seconds. The distance between successive troughs is 9 m. The height of the waveform trough to crest is 1.5 m.



Note that you have to draw on your prior knowledge about wave characteristics in this question.

a. How many complete waves are indicated in the sketch?
b. Write down the letters that indicate any TWO points that:
   i. are in phase
   ii. are out of phase
   iii. represent ONE wavelength.
c. Calculate the amplitude of the wave.
d. Show that the period of the wave is $0.625\ \mathrm{s}$.
e. Calculate the velocity of the waves.

7. Wind gusts create ripples on the ocean that have a wavelength of $0.5\ \mathrm{m}$ and propagate at $2.00\ \mathrm{m \cdot s^{-1}}$. What is their frequency?
8. What is the wavelength of an earthquake that shakes you with a frequency of $10.0\ \mathrm{Hz}$ and gets to another city $84.0\ \mathrm{km}$ away in $12.0\ \mathrm{s}$?
9. Your ear can differentiate sounds that arrive at the ear in just $1.00\ \mathrm{ms}$. What is the minimum distance between two speakers that produce sounds that arrive at noticeably different times on a day when the speed of sound is $340\ \mathrm{m \cdot s^{-1}}$?
10. A $660\ \mathrm{Hz}$ source emits a wave of $30\ \mathrm{cm}$. How much time is needed for the wave to travel $594\ \mathrm{m}$?

The full solutions are at the end of the unit.

Unit 3: Solutions

Exercise 3.1

1.

a.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{15} \\ &= 0.067\ \mathrm{s} \end{aligned}$$

b. The distance from a crest to the next trough is $2.5\ \mathrm{cm}$, which is half a wavelength. A full wavelength is therefore $5\ \mathrm{cm}$. This must be converted to metres to be used in the wave equation: $5\ \mathrm{cm} = 0.05\ \mathrm{m}$.

$$\begin{aligned} v &= \lambda \cdot f \\ &= (0.05\ \mathrm{m})(15\ \mathrm{Hz}) \\ &= 0.75\ \mathrm{m \cdot s^{-1}} \end{aligned}$$

2.

$$\begin{aligned} v &= \lambda \cdot f \\ \therefore f &= \frac{v}{\lambda} \\ &= \frac{6.0\ \mathrm{m \cdot s^{-1}}}{1.8\ \mathrm{m}} \\ &= 3.33\ \mathrm{Hz} \end{aligned}$$

3. Frequency should first be converted to the SI unit, hertz:
$f = 2\ 540\ \mathrm{MHz} = 2\ 540 \times 10^{6}\ \mathrm{Hz} = 2.540 \times 10^{9}\ \mathrm{Hz}$

$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (0.122\ \mathrm{m})(2.540 \times 10^{9}\ \mathrm{Hz}) \\
&= \ 3.09\ \times\ 10^{8}\ \mathrm{m \cdot s^{-1}}
\end{aligned}
$$

4. The description of 4 waves passing in 8 seconds translates to a frequency of 0.5 waves per second. Therefore, the frequency is $0.5\ \mathrm{Hz}$.
   The distance from crest to crest is estimated to be $4\ \mathrm{m}$, which represents the wavelength.
$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (4\ \mathrm{m})(0.5\ \mathrm{Hz}) \\
&= \ 2\ \mathrm{m \cdot s^{-1}}
\end{aligned}
$$

Back to Exercise 3.1

Unit 3: Assessment

1. A
   We know that period is the inverse of frequency. We can therefore rewrite the wave equation as $v = \lambda \cdot \dfrac{1}{T}$. Manipulating the equation to make period (*T*) the subject gives $T = \lambda \cdot \dfrac{1}{v}$. This tells us that for period (*T*) to be directly proportional to wavelength (λ), velocity (*v*) has to be reduced. The only option that describes a reduction in velocity is A.
2. A
   The frequency is $0.5\ \mathrm{Hz}$ and the wavelength is given as $3\ \mathrm{m}$. To calculate the speed of the wave, we use the wave equation:
$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (3\ \mathrm{m})(0.5\ \mathrm{Hz}) \\
&= \ 1.5\ \mathrm{m \cdot s^{-1}}
\end{aligned}
$$
3. C
   The distance from trough to crest represents half a wavelength. If it takes the boat $3\ \mathrm{s}$ to complete half a wavelength, it will take $6\ \mathrm{s}$ to complete a full wavelength. The period of the wave is therefore $6\ \mathrm{s}$. This translates to a frequency of $f = \dfrac{1}{T} = \dfrac{1}{6\ \mathrm{s}} = 0.167\ \mathrm{Hz}$.
   According to the wave equation then:
$$
\begin{aligned}
v &= \lambda \cdot f \\
\therefore \lambda &= \frac{v}{f} \\
&= \frac{5\ \mathrm{m \cdot s^{-1}}}{0.167\ \mathrm{Hz}} \\
&= \ 29.9\ \mathrm{m} \\
&\approx 30\ \mathrm{m \cdot s^{-1}}
\end{aligned}
$$
4.
   a. The frequency is given as $2\ \mathrm{Hz}$. Therefore $T = \dfrac{1}{f} = \dfrac{1}{2} = 0.5\ \mathrm{s}$.
   b.
$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (0.9\ \mathrm{m})(2\ \mathrm{Hz}) \\
&= \ 1.8\ \mathrm{m \cdot s^{-1}}
\end{aligned}
$$
5.
   a.

$$
\begin{aligned}
v &= \lambda \cdot f \\
\therefore \lambda &= \frac{v}{f} \\
&= \frac{1.5 \text{ m} \cdot \text{s}^{-1}}{7.5 \text{ Hz}} \\
&= 0.2 \text{ m}
\end{aligned}
$$

b.

$$
\begin{aligned}
T &= \frac{1}{f} \\
&= \frac{1}{7.5} \\
&= 0.13 \text{ s}
\end{aligned}
$$

6.

a. Three complete waves are shown.

b.

i. Any of the pairs: B and D; D and F; E and G; C and E; or A and H.

ii. Some examples are: A and B; A and D; B and C; A and C; C and D; D and E; E and F; F and G; or E and H.

iii. Any of the pairs: B and D; C and E; D and F; or E and G.

c. Amplitude is defined as the deviation from the rest position. Therefore amplitude is $\frac{1.5 \text{ m}}{2} = 0.75 \text{ m}$.

d. If 8 waves hit the wall in 5 seconds, it means 1.6 waves hit the wall every second. Therefore: $T = \frac{1}{f} = \frac{1}{1.6} = 0.625 \text{ s}$

e.

$$
\begin{aligned}
v &= \lambda \cdot f \\
&= (9 \text{ m})(1.6 \text{ Hz}) \\
&= 14.4 \text{ m} \cdot \text{s}^{-1}
\end{aligned}
$$

7.

$$
\begin{aligned}
v &= \lambda \cdot f \\
\therefore f &= \frac{v}{\lambda} \\
&= \frac{2 \text{ m} \cdot \text{s}^{-1}}{0.05 \text{ m}} \\
&= 40 \text{ Hz}
\end{aligned}
$$

8. It takes the wave 12.0 s to travel 84.0 km. The speed of the wave is therefore: $7 \text{ km} \cdot \text{s}^{-1} = 7\ 000 \text{ m} \cdot \text{s}^{-1}$.

$$
\begin{aligned}
v &= \lambda \cdot f \\
\therefore \lambda &= \frac{v}{f} \\
&= \frac{7\ 000 \text{ m} \cdot \text{s}^{-1}}{10.0 \text{ Hz}} \\
&= 700 \text{ m}
\end{aligned}
$$

9. We know that speed is defined as distance over time. If we define the distance here as D, we can write $v = \frac{D}{t}$.

$$
\begin{aligned}
\therefore D &= vt \\
&= (340)(0.001 \text{ s}) \\
&= 0.34 \text{ m}
\end{aligned}
$$

The minimum distance of the two speakers should therefore be 0.34 m.

10. The speed of the wave described here is $v = \lambda \cdot f = (0.3 \text{ m})(660 \text{ Hz}) = 198 \text{ m} \cdot \text{s}^{-1}$.

To cover a distance of $594\ \text{m}$, we use the relationship: $v = \frac{D}{t}$.

$\therefore t = \frac{D}{v} = \frac{594\ \text{m}}{198\ \text{m} \cdot \text{s}^{-1}} = 3\ \text{s}$

Back to Unit 3: Assessment

Media Attributions

Unit 4: Standing waves

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Unit outcomes

By the end of this unit you will be able to:

- Distinguish between standing and moving waves.
- Identify and describe superposition in standing waves.

What you should know

Before you start this unit, make sure you can:

- Describe what a wave is, as covered in Subject outcome 3.1, Unit 1.
- Define the following properties of a wave: amplitude, frequency, period and wavelength, as covered in Subject outcome 3.1, Unit 1.

Introduction

In this unit[1] you will learn how the properties of waves apply in practical contexts such as building structures and acoustics.

As you know by now, energy is transferred by waves. You also know that:

- waves are caused by a medium starting to vibrate.
- waves represent periodic motion, which means that the motion repeats in a regular, oscillating pattern. Periodic motion is also called simple harmonic motion.
- we describe waves in terms of their properties such as amplitude, frequency, period and wavelength.

You will build on this knowledge of the basic properties of waves to understand the effects of wave interaction.

Standing waves in the world around us

Every material has a natural frequency at which it will vibrate, in other words, start to move back and forth. This is the frequency at which resonance will occur in the material. When a material resonates, its natural

1. Parts of the text in this unit were sourced or adapted from the OpenStax textbook College Physics, p.632–636, released under a CC-BY 4.0 licence and from Siyavula Physical Science Gr 10 Learner's Book, p. 139–152, released under a CC-BY licence.

vibration is amplified when it is excited by another vibration that matches its natural frequency. This means the amplitude of the wave increases. Resonance is the result of a phenomenon called standing waves.

Note

You can see resonance in action in the video called Vibrating wine glass (Duration: 05.54).

Understanding the concept of standing waves and resonance is important in practical applications such as structural engineering and acoustics. A famous example of resonance having a disastrous effect is the collapse of the Tacoma Narrows Bridge in the US in 1940.

Note

You can see what happened in the video called Tacoma Bridge (Duration: 02.12).

The structural engineers who designed the bridge failed to consider the effect harmonic motion would have on the bridge. On the day of the collapse, wind caused the bridge to swing. The frequency of the swinging motion matched the natural frequency of the material the bridge was constructed of, and it started to resonate. The amplitude of the oscillations of the bridge increased so much that the forces eventually exceeded the material strength of the bridge, and it collapsed.

The concept of standing waves

Standing waves are waves that *appear* to stand still. In other words, they do not appear to travel from one place to another, and so there is no net transfer of energy. In contrast, a travelling wave is moving; it transfers energy from one place to another.

Superposition and interference

Standing waves and travelling waves are not unrelated. In fact, a standing wave results from a travelling wave being reflected (bounced back) from a fixed boundary, and the reflected wave then meeting with the incident wave. The two travelling waves therefore move in opposite directions.

Take note!

A standing wave is not an actual wave, but rather the *perceived* wave pattern resulting from two travelling waves of the same frequency interacting with each other in the same medium.

When two (or more) waves arrive at the same point, they superimpose themselves on each other. This means they interfere with each other. Such interference is called superposition, and results in the amplitudes of the individual disturbances at the meeting point combining (adding up), creating a greater or smaller amplitude.

The principle of superposition states that when two disturbances occupy the same space at the same time the resulting disturbance is the sum of the two disturbances.

Constructive and destructive interference

Superposition of waves can cause constructive or destructive interference.

- Figure 1 shows two identical waves that arrive at the same point exactly in phase. The crests of the two waves are precisely aligned, as are the troughs. This superposition produces pure constructive interference. Because the disturbances combine, pure constructive interference produces a wave that has twice the amplitude of the individual waves, but the same wavelength.

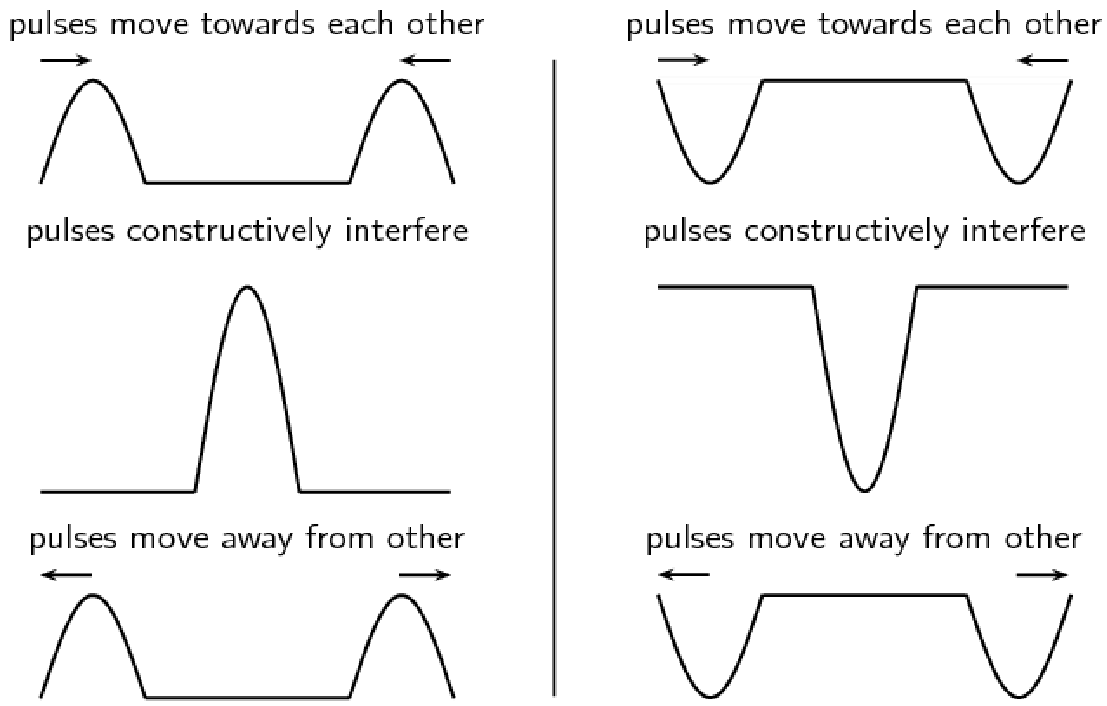

Figure 1: Superposition of two waves causing constructive interference

- Figure 2 shows how superposition causes destructive interference. Because the disturbances occur in opposite directions relative to the rest position for this superposition, the resulting amplitude is smaller than the larger of the two original disturbances. The left-hand panel shows pure destructive interference, as the two disturbances are of the same size, and so cancel each other out. The right-hand panel shows a partial cancellation of the two disturbances, as their amplitudes are not of the same size.

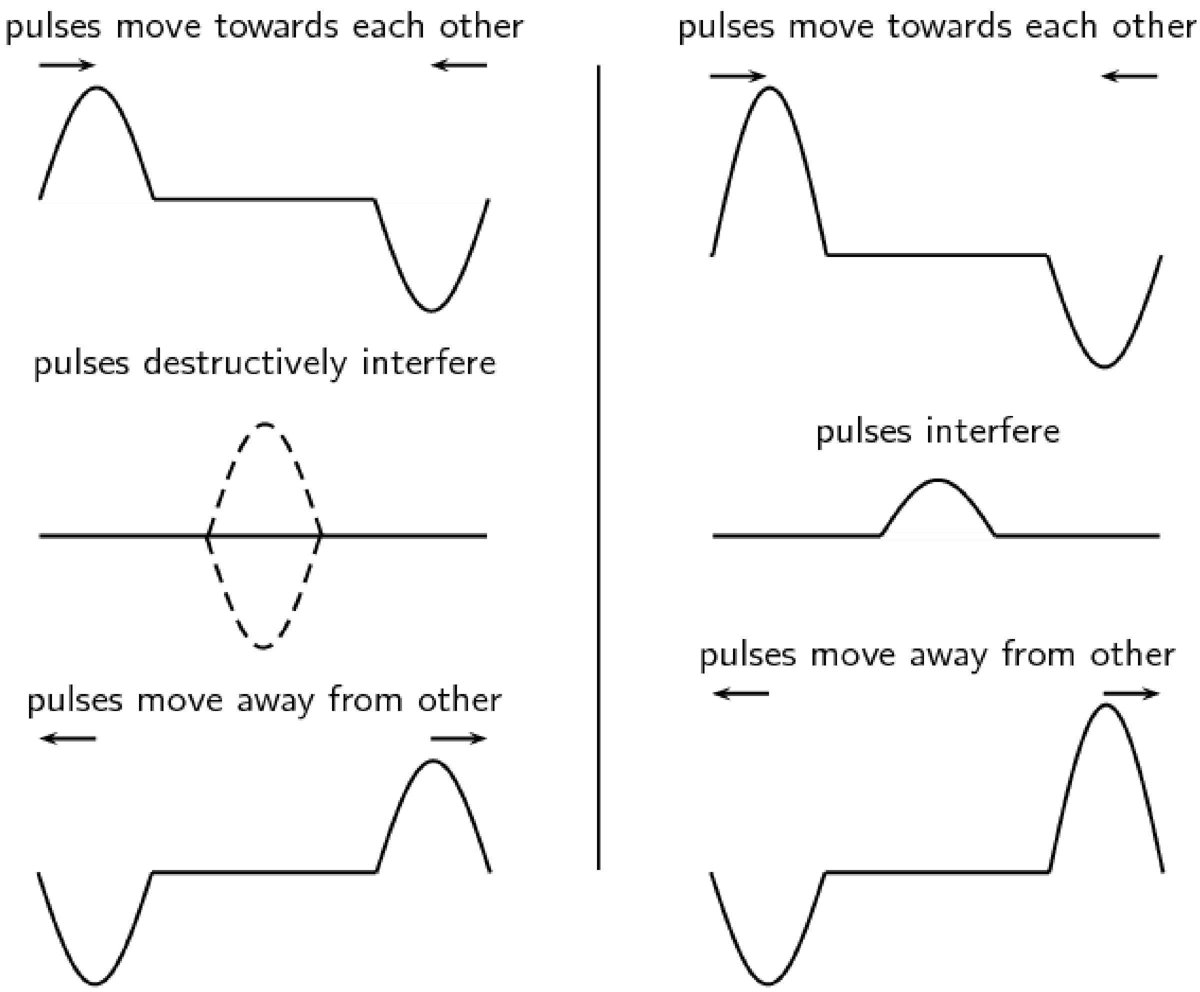

Figure 2: Superposition of two waves causing destructive interference

Properties of standing waves

In a standing wave, there are points of destructive interference and points of constructive interference.

- A point of perfect destructive interference in a standing wave is called a node. At this point, the amplitudes of the interacting waves will therefore cancel each other exactly, and the resulting amplitude will be zero.
- A point of perfect constructive interference in a standing wave is called an antinode. At this point, each of the interacting waves will be at their maximum amplitude, and the resulting amplitude of the standing wave will therefore also be at its maximum.

The simplest example to illustrate how a standing wave forms is to consider a taut string fixed at its two opposite ends, such as a string on a guitar (see Figure 3a).


Figure 3a: A stretched string

Because the two ends are fixed, there can be no displacement at those points when the string is plucked, and so they represent two nodes (Figure 3b).

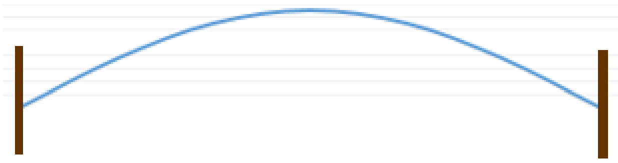

Figure 3b: A stretched string that has been disturbed (plucked)

Standing waves on strings have a frequency that is related to the propagation speed (*v*) of the disturbance on the string. The wavelength is determined by the distance between the points where the string is fixed in place, in other words the length of the string.

The fundamental frequency is the frequency associated with the longest wavelength of the standing wave. It is also called the first harmonic frequency (often simply called the first harmonic). We can see from Figure 3c that the length of the string (*L*) is equal to half the wavelength (λ) of the standing wave in the first harmonic.

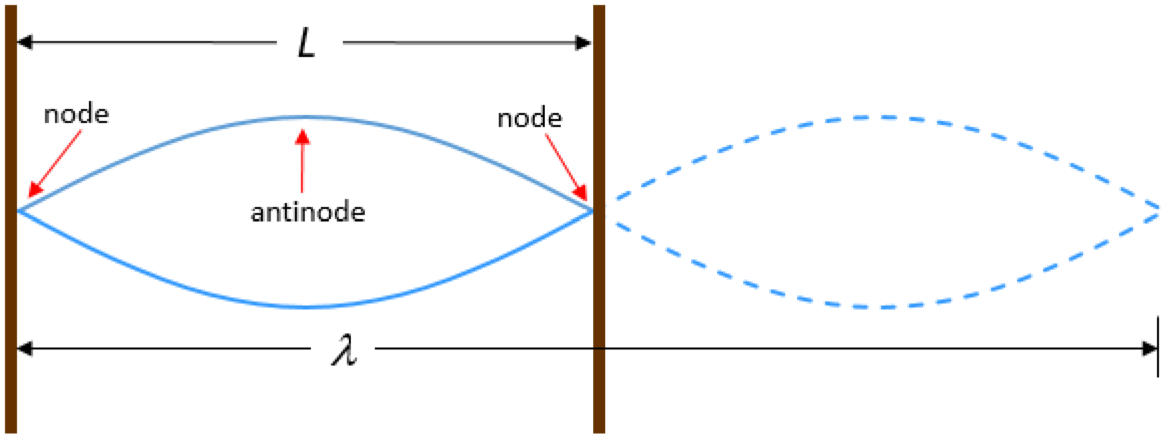

Figure 3c: Standing wave pattern, first harmonic

Shorter wavelengths give rise to subsequent harmonics, as shown in Figure 3d and Figure 3e.

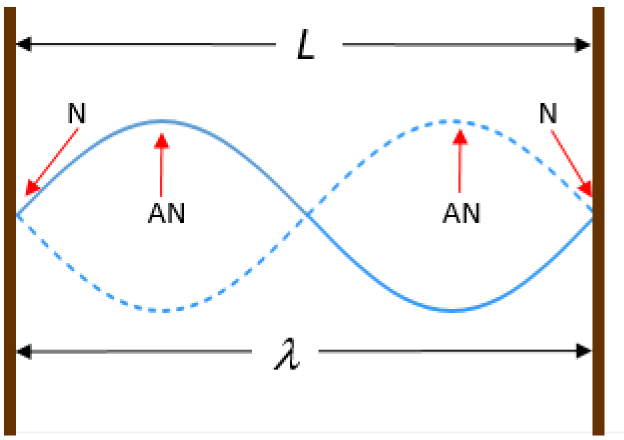

Figure 3d: Standing wave pattern, second harmonic

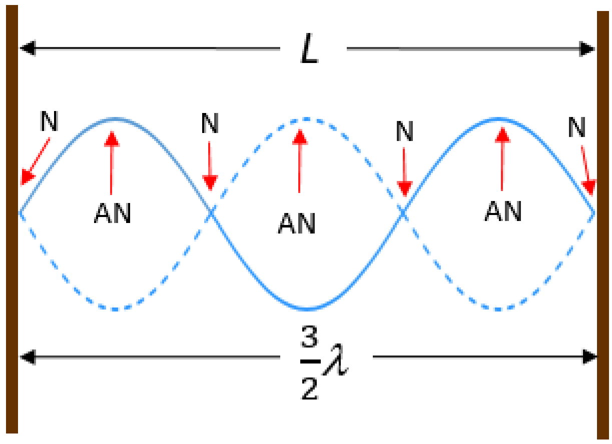

Figure 3e: Standing wave pattern, third harmonic

In general we can use the length of the string to derive the wavelength for each harmonic as $L = \frac{n\lambda_n}{2}$, with $n = 1,\ 2,\ 3\ \ldots$. The integer *n* denotes the number of the harmonic (and is easily found by counting the number of loops in the standing wave).

From here we can write the wavelength in terms of the length of the string: $\lambda_n = \frac{2L}{n}$.

By using the wave equation, we can then calculate the frequency of each subsequent harmonic. These frequencies will be integer multiples of the fundamental frequency (first harmonic), as shown in Example 4.1.

The frequencies of harmonics can be changed by adjusting the tension in the string, because, as you will recall from Unit 3, the tension of the medium affects the propagation speed of the wave. So, the greater the tension, the greater speed, and because speed and frequency are directly proportional, the frequency will also increase.

Note

Standing waves can also form in a tube (filled with a fluid medium such as gas or liquid). In such cases, standing waves can form when both ends of the tube are open or when one end of the tube is closed while the other is open. However, we will deal only with standing waves on a string in this unit to explain the concept of standing waves.

Example 4.1

A string on a guitar is tuned to a fundamental frequency of $392\ \mathrm{Hz}$. Show that the second harmonic will have a frequency of $784\ \mathrm{Hz}$.

Solution

To solve this problem, we should write the fundamental frequency (f_1) in terms of the wave equation, where v_w denotes the velocity of the standing wave. We can then express the length of the string in terms of f_1.

$$v_w = f_1 \cdot \lambda_1$$
$$\therefore f_1 = \frac{v_w}{\lambda_1}$$

We know that the wavelength of the fundamental (that is, the first harmonic) is double the length of the string (look at Figure 3a again to see why this is so).
Therefore:

$$f_1 = \frac{v_w}{2L} \qquad \text{(Equation 1)}$$

From the wave equation we can write the frequency of the second harmonic, f_2, as $f_2 = \frac{v_w}{\lambda_2}$, and because we know $\lambda_2 = L$, we can rewrite this as:

$$f_2 = \frac{v_w}{L} \qquad \text{(Equation 2)}$$

We can then rearrange equation 1 in terms of length (L):

$$L = \frac{v_w}{2f_1} \qquad \text{(Equation 3)}$$

If we substitute equation 3 into equation 2, we can show that:

$$\begin{aligned} f_2 &= \frac{v_w}{L} \\ &= \frac{v_w}{\frac{v_w}{2f_1}} \\ &= v_w \times \frac{2f_1}{v_w} \\ &= 2f_1 \end{aligned}$$

Therefore $f_2 = 2(362\ \text{Hz}) = 784\ \text{Hz}$.

We can use these relationships to determine the properties of standing waves and their harmonics.

Example 4.2

A string of $35.5\ \text{cm}$ produces a standing wave with a fundamental frequency of $440\ \text{Hz}$:

1. Which harmonic will be associated with a wavelength of $23.67\ \text{cm}$?
2. What will be its frequency?

Solutions

1. We know the wavelength of the fundamental frequency (first harmonic) is equal to twice the length of the string: $2 \times 35.5\ \text{cm} = 71\ \text{cm}$.
   We can use the relationship $\lambda_n = \frac{2L}{n}$ to calculate the wavelength of a subsequent harmonic.
   Therefore:

$$
\begin{aligned}
n &= \frac{2L}{\lambda_n} \\
&= \frac{2(35.5)}{23.67} \\
&= 2.999 \\
&\approx 3
\end{aligned}
$$

The third harmonic will therefore be associated with a wavelength of $23.67\ \text{cm}$.

2. We know that the frequencies of subsequent harmonics are integer multiples of the first. Therefore: $f_3 = 3f_1 = 3(440\ \text{Hz}) = 1\ 320\ \text{Hz}$

Activity 4.1

Time required: 20 minutes

What you need:

- an internet connection
- a computer or tablet
- a calculator
- a pen and a notebook

What to do:

1. Access the simulation of standing waves:

2. Set $n = 1$ and let the simulation run. Notice the standing wave pattern that forms from the interaction of the two travelling waves moving in opposite directions (blue and red).
3.
   a. Identify the positions of the nodes.
   b. How many antinodes does the standing wave have?
4. Pause the simulation at a moment of perfect destructive interference (amplitude = 0). (You can use the 'step' function to reach this point accurately.) Consider the wave forms of the blue and red waves. Can you see why the resultant standing wave has no displacement here?
5. Continue the simulation and then pause at a moment of perfect constructive interference. Use the 'step' function as necessary. Can you see why the resultant standing wave has maximum displacement here? What is the maximum displacement?
6. Determine the frequency of the first harmonic (that is, the fundamental frequency). Do the follow-

ing:

a. Let the simulation run to a point where the standing wave reaches zero displacement. Use the 'step' function to get this point accurately. Note the time.
b. Let the simulation run to complete a full wave cycle, and again note the time.
c. Calculate the frequency of this wave.

7. Now set $n = 4$ (the fourth harmonic). Determine the frequency, as you did in step 6.

What did you find?

- The standing wave has nodes at $x = 0\ \text{m}$ and $x = 10\ \text{m}$, the ends of the string (step 3a).
- The wave has only one antinode (step 3a).
- When there is perfect destructive interference, the amplitudes of the two interacting waves are exactly opposite, and therefore cancel each other out at every position (step 4).
- Similarly, when there is perfect constructive interference, each of the contributing waves has maximum displacement, so the displacement of the standing wave is also at a maximum here (step 5).
- A full wave cycle takes $0.500\ \text{s}$ to complete. This represents the period of the wave, and therefore $f = \frac{1}{T} = \frac{1}{0.5} = 2\ \text{Hz}$ (step 6).
- On setting $n = 4$, we find that it takes $0.125\ \text{s}$ for a full wave cycle to complete. Therefore $f = \frac{1}{T} = \frac{1}{0.125} = 8\ \text{Hz}$. This confirms that the frequency of subsequent harmonics are integer multiples of the fundamental frequency, with the integer being equal to the harmonic number.

Summary

In this unit you have learnt the following:

- A standing wave is a perceived wave pattern that results from the interaction of two travelling waves moving in opposite directions. A standing wave appears to stand still.
- The interaction of two or more waves in the same location is called superposition.
- The amplitudes of two superimposed waves combine.
- Constructive interference occurs when two positive or two negative disturbances combine, resulting in a bigger amplitude than either of the two individual amplitudes.
- Destructive interference occurs when a positive and a negative disturbance combine, resulting in a smaller amplitude than that of the bigger of the two original amplitudes.
- A point of perfect destructive interference in a standing wave is called a node. A node represents a point of zero amplitude on a standing wave.
- A point of perfect constructive interference in a standing wave is called an antinode. An antinode represents a point of maximum amplitude on a standing wave.
- Waves on a string are resonant standing waves with a fundamental frequency and can occur at higher multiples of the fundamental in a standing wave.
- The wavelength of a standing wave on a string can be expressed in terms of the length of the string according to the equation $\lambda_n = \frac{2L}{n}$, where $n = 1,\ 2,\ 3\ \ldots$

Unit 4: Assessment

Suggested time to complete: 20 minutes

Questions 1–4 were taken from the [OpenStax textbook College Physics, p. 636 and p. 647](), released under a CC-BY 4.0 licence.

1. Imagine you are holding one end of a skipping rope, and your friend is holding the other. If your friend holds her end still, you can move your end up and down, creating a transverse wave. If your friend then begins to move her end up and down, generating a wave in the opposite direction, what resultant wave forms would you expect to see in the skipping rope?
2. Define nodes and antinodes.
3. When testing a stereo sound system, you notice that in one corner of the room, the sounds seem dull. In another area, the sounds seem excessively loud. Use the concept of wave interference to describe how the sound waves moving about the room could produce these effects.
4. A wave travelling on a slinky spring that is stretched to $4\ \mathrm{m}$ takes $2.4\ \mathrm{s}$ to travel the length of the slinky spring and back again.
   a. What is the speed of the wave?
   b. Using the same slinky spring stretched to the same length, a standing wave is created that consists of three antinodes and four nodes. At what frequency must the slinky be oscillating?
5. The distance between the first and the fourth nodes of a standing wave on a string is $750\ \mathrm{cm}$. What is the wavelength of the component waves?
6.
   a. A string of $4.0\ \mathrm{m}$ long is stretched between two fixed points and a standing wave with two loops is produced. The string moves up and down six times per second. What is the speed of the component waves in the string?
   b. What is the wavelength that will produce the next harmonic, and what would its frequency be?

The [full solutions]() are at the end of the unit.

Unit 4: Solutions

Unit 4: Assessment

1. The rope would alternate between having waves with amplitudes two times the original amplitude and reaching equilibrium with no amplitude at all. The wavelengths will result in both constructive and destructive interference.
2. Nodes are areas of wave interference where there is no motion. Antinodes are areas of wave interference where the motion is at its maximum point.
3. With multiple speakers putting out sounds into the room, and these sounds bouncing off walls, there is bound to be some wave interference. In the dull areas, the interference is probably mostly destructive. In the louder areas, the interference is probably mostly constructive.
4. A standing wave pattern of two full cycles in $2.4\ \mathrm{s}$ forms, which means that the period (*T*) of the wave is $1.2\ \mathrm{s}$. The frequency of the component waves is therefore $f = \frac{1}{T} = \frac{1}{1.2} = 0.833\ \mathrm{Hz}$. Two loops form, which means the wavelength is equal to the length of the slinky: $4\ \mathrm{m}$.
   a.

$$\begin{aligned} v &= f \cdot \lambda \\ &= (0.833 \text{ Hz})(4 \text{ m}) \\ &= 3.33 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

b. The wave pattern originally described represents the second harmonic. Therefore the fundamental frequency is $f_1 = \frac{f_2}{2} = \frac{0.833 \text{ Hz}}{2} = 0.417 \text{ Hz}$. A standing wave of three antinodes and four nodes represents the third harmonic, which has a frequency of $3f_1 = 3(0.417 \text{ Hz}) = 1.251 \text{ Hz}$.

5. The standing wave pattern described here represents 1.5 wavelengths. Therefore:
$750 \text{ cm} \div \frac{3}{2} = 500 \text{ cm}.$

6.

a. Two loops are formed, which means that one full wave is completed. Therefore, the wavelength, λ, is equal to the length of the string. The frequency is given as 6.0 Hz. Therefore:

$$\begin{aligned} v &= f \cdot \lambda \\ &= (6.0 \text{ Hz})(4.0 \text{ m}) \\ &= 24.0 \text{ m.s}^{-1} \end{aligned}$$

b. The wave pattern described in (a) represents the second harmonic. Therefore, the fundamental frequency, f_1) is 3.0 Hz, and $f_3 = 3f_1 = 3(30.\text{ Hz}) = 9.0\text{Hz}$.
From the wave equation:

$$\begin{aligned} v &= f \cdot \lambda \\ \therefore \lambda &= \frac{v}{f} \\ &= \frac{24.0}{9.0} \\ &= 2.67 \text{ m.s}^{-1} \end{aligned}$$

Back to Unit 4: Assessment

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SUBJECT OUTCOME VI

WAVES, SOUND AND LIGHT: IDENTIFY, DESCRIBE AND APPLY PRINCIPLES OF GEOMETRICAL OPTICS IN EVERYDAY CONTEXTS

Subject outcome

Subject outcome 3.2: Identify, describe and apply principles of geometrical optics in everyday contexts .

Learning outcomes

- Identify light as a transverse wave.
- Identify and describe the wave properties of light: reflection and refraction.
- Draw diagrams showing reflection, angle of incidence and angle of reflection using plane, concave and convex mirrors and the type, size and distance of image formed.
- Draw and interpret diagrams showing refraction (angle of the light ray in the two media and normal).

  Range: Media can be air, glass, Perspex, water and oil.

- Draw and interpret diagrams showing total internal reflection.

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify light as a transverse wave.
- Identify and describe the wave properties of light with reference to:
  - refraction
  - reflection
- Draw and interpret diagrams of refraction, showing:
  - the angle of the light ray in two media
  - the normal.
- Draw and interpret diagrams showing total internal reflection.

Unit 2 outcomes

By the end of this unit you will be able to:

- Draw diagrams showing reflection with reference to plane, concave and convex mirrors, indicating for each diagram:
  - the angle of incidence
  - the angle of reflection
  - the type and size of the image and the distance at which it is formed.

Unit 1: Wave properties of light: Reflection and refraction

LINDA PRETORIUS

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify light as a transverse wave.
- Identify and describe the wave properties of light with reference to:
  - refraction
  - reflection
- Draw and interpret diagrams of refraction, showing:
  - the angle of the light ray in two media
  - the normal.
- Draw and interpret diagrams showing total internal reflection.

Introduction

Mirrors, reading glasses, telescopes, methods of communication, spotlights and car headlights all manipulate the way light reflects off surfaces or refracts in different media. Reflection and refraction are phenomena that occur because of the wave properties of light. If light did not behave the way it does, we would not be able to use a mirror to see how we look before going out, use glasses to correct eye problems, look at objects far away or communicate over long distances.

In this unit[1] you will build on your knowledge of the properties of transverse waves to understand how light behaves, and draw simple ray diagrams to support your understanding. This will help you to understand how we use the behaviour of light in practical applications.

Light is a wave

You know from Subject outcome 3.1 on waves that energy travels in waves. Light is a form of energy, and it follows that light also travels in waves. Although we generally cannot see these waves, it is useful to understand light as a transverse wave to help us understand how it behaves and how to manipulate it to create specific effects.

In physics we use the idea of a light ray to show the direction in which the wave propagates, in other words, the direction in which light travels. Light rays are generally shown as straight arrows.

1. Parts of the text in this unit were sourced or adapted from Siyavula Physical Science Gr 11 Learner's Book, p. 194–199, released under a CC-BY licence.

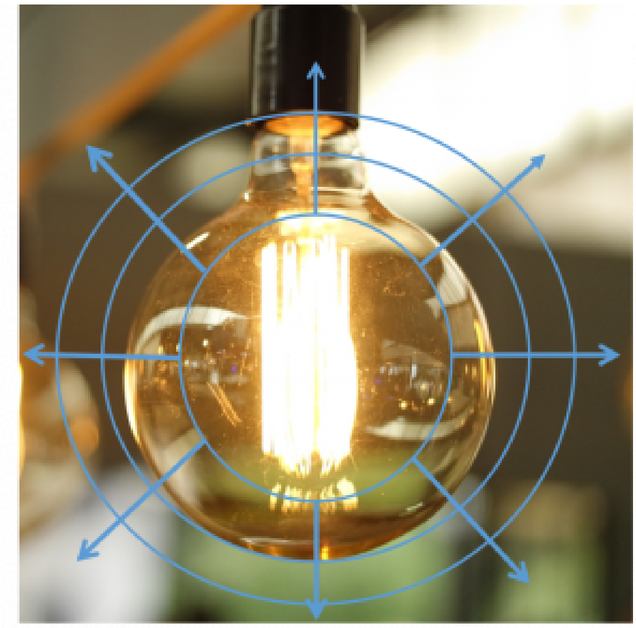


Figure 1: Light rays are drawn as straight lines to show how light waves travel

The light bulb in Figure 1 is a source of light. The wavefronts are shown by the concentric circles coming from the bulb. We represent the direction in which the wavefronts are moving by drawing light rays (the arrows) perpendicular to the wavefronts. You can think of a light ray as the path of a point on the crest of a wave.

The study of how light interacts with materials is called optics. When dealing with light rays, we are usually interested in the shape of a surface and the angles at which light rays hit it. From these angles, we can determine, for example, the distance between an object and its reflection. We call these methods geometrical optics.

In geometrical optics, we represent light rays as straight arrows to show how light propagates. Light rays are not an exact description of the light; rather they show the direction in which the light wavefronts are travelling.

We can only see an object when light from the object enters our eyes. The object must either be a source of light (e.g. a light bulb) or it must reflect light from a source (e.g. the moon which reflects light from the sun), and the light must enter our eyes.

When light interacts with an object or a medium, such as glass or water, it displays certain characteristic behaviours: it can be reflected, refracted, absorbed or transmitted. Let us look at reflection in more detail.

Reflection

Reflection occurs when a wave bounces off a surface, such as when light hits a shiny material such as polished metal or a mirror. Figure 2 shows a summary of what happens when light is reflected off a smooth reflective surface.

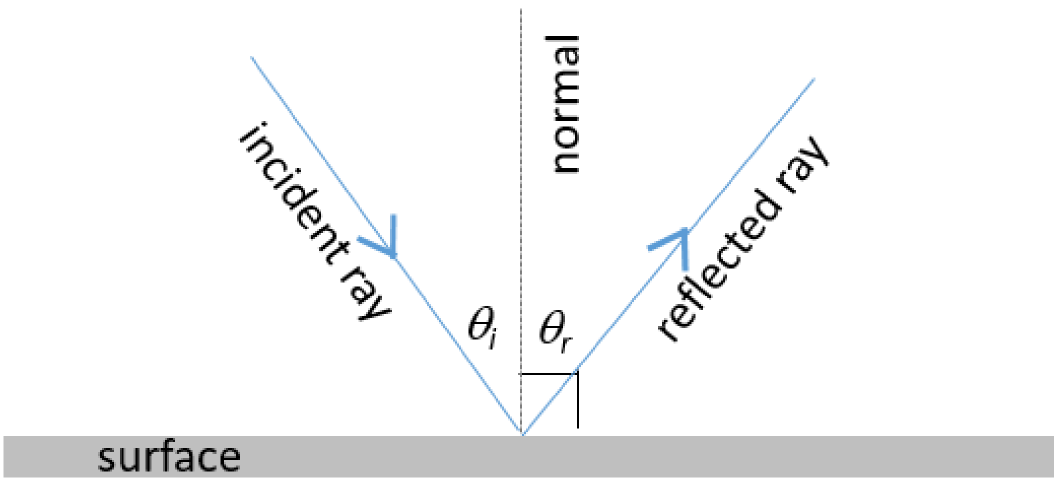


Figure 2: Reflection of light

- The light ray that falls on the surface is called the *incident ray*. The light ray moving away from the surface is the *reflected ray*.
- The angle of the light ray in relation to the reflecting surface determines the nature of the reflection. These angles are measured with respect to the *normal* of the surface. The normal is an imaginary line perpendicular to the surface.
  - The *angle of incidence*, θ_i, is measured between the incident ray and the normal.
  - The *angle of reflection*, θ_r, is measured between the reflected ray and the normal.
- When light is reflected, the angle of incidence is equal to the angle of reflection.
- The incident ray, the reflected ray and the normal all lie in the same plane.

The **law of reflection** states that the angle of incidence is equal to the angle of reflection: $\theta_\text{i} = \theta_\text{r}$ and the incident ray, the reflected ray and the normal all lie in the same plane.

From the law of reflection, it therefore follows that if a light ray strikes a surface at $60°$ to the normal, the angle that the reflected ray makes with the normal will also be $60°$, as shown in the following ray diagram.

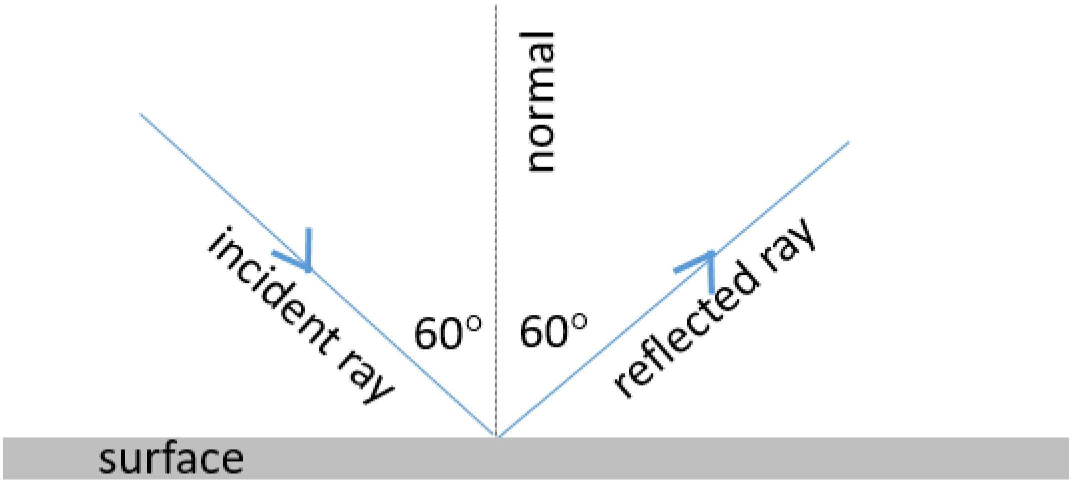


Figure 3: Law of reflection

Exercise 1.1

1. A ray of light strikes a surface at $15°$ to the normal.
   a. Draw a simple ray diagram showing the incident ray, reflected ray and surface normal.
   b. Fill in the angles of incidence and reflection on the diagram.
2. A ray of light strikes a surface at $25°$. Draw a ray diagram showing the incident ray, reflected ray and surface normal. Calculate the angles of incidence and reflection and fill them in on your diagram.

The full solutions are at the end of the unit.

Refraction

In the previous section we studied light reflecting off various surfaces. What happens when light passes from one medium into another, in other words it crosses a boundary between two mediums?

As you learnt in SO 3.1 Unit 3, the speed of a wave depends on the properties of the medium it travels in. When a wave crosses into a denser medium, it slows down. Conversely, when it crosses into a less dense medium, it speeds up. The same applies to light, because light is also a wave. In the case of light, we refer to the optical density of the medium. You will learn more about this later in this unit.

One of the most exciting discoveries in physics during the last century, and the cornerstone of Einstein's theory of relativity, is that light travels at a *constant* speed in a given medium. Light also has a *maximum* speed at which it can propagate, and nothing can move faster than the speed of light.

Light travels at its maximum speed through a vacuum. We use the symbol *c* to represent the speed of light in a vacuum and approximate it as $c = 3 \times 10^8 \text{ m} \cdot \text{s}^{-1}$. The speed of light in air is very close to that in a vacuum, and therefore we can confidently use this value for calculations that involve light travelling through air.

The speed of light is constant in a given medium and has a maximum speed in a vacuum:
$c = 3 \times 10^8 \text{ m} \cdot \text{s}^{-1}$

When light moves from one medium into another (for example, from air to glass), its speed changes. This change in speed is usually associated with a change in the direction of the light ray. That is, if the light ray hits the boundary of the new medium (for example, the edge of a glass block) at any angle that is not perpendicular to or parallel with the boundary, the light ray will change its direction through the next medium. The light ray will therefore appear to 'bend'. This is called refraction of light. It is important to note that while the speed of the light changes when it passes into the new medium, the frequency of the light remains the same.

Refraction is nicely demonstrated when you look from above but at an angle at a drinking straw in a glass of water. The straw appears bent in the liquid. This is because the light rays reflecting off the straw change direction when they hit the surface between the liquid and the air. Your eyes trace the light rays backwards as straight lines to the point they would have come from if they had not changed direction and as a result you see the tip of the straw as being shallower in the liquid than it really is, as shown in Figure 4.

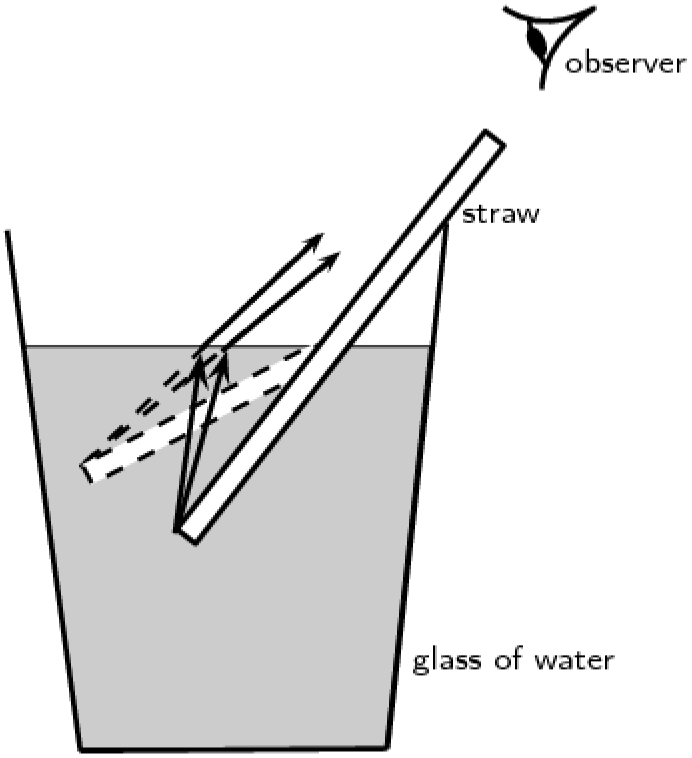


Figure 4: Refraction causes an object in water to appear bent

Refractive index and optical density

The speed of light, and therefore the degree of bending of the light, depends on the **refractive index** of the material through which the light passes. The refractive index (symbol *n*) is the ratio of the speed of light in a vacuum to its speed in the material, and gives an indication of how difficult it is for light to get through the material.

The refractive index of a material is given as $n = \frac{c}{v}$ where: n = refractive index (no unit) c = speed of light in a vacuum ($3 \times 10^{8}\ \text{m} \cdot \text{s}^{-1}$) v = speed of light in a given medium (m.s^{-1})

From the definition of the refractive index, $n = \frac{c}{v}$, we can see that the speed of light in a given medium (*v*) and the refractive index (*n*) are inversely proportional. Because the speed of light in a vacuum (*c*) is constant, it follows that if the refractive index increases, the speed of light in the material must decrease. Therefore light travels slower through materials of high refractive index.

Table 1 shows refractive indices for various materials. Light travels slower in any material than it does in a vacuum, so all values for n are greater than 1.

Table 1: Refractive indices of various materials

Refractive indices					
Gases		**Liquids**		**Solids**	
Vacuum	1	Liquid water (20°)	1.333	Ice	1.31
Helium	1.000036	Acetone	1.36	Fused quartz	1.46
Air	1.0002926	Ethanol	1.36	Glass	1.5 to 1.9
Carbon dioxide	1.00045	Glycerine	1.4729	Sodium chloride (table salt)	1.59
		Sugar solution (80%)	1.49	Diamond	2.419
				Silicon	4.01

Optical density is a measure of the refracting power of a medium. In other words, the higher the optical density, the more the light will be refracted or slowed down as it moves through the medium. Optical density is related to refractive index in that materials with a high refractive index will also have a high optical density. Light will travel slower through a medium with a high refractive index and high optical density, and faster through a medium that has a low refractive index and a low optical density.

Example 1.1

Calculate the speed of light through glycerine.

Solution

From Table 1, we know that the refractive index (*n*) of glycerine is 1.4729. We also know that the speed of light in a vacuum is a constant: $c = 3 \times 10^{8}\ \text{m} \cdot \text{s}^{-1}$.

To calculate the speed of light in glycerine, we rearrange the equation $n = \frac{c}{v}$ to make speed the subject:

$$\begin{aligned} v &= \frac{c}{n} \\ &= \frac{3 \times 10^{8}\ \text{m} \cdot \text{s}^{-1}}{1.4729} \\ &= 2.04 \times 10^{8}\ \text{m} \cdot \text{s}^{-1} \end{aligned}$$

Activity 1.1: Explore how light bends

Time required: 10 minutes

What you need:

- an internet connection
- a computer or tablet
- a calculator

- a pen and a notebook

What to do:

1. Access the simulation called Bending light.

   Choose the 'Intro' option.
2.
   a. Set both mediums to 'Air' using the control panels on the right of the screen. Notice that the horizontal line represents the boundary between the two mediums. The dashed vertical line represents the normal to the surface.
   b. Switch on the torch. What do you notice?

   > **Note**
   >
   > You can also move the torch around to change the angle of the beam.

   c. Set both mediums to water or glass now. What do you notice?
3. Now set the bottom medium to water.
   a. Notice the index of refraction.
   b. How did the direction of the light beam change?
   c. What does the feint line above the boundary represent?
4. Now set the incident medium to a higher index of refraction (e.g. water) and let the refracting medium have a lower index (e.g. air). Notice the appearance of the reflected ray.
   a. How does the direction of the beam change?
   b. What happens when you increase the index of refraction of the refracting medium gradually?
   c. What change do you notice in the reflected ray?
5. Make the two mediums the same again (e.g. air, $n = 1.00$). Increase the index of refraction of the incident medium (top) gradually using the slider.
   a. How does the reflected ray change?
   b. Up to what point does the angle of refraction keep on increasing? What happens after that point?

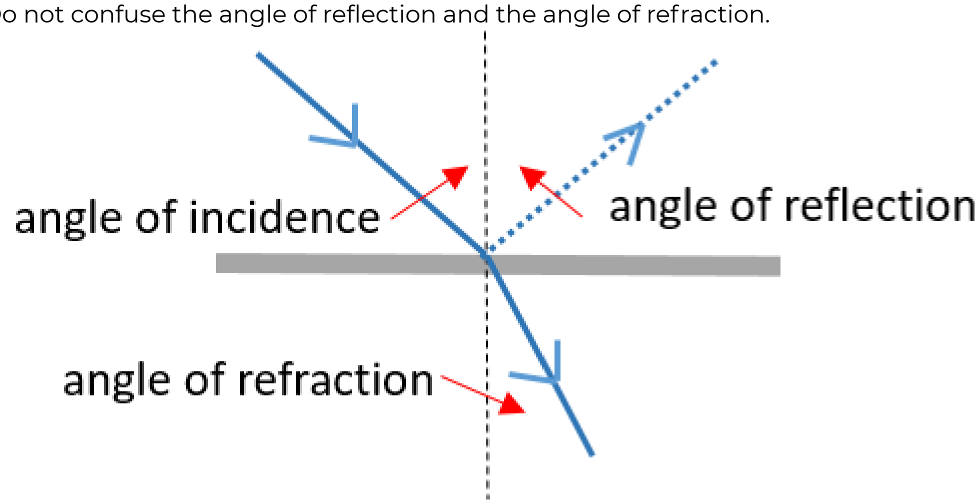
What did you find?

- The light beam travels straight when the mediums are the same; no refraction occurs (step 2). It does not matter whether the refractive index is high or low; as long as they are the same for both mediums, no refraction occurs.
- The index of refraction of the bottom medium is now 1.33 (step 3), which is higher than the index

of refraction of air ($n = 1.00$). The light ray now bends towards the normal, and the angle of refraction is smaller than the angle of incidence. The higher index of refraction tells us that the optical density has increased. The wave therefore slows down in the refracting medium, which causes it to bend towards the normal.
We also notice a feint ray above the boundary, which shows that some reflection also occurs. Notice that the angle of incidence is equal to the angle of reflection: $\theta_i = \theta_r$.

Take note!

Do not confuse the angle of reflection and the angle of refraction.



- When the refracting medium (bottom) has a lower optical density compared with the incident (top) medium (step 4), the ray bends away from the normal, and the angle of refraction becomes bigger than the angle of incidence. The wave therefore moves faster through the refracting medium and so bends away from the normal.
  The angle of refraction decreases as the index of refraction is increased. This is because the optical density increases, and the wave moves slower. The ray therefore bends towards the normal again. The more the ray is refracted towards the normal, the feinter the reflected ray becomes. This tells us that there is less reflection off the surface of the boundary.
- When the index of refraction of the incident medium is higher than that of the refracting medium (step 5), the refracted ray will bend way from the normal. At some critical index, the angle of refraction exceeds 90° and all the light it reflected off the boundary surface. No refraction occurs beyond this value. You will learn more about this phenomenon later in the section.

Ray diagrams of refraction

It is useful to draw ray diagrams to understand how the geometrical optics concepts work. In ray diagrams, we have to show the:

- incident ray
- refracted ray
- angle of incidence
- angle of refraction
- boundary between the mediums
- normal.

It is useful to label the mediums or at least show the indices of refraction.

Also remember the following concepts:

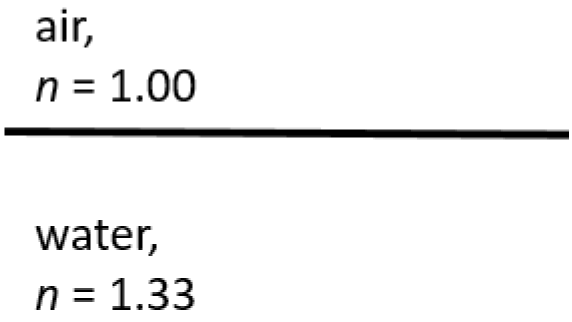
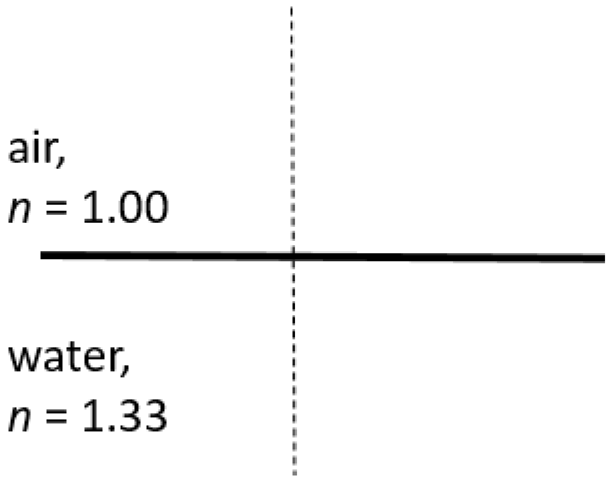
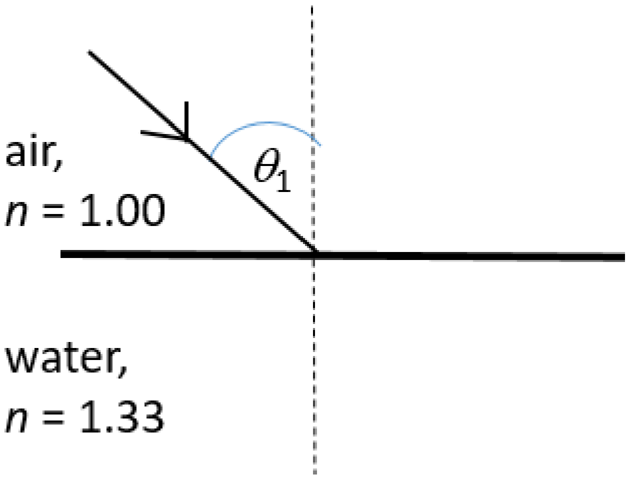
- normal – the line that is perpendicular to the plane of the surface
- angle of incidence – the angle between the normal and the incident light ray
- angle of refraction – the angle between the normal and the refracted light ray.

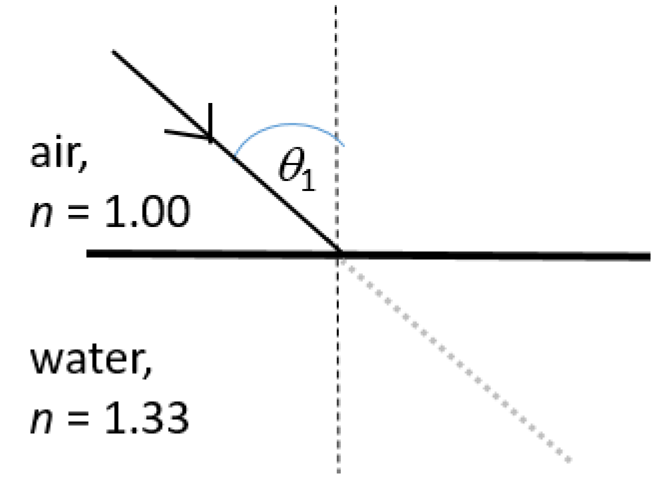
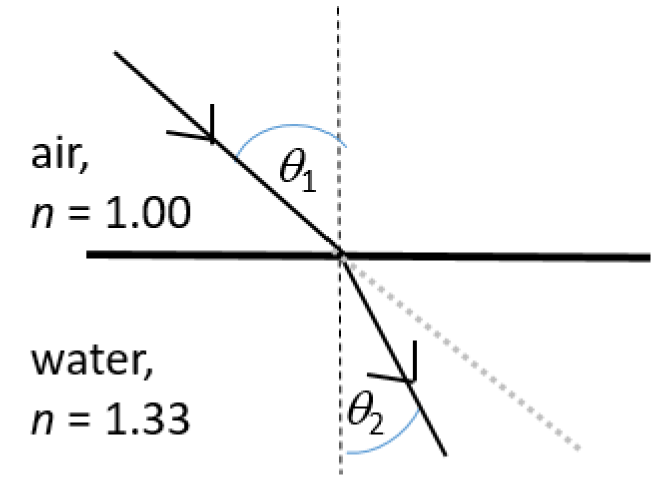
Let's look at an example.

Example 1.2

Draw a ray diagram to show the refraction of a light ray moving from air $(n = 1.00)$ into water $(n = 1.33)$.

Solution

	• Draw a line to represent the boundary between the two mediums. Label each medium.
	• Draw a dotted line perpendicular to the boundary. This is the normal.
	• Draw a straight arrow from the incident medium to hit the boundary at an angle. This is the incident ray. It is useful to label the angle.

	• Consider the index of refraction of the second medium compared with that of the incident medium. It is useful to draw a feint line to show the direction of the ray if were not refracted, to serve as a reference. ◦ If the ray moves into a medium with a higher index of refraction (that is, higher optical density), it will bend towards the normal. The angle of refraction will be smaller than the angle of incidence. ◦ Conversely, if the light ray moves into a medium of lower optical density (in other words, with a smaller index of refraction), it will bend away from the normal. The angle of refraction will therefore be bigger than the angle of incidence.
	• Use the rules described here to draw the refracted ray as a straight arrow at an appropriate angle. Label the angle.

Activity 1.2: Understand refraction of light

Time required: 15 minutes

What you need:

- a computer, tablet or phone connected to the internet
- a pen and a notebook

What to do:

1. Watch the video called Refraction of light (Duration 09.40).

2. Note the angle of incidence.
3. Describe how the direction of the ray changes as it moves through the glass block.

What did you find?

- The angle of incidence is $30°$. The pins show the path of light in air. Connecting the point of entrance into and point of exit out of the glass shows the path of the ray inside the glass block. We can see that the ray was refracted twice: once when it moved from the air into the glass block, and again when it moved out of the glass block back into the air.
- When the light entered the glass block, it bent towards the normal: the angle of refraction is smaller than the angle of incidence.
- A new angle of incidence is defined for the ray that strikes the boundary between glass and air at the exit point. When the light moved out of the glass block, back into air, this ray bent away from the normal. The angle of refraction is bigger than the newly defined angle of incidence.

Total internal reflection

Recall from the last part of Activity 1.1 that for a specific combination of optical mediums, no refraction occurred when the light ray moved from the optically denser medium into the one that was less dense. Instead all the light was reflected. This phenomenon is called total internal reflection. In other words, all the light is reflected back into the incident medium once it hits the boundary between the two mediums.

Total internal reflection is a special case of refraction (see Figure 5). For each pair of optical mediums there is a specific angle – called the critical angle – at which an incident ray will be refracted by $90°$ when it reaches the boundary between the two mediums. If the incident ray strikes the boundary between the two mediums at any angle greater than the critical angle, the light ray will be reflected back into the incident medium, and not be refracted at all.

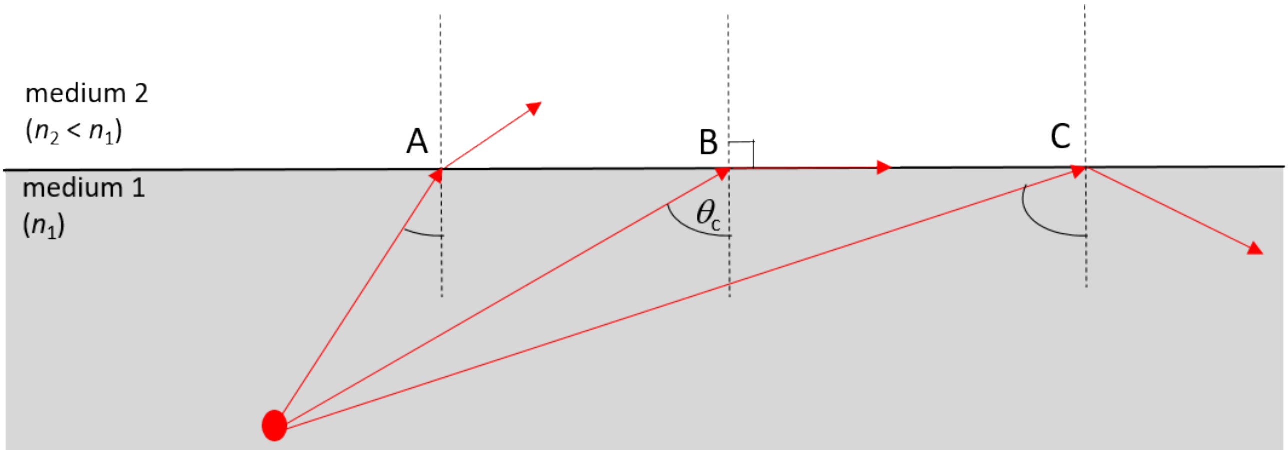


Figure 5: (A) When a light ray moves from an optically denser medium to one that is less dense, it is refracted away from the normal if the angle of incidence is smaller than the critical angle.
(B) When the angle of incidence is equal to the critical angle (θ_c), the light ray is refracted by $90°$.
(C) When the angle of incidence is greater than the critical angle, no refraction occurs and the light ray is reflected back into the incident medium.

Do Activity 1.3 to explore critical angles and total internal reflection.

Activity 1.3: Explore critical angles and total internal reflection

Time required: 5 minutes

What you need:

- an internet connection
- a computer or tablet
- a calculator
- a pen and a notebook

What to do:

1. Access the simulation called Bending light.

   Choose the 'Intro' option.
2. Set the incident medium (top) to 'Water' and the other medium (bottom) to 'Air' using the control panels on the right of the screen.
3. Move the torch towards the normal to create a fairly small angle of incidence. Switch on the torch. What do you notice?

4. Move the torch away from the normal to gradually increase the angle of incidence. What do you notice?
5. Increase the angle of incidence some more. What do you notice?

What did you find?

- When the angle of incidence is small (step 3), the light ray is refracted away from the normal at the boundary between the two mediums.
- As the angle of incidence increases (step 4), the angle of refraction also increases. Beyond a specific angle, the light ray is not refracted at all, but rather reflected back into the incident medium.
- The light ray remains internally reflected even as the angle of incidence increases more (step 5). The angle of incidence is always equal to the angle of reflection.

The two conditions for total internal reflection are that:

1. light must be travelling from an optically denser medium (higher refractive index) to an optically less dense medium (lower refractive index)
2. the angle of incidence must be greater than the critical angle for the pair of mediums.

Total internal reflection is useful in optical instruments such as binoculars and telescopes because light is reflected with very little loss. This helps to create sharp images.

Total internal reflection is also used in fibre-optic technology. An optical fibre is a very thin, transparent fibre, usually made of glass or plastic, for transmitting light. The basic functional structure of an optical fibre consists of an outer protective cladding and an inner core through which light pulses travel. The overall diameter of the fibre is about $125\ \mu\text{m}$ and that of the core is only about $50\ \mu\text{m}$.

The difference in refractive index of the cladding and the core allows total internal reflection to occur in the same way as happens at an air–water surface. If light is incident on a cable end with an angle of incidence greater than the critical angle, then the light will remain trapped inside the glass strand. In this way, light travels very quickly down the length of the cable.

Calculating the critical angle

Remember that each pair of optical mediums has a specific critical angle. For example, the critical angle for light moving from glass to air is 42°, and that of water to air is 48.8°.

Instead of always having to measure the critical angles of different materials, it is possible to calculate the critical angle at the surface between two media using **Snell's Law**.

Snell's Law states:
$n_1 \sin\theta_1 = n_2 \sin\theta_2$

where n_1 is the refractive index of material 1, n_2 is the refractive index of material 2, θ_1 is the angle of incidence and θ_2 is the angle of refraction.

For total internal reflection, we know that the angle of incidence is the critical angle. So: $\theta_2 = \theta_{\text{c}}$.
However, we also know that the angle of refraction at the critical angle is 90°. So we have:
$\theta_2 = 90^{\circ}$

We can then write Snell's Law as:
$n_1 \sin\theta_c = n_2 \sin 90^\circ$

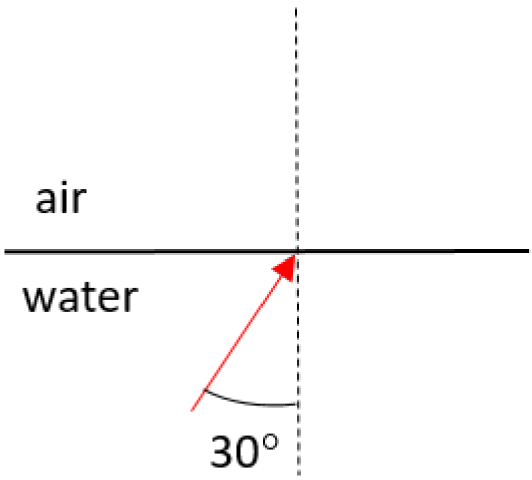
Solving for θ_c gives:

$$\begin{aligned} n_1 \sin\theta_c &= n_2 \sin 90^\circ \\ \sin\theta_c &= \frac{n_2}{n_1}(1) \\ \therefore \theta_c &= \sin^{-1}(\frac{n_2}{n_1}) \end{aligned}$$

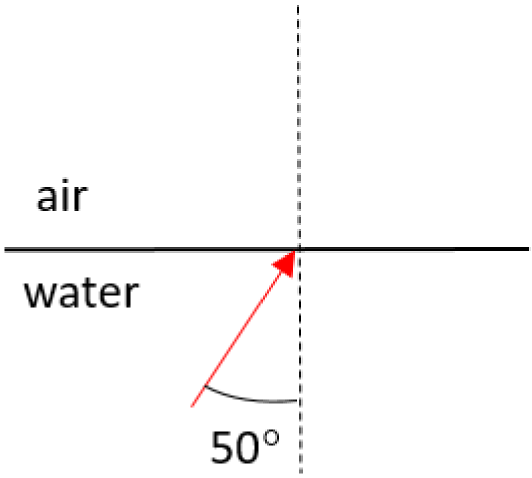
Exercise 1.2

1. Describe total internal reflection by using a diagram and referring to the conditions that must be satisfied for total internal reflection to occur.
2. Define what is meant by the critical angle when referring to total internal reflection. Include a ray diagram to explain the concept.
3. Complete the following ray diagrams to show the path of light in each situation.

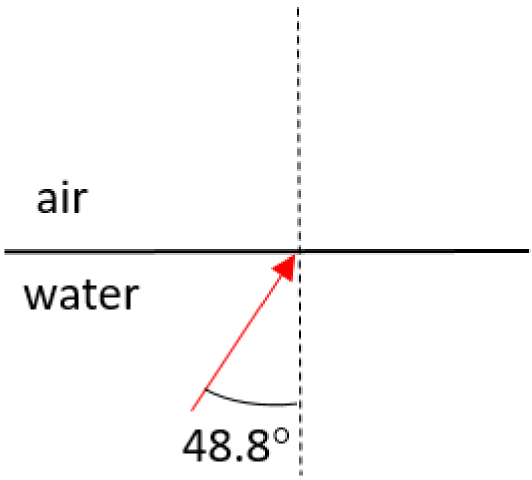
a.



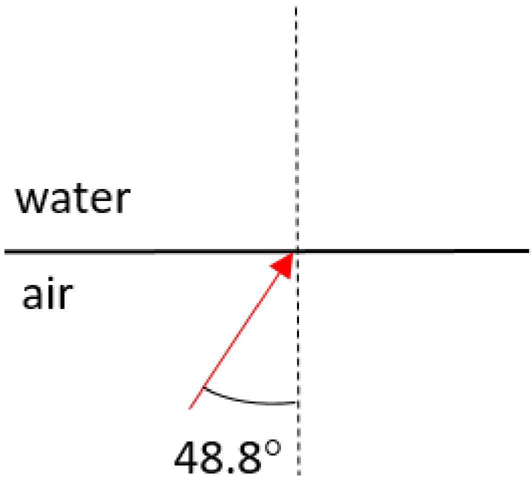
b.



c.



d.



The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- Light energy travels as a wave.
- The study of how light interacts with materials is called optics.
- In geometrical optics, we represent light rays as straight arrows to show how light propagates.
- Reflection occurs when a wave bounces off a surface, such as when light hits a shiny material like polished metal or a mirror.
- The law of reflection states that the angle of incidence is equal to the angle of reflection: $\theta_{\text{i}} = \theta_{\text{r}}$. The incident ray, the reflected ray and the normal all lie in the same plane.
- When light moves from one medium into another at an angle, its speed changes and consequently it changes direction. The light ray will therefore appear to 'bend'. This is called refraction of light.
- The speed of light, and therefore the degree of refraction, depends on the refractive index of the material through which the light passes.
- The refractive index of a material is given as $n = \frac{c}{v}$.
- Light travels at its maximum speed through a vacuum: $c = 3 \times 10^{8}\ \text{m.s}^{-1}$.

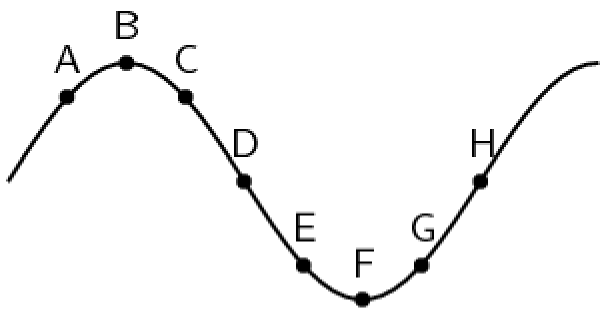
- Optical density is a measure of the refracting power of a medium. The higher the optical density, the more the light will be refracted (slowed down) as it moves through the medium.
- Ray diagrams are useful to understand refraction. A ray diagram shows the incident and refracted rays, the angles of incidence and refraction, the boundary between the mediums, and the normal ray.
- When light travels from an optically denser medium to one that is less dense, the ray will be refracted by 90° if the angle of incidence is equal to the critical angle for the combination of mediums.
- Total internal reflection occurs for any angle of incidence greater than the critical angle when light travels from an optically denser medium to one that is less dense.
- Total internal reflection is useful in applications such as fibre optics, telescopes and binoculars.

Unit 1: Assessment

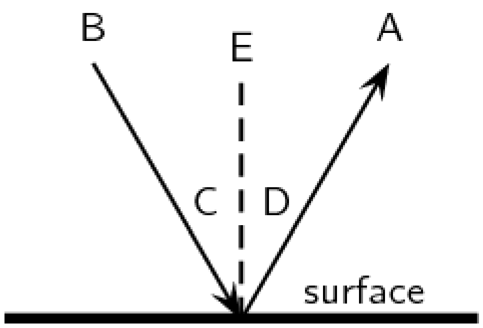
Suggested time to complete: 35 minutes

Questions were taken from exercises 5-1, 5-2, 5-3 and the End-of-Chapter exercise in the [Siyavula Gr 11 Physical Science Learner's Book on pp. 199–200, 205, 210–211, and 230–231](), released under a CC-BY licence.

1. Give one word for each of the following descriptions:
    a. The perpendicular line that is drawn at right angles to a reflecting surface at the point of incidence.
    b. The bending of light as it travels from one medium to another.
    c. The bouncing of light off a surface.
2. The diagram below shows a curved surface. Draw normals to the surface at the marked points.

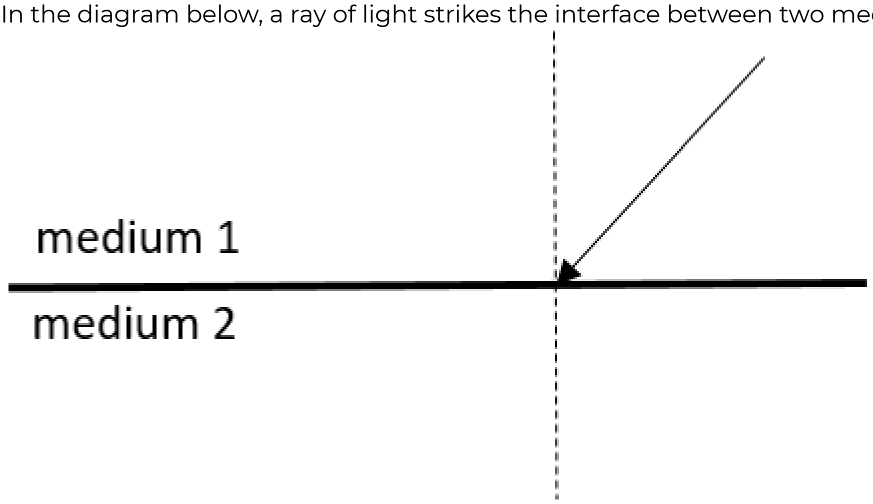


3. Which of the labels, A–E, in the diagram, correspond to the following:



    a. normal
    b. angle of incidence
    c. angle of reflection
    d. incident ray
    e. reflected ray

4. Use the values given in Table 1, and the definition of refractive index, to calculate the speed of light in water (ice).
5. Calculate the refractive index of an unknown material through which the speed of light is $1.974 \times 10^8\ \text{m} \cdot \text{s}^{-1}$. Round off your answer to two decimal places. Using Table 1, identify what the unknown material is.
6. A ray of light leaves a surface at $65°$ to the surface. Draw a ray diagram showing the incident ray, the reflected ray and the normal. Calculate the angles of incidence and reflection and fill them in on the diagram.
7. Light travels from glass ($n = 1.5$) to acetone ($n = 1.36$).
   a. Describe the path of light as it moves into the acetone.
   b. What happens to the speed of the light as it moves from the glass to the acetone?
   c. What happens to the wavelength of the light as it moves into the acetone?
8. In the diagram below, a ray of light strikes the interface between two mediums.



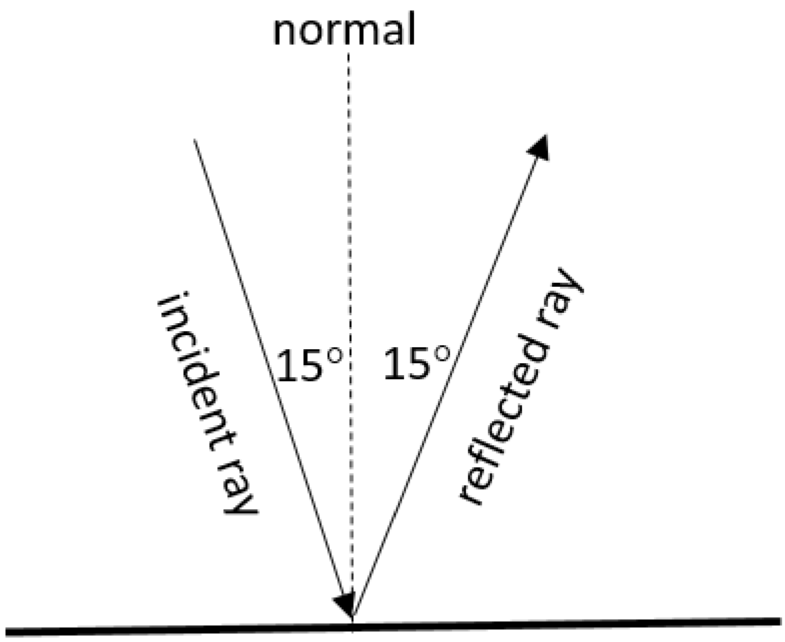
   Draw what the refracted ray would look like if:
   a. medium 1 had a higher refractive index than medium 2.
   b. medium 1 had a lower refractive index than medium 2.
9. Will light travelling from diamond to silicon undergo total internal reflection? Give a reason for your answer.
10. Light travelling from diamond to water strikes the interface with an angle of incidence of $86°$. Determine whether the light will be refracted or totally internally reflected. Draw a diagram to support your answer.

The full solutions are at the end of the unit.

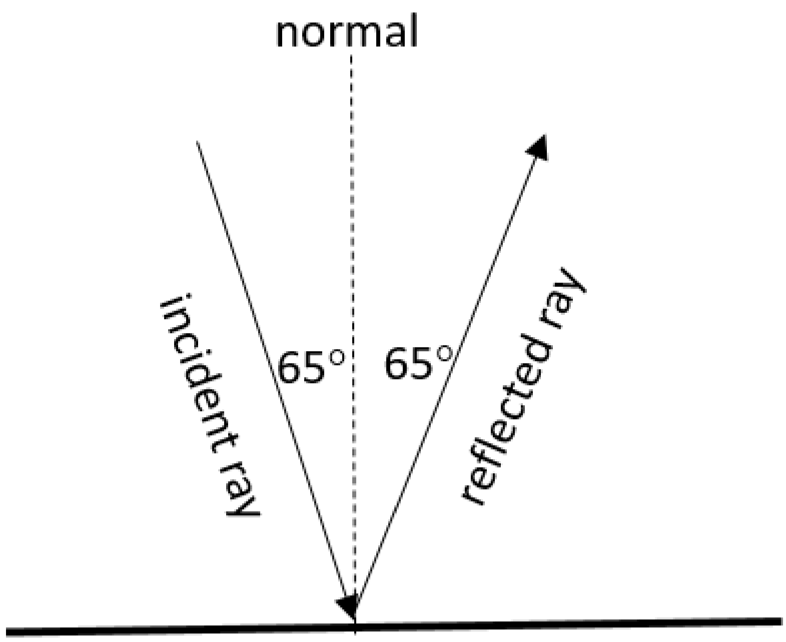
Unit 1: Solutions

Exercise 1.1

1.
   a. and b.



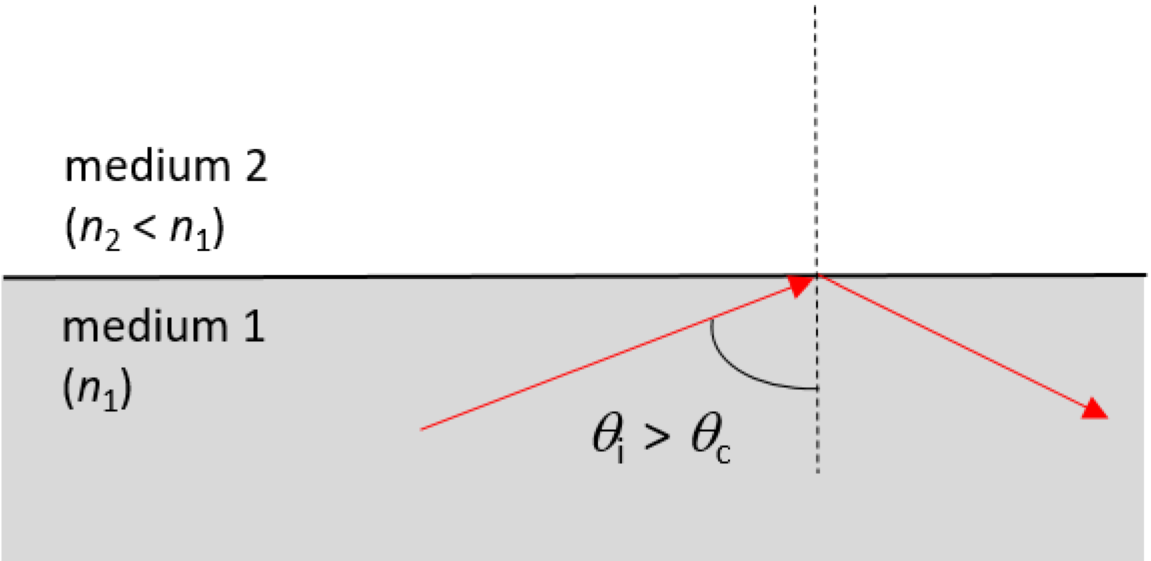
2. If the ray strikes the surface at 25°, it means the ray makes an angle of $90^\circ - 25^\circ = 65^\circ$ with the normal, which represents the angle of incidence.



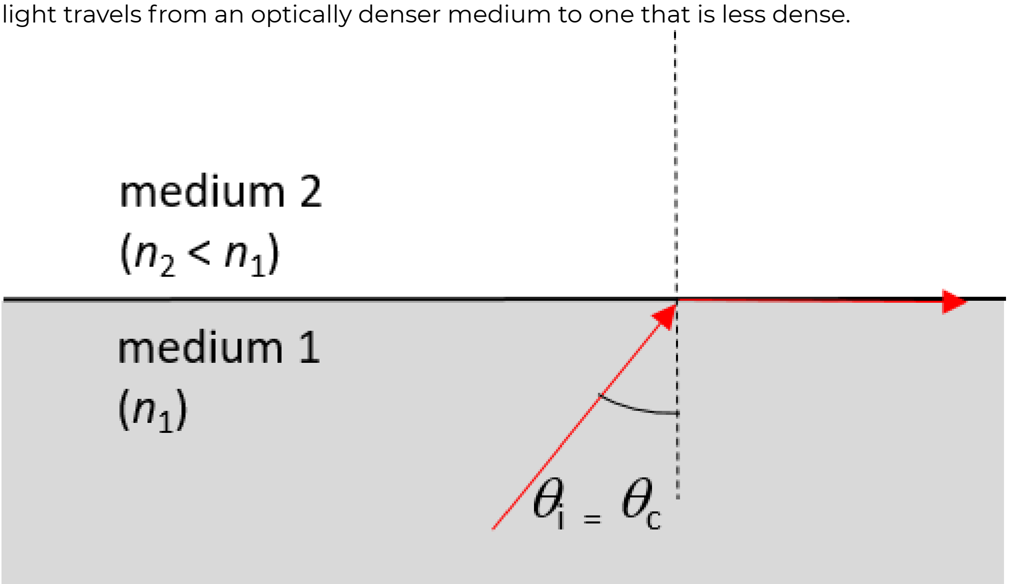
Back to Exercise 1.1

Exercise 1.2

1. Total internal reflection occurs when light travelling from an optically denser medium to one that is less dense strikes the boundary between the mediums at an angle greater than the critical angle.



2. The critical angle is the angle of incidence that will result in a light ray being refracted by 90° when light travels from an optically denser medium to one that is less dense.

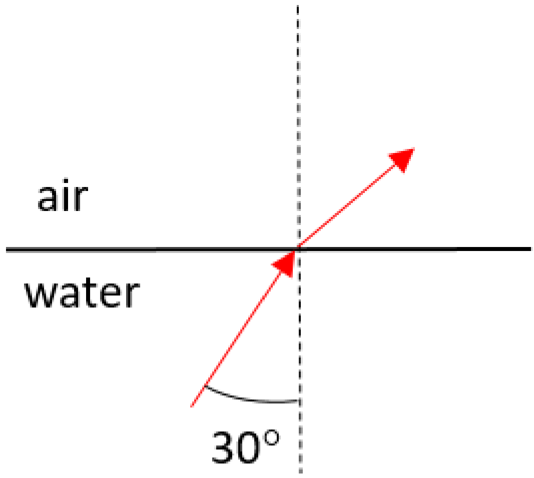


3. First determine the critical angle for the air–water combination. If the light ray moves from water (medium 1) to air (medium 2), as in diagrams (a)–(c), $n_1 = 1.33$ and $n_2 = 1.00$.

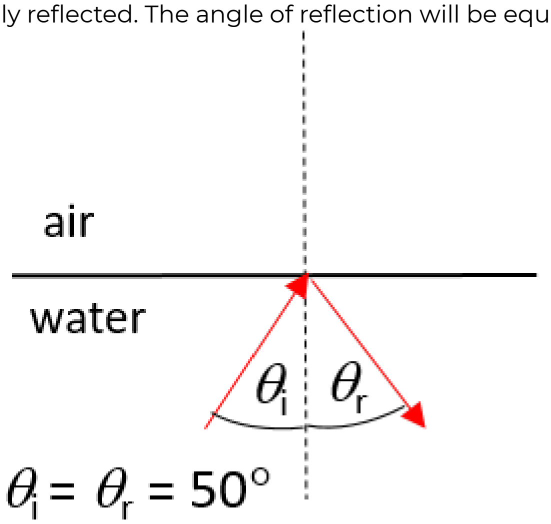
   From Snell's law:

$$\begin{aligned} n_1 \sin\theta_c &= n_2 \sin 90^\circ \\ \sin\theta_c &= \frac{1.00}{1.33}(1) \\ \therefore \theta_c &= \sin^{-1}(0.7518) \\ &= 48.8^\circ \end{aligned}$$

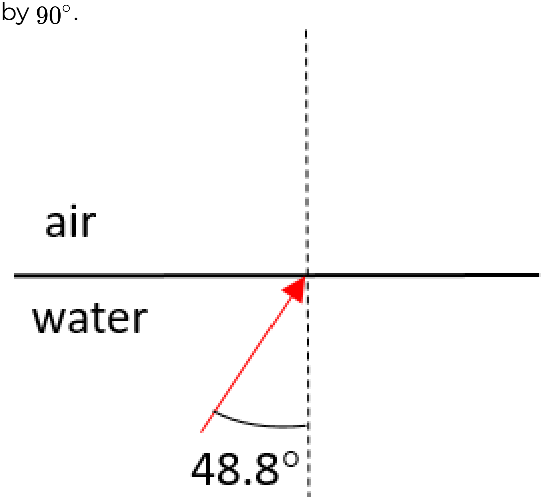
   a. $\theta_i = 30^\circ$, which is smaller than the critical angle (48.8°). The light ray will therefore be refracted away from the normal as it moves into the air.



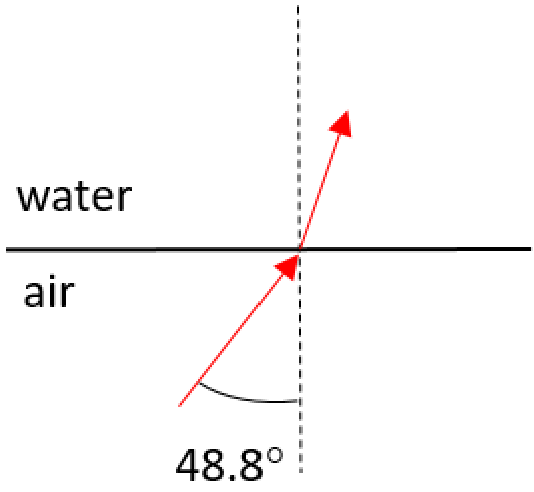
b. $\theta_{\text{i}} = 50°$, which is greater than the critical angle ($48.8°$). The light ray will therefore be totally internally reflected. The angle of reflection will be equal to the angle of incidence.



c. The angle of incidence is equal to the critical angle: $48.8°$. The light ray will therefore be refracted by $90°$.



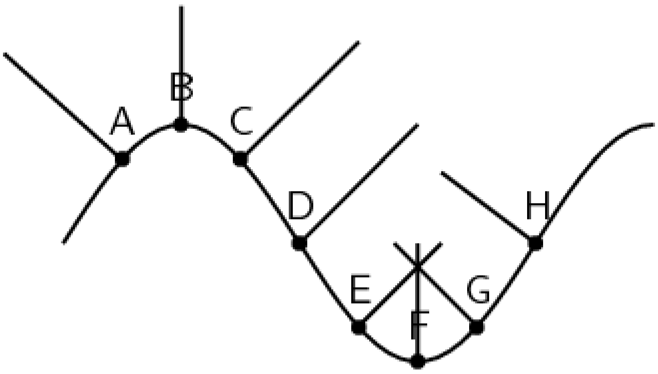
d. The light ray now moves from air ($n = 1.00$) to water ($n = 1.33$). Air is optically less dense than water, so we know that the light ray will be refracted towards the normal; internal reflection is not possible.



Back to Exercise 1.2

Unit 1: Assessment

1.
   a. normal
   b. refraction
   c. reflection
2.



3.
   a. E
   b. C
   c. D
   d. B
   e. A
4. The refractive index of ice is 1.31. To calculate the speed of light in ice:

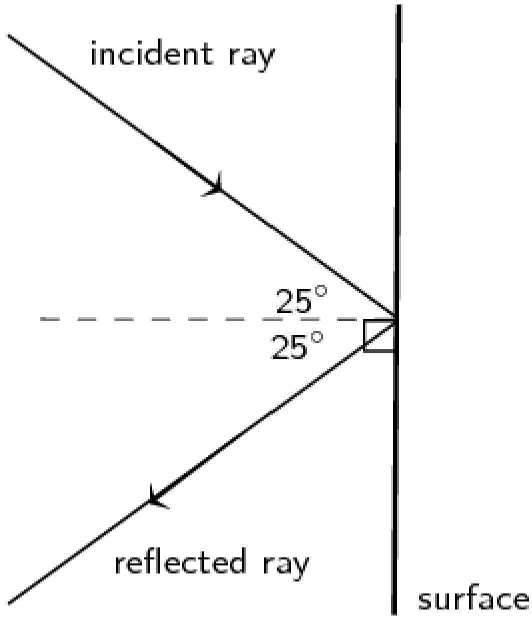
$$
\begin{aligned}
n &= \frac{c}{v} \\
\therefore v &= \frac{c}{n} \\
&= \frac{3.8 \times 10^8 \text{ m} \cdot \text{s}^{-1}}{1.31} \\
&= 2.29 \times 10^8 \text{ m} \cdot \text{s}^{-1}
\end{aligned}
$$

5.

$$
\begin{aligned}
n &= \frac{c}{v} \\
&= \frac{3.8 \times 10^8 \text{ m} \cdot \text{s}^{-1}}{1.974 \times 10^8 \text{ m} \cdot \text{s}^{-1}} \\
&= 1.52
\end{aligned}
$$

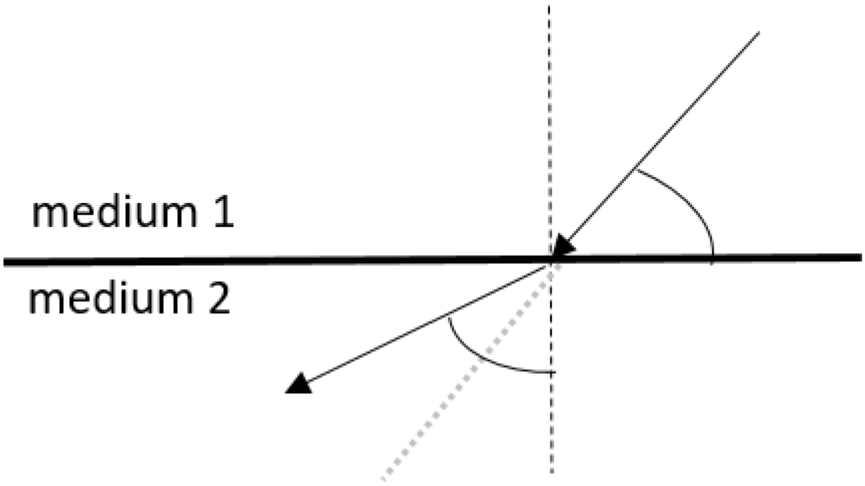
According to the values in Table 1, the material is a form of glass.

6. The angle between the reflected ray and the *surface* is 65°. This means the angle between the reflected ray and the normal (the angle of reflection) must be $90^\circ - 65^\circ = 25^\circ$. The law of reflection states that the angle of reflection is equal to the angle of incidence. Therefore, the angle of incidence is 25°.

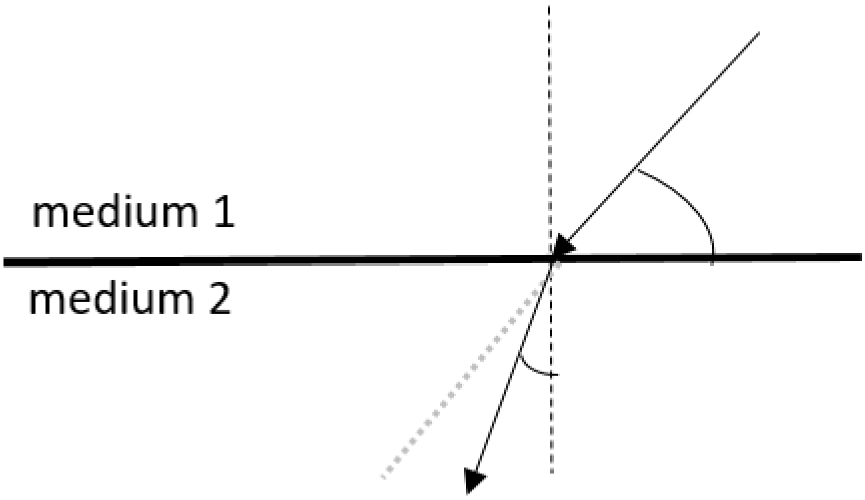


7.
   a. The ray bends away from the normal.
   b. The speed increases.
   c. The wavelength increases because the frequency remains constant.

8.
   a.



b.

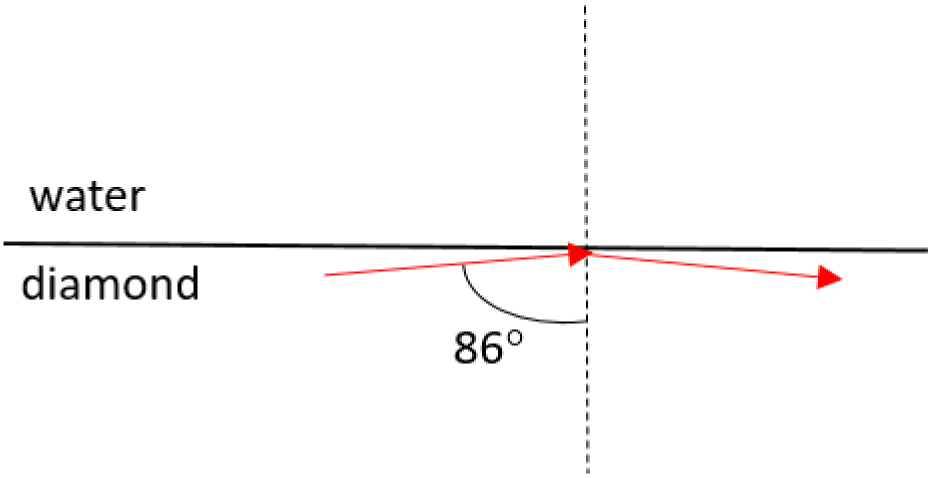


9. Diamond ($n = 2.42$) is optically less dense than silicon $n = 4.01$ and so total internal reflection cannot occur.
10. The light ray moves from an optically denser medium, diamond ($n_1 = 2.42$) to an optically less dense medium, water ($n_2 = 1.33$). Total internal reflection is therefore possible if the critical angle is exceeded.

    From Snell's law:

    $$\begin{aligned} n_1 \sin\theta_c &= n_2 \sin 90^\circ \\ \sin\theta_c &= \frac{n_2}{n_1}(1) \\ \sin\theta_c &= \frac{1.33}{2.42}(1) \\ \therefore \theta_c &= \sin^{-1}(0.5496) \\ &= 33.34^\circ \end{aligned}$$

    $\theta_i = 86^\circ$, which exceeds the critical angle, and therefore the light will be internally reflected. Note that the angle of reflection will be equal to the angle of incidence, in accordance with the law of reflection.



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Unit 2: More on reflection of light

LINDA PRETORIUS

Unit outcomes

By the end of this unit you will be able to:

- Draw diagrams showing reflection with reference to plane, concave and convex mirrors, indicating for each diagram:
  - the angle of incidence
  - the angle of reflection
  - the type and size of the image and the distance at which it is formed.

What you should know

Before you start this unit, make sure you can:

- Describe what reflection is, as covered in Subject outcome 3.2, Unit 1.
- State the law of reflection, as covered in Subject outcome 3.2, Unit 1.
- Interpret a diagram showing reflection, as covered in Subject outcome 3.2, Unit 1.

Introduction

In this unit you will learn how the principle of reflection applies to mirrors. You will also learn to draw ray diagrams to understand how images are formed by different types of mirrors.

An introduction to mirrors and images

We see mirrors all around us in everyday life. A mirror is useful to check whether we look neat before we go out, or to shave or put on make-up in the bathroom. In a car, rear-view and side mirrors help us to see what is happening on the road behind us. We also use mirrors in alleys, hallways or on the corner of roads to show oncoming traffic. We use mirrors even in space, and to understand more about the universe. Telescopes, such as the Southern African Large Telescope in Sutherland and the Hubble Space Telescope, use mirrors to reflect and focus light.

A mirror is a shiny, polished surface that reflects light to produce a representation of an object, called an image. An image is formed at a point in space where all the light rays reflecting off the mirror's surface intersect, or appear to intersect.

There are different types of mirrors (see Figure 1). A mirror with a flat surface is called a **plane mirror**. In contrast, the reflective surface of a **spherical mirror** is curved, and can be either concave or convex. In a concave mirror, the reflective surface bulges inwards; in a convex mirror, it bulges outwards. Figure 2 shows that you can understand a curved mirror as a section cut from a sphere (ball), and then silvered either on the inside to form a concave mirror, or on the outside to form a convex mirror.

Figure 1: Types of mirrors

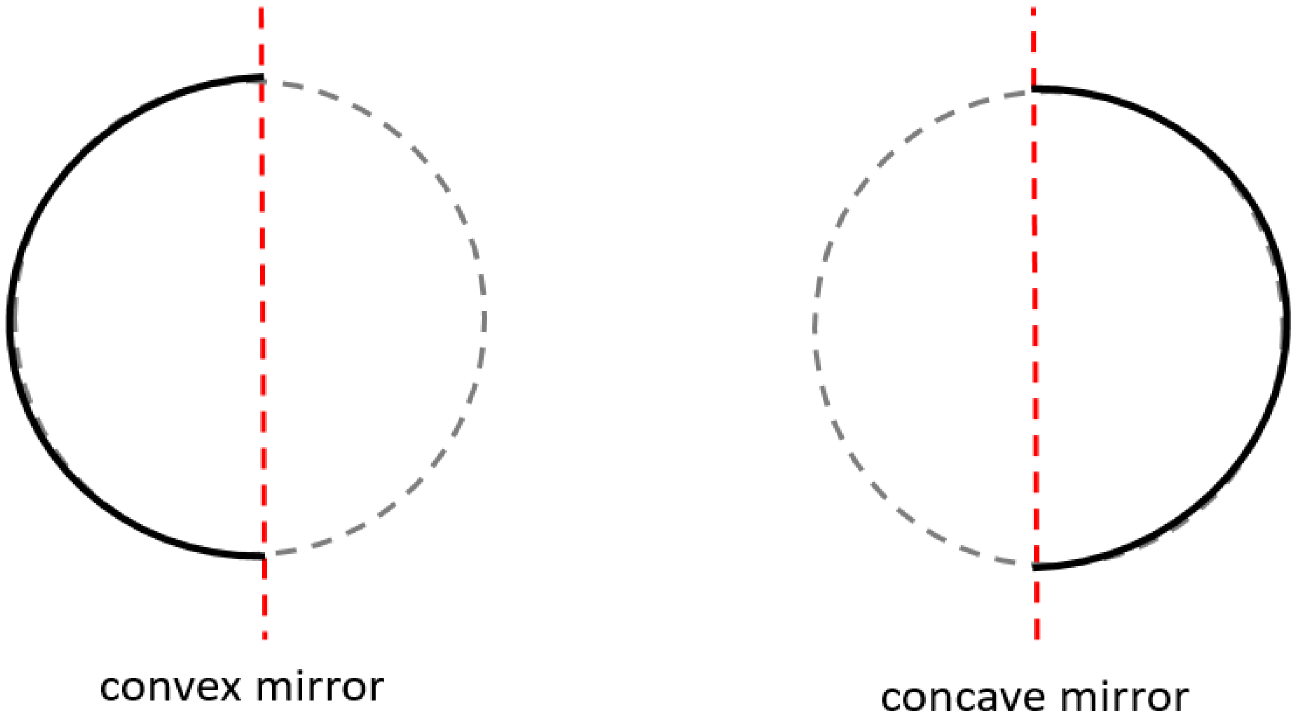


Figure 2: Curved mirrors can be thought of as a section cut from a sphere (dashed lines). The reflective surface is shown as the solid black curve in each diagram.

As you will learn from drawing ray diagrams, mirrors can also be described as converging or diverging based on the way they cause light rays to reflect. Plane mirrors and convex mirrors always cause light rays to diverge; concave mirrors can cause light rays to converge or diverge.

Different types of mirrors form different types of images, which we can describe according to the following characteristics:

- The **location** of the image – in other words *where* the image appears to form relative to the reflective surface, and can either be virtual or real. A virtual image appears to form from *behind* the mirror, which is a virtual (non-real) space. In contrast, a real image appears to form in *front* of the mirror, and therefore in a real (actual) space.
- The **size** of the image can be bigger or smaller than the object. An image that is bigger than the object is magnified; an image that is smaller than the object is reduced.
- The **orientation** of the image can be upright or inverted (upside down).

Activity 2.1: Observe an image formed by a plane mirror

Time required: 5 minutes

What you need:

- a flat reflective surface, such as a bathroom mirror
- a sheet of white paper and a marker pen
- a ruler
- an object of which the top and bottom, and left and right side can be seen clearly (e.g. a small cup).

What to do:

1. Set a plane mirror up against a wall or upright support.
2. Measure out a distance from the edge of the paper to where you will place the object (e.g. $10\ \text{cm}$). Draw a line along the length of this distance on the paper.
3. Place the paper in front of the mirror, with the edge from where you drew the line close to but not touching the edge of the mirror.
4. Put the object behind the line.
5. Describe the image you see in the mirror:
   a. Where does the image appear to form: behind or in front of the mirror?
   b. Is the image bigger, smaller or the same size as the object?
   c. Is the image upright or inverted?
   d. Is the horizontal orientation (in other words, the left and right side) the same in the image as in the object?

What did you find?

- The image appears to be at a point behind the mirror, at the same distance as the object. It is a virtual image.
- The image is upright and it is the same size as the object.
- The left and right sides of the object appear reversed in the image.

Note

If you do not have a mirror to set up the activity described here, go to this simulation to see a similar activity.

Activity 2.2: Observe an image formed by a curved mirror

Time required: 5 minutes

What you need:

- a large, shiny spoon

What to do:

1. Look at the back of the spoon. Is the surface convex or concave?
2. Hold the back of the spoon in front of your face. Describe the image you see in the spoon with regard to its:
   a. location
   b. size
   c. vertical orientation.
3. Move the spoon away from your face. What do you notice?
4. Now turn the spoon around so that you have the bowl (hollow side) in front of your face. Start quite close to your face and then gradually move it away from your face. Describe the image you see in the spoon with regard to its:
   a. location
   b. size
   c. vertical orientation.

What did you find?

- Steps 1–3: The back of the spoon represents a convex mirror. Holding it in front of an object creates an image that appears to be located behind the reflective surface. It is therefore a virtual image. The image is upright and smaller than the actual object. The image becomes smaller when the spoon (reflective surface) is moved away from the object. A wide view of the background is visible.
- Step 4: The bowl of the spoon represents a concave mirror. It creates a real, inverted image that is bigger than the object. When the spoon is moved away from the object, the image becomes

smaller and remains inverted. If you were able to move it away far enough, the image would become upright and virtual at some point, and then start to enlarge.

Ray diagrams for images formed by mirrors

Ray diagrams are useful to help us understand the characteristics of images formed by mirrors. As you learnt in Unit 1, a ray diagram is a diagram that shows the path of light rays as they interact with an optical surface. In the case of a ray diagram for images formed by reflection off mirrors, we can see at what distance an image will form relative to the reflecting surface and what its characteristics will be.

Although light emanates in all directions from an object when the image is formed, drawing only a few specific rays makes it easier to interpret the diagram. To draw a ray diagram for images formed by mirrors, we always show the:

- object
- reflective surface (mirror)
- incident rays
- reflected rays.

Note that each pair of incident and reflected rays are relative to a specific point on the object.

Take note!

To check yourself when drawing ray diagrams for mirror images, always keep the law of reflection in mind, which states that the angle of incidence is equal to the angle of reflection: $\theta_{\text{i}} = \theta_{\text{r}}$

Ray diagrams for images formed by a plane mirror

In Activity 2.1, we saw that the image formed by a plane mirror is always:

- virtual
- upright
- the same size as the object
- formed at the same distance behind the mirror as the object.

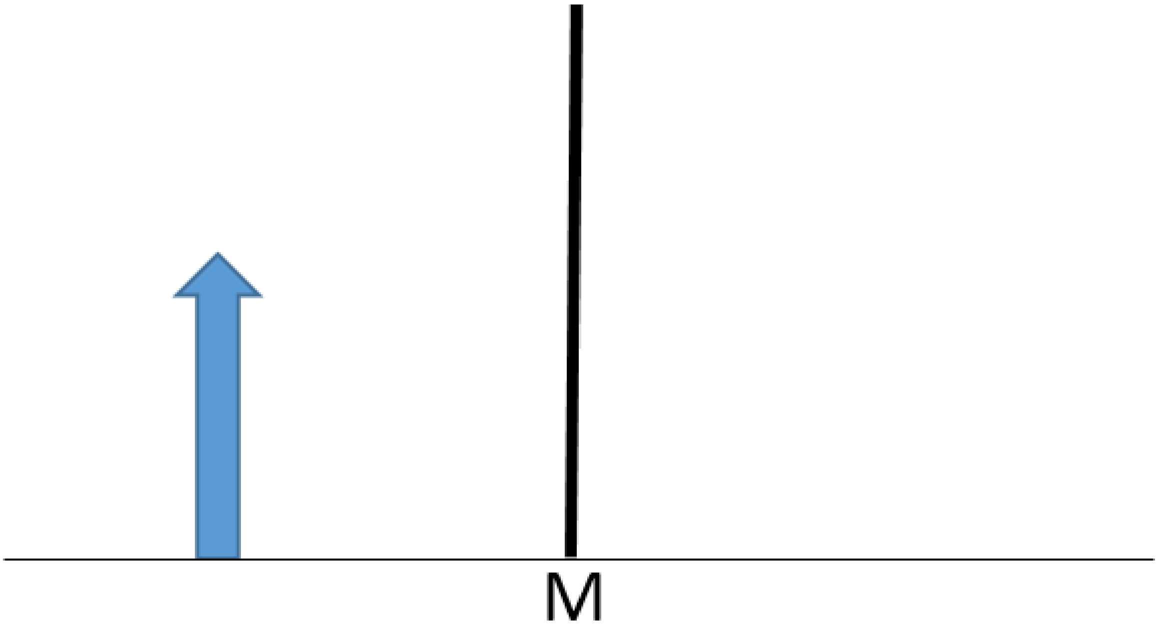
Let's look at an example to see how these characteristics are used when drawing a ray diagram.

Example 2.1

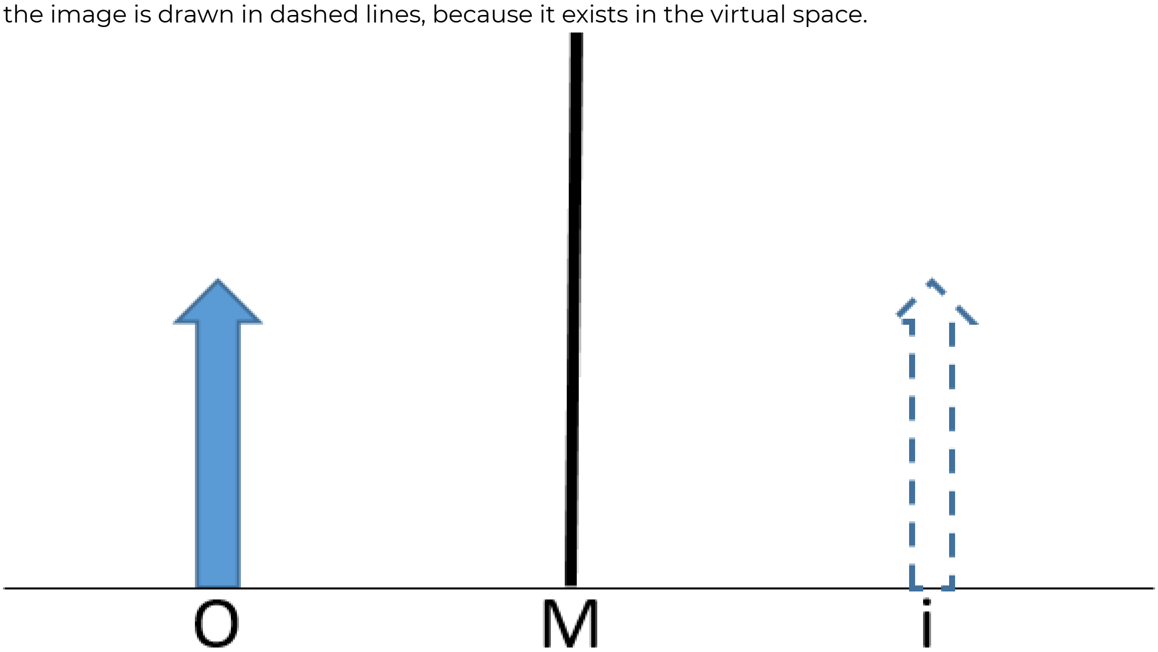
Draw a ray diagram for an image formed by a plane mirror.

Solution

1. Start by drawing the mirror, as viewed from the side, and the object placed in front of the mirror. The object is often drawn as an arrow. For the purpose of the example we denote the mirror 'M' and the object 'O', but these labels do not have to be shown in your diagram.

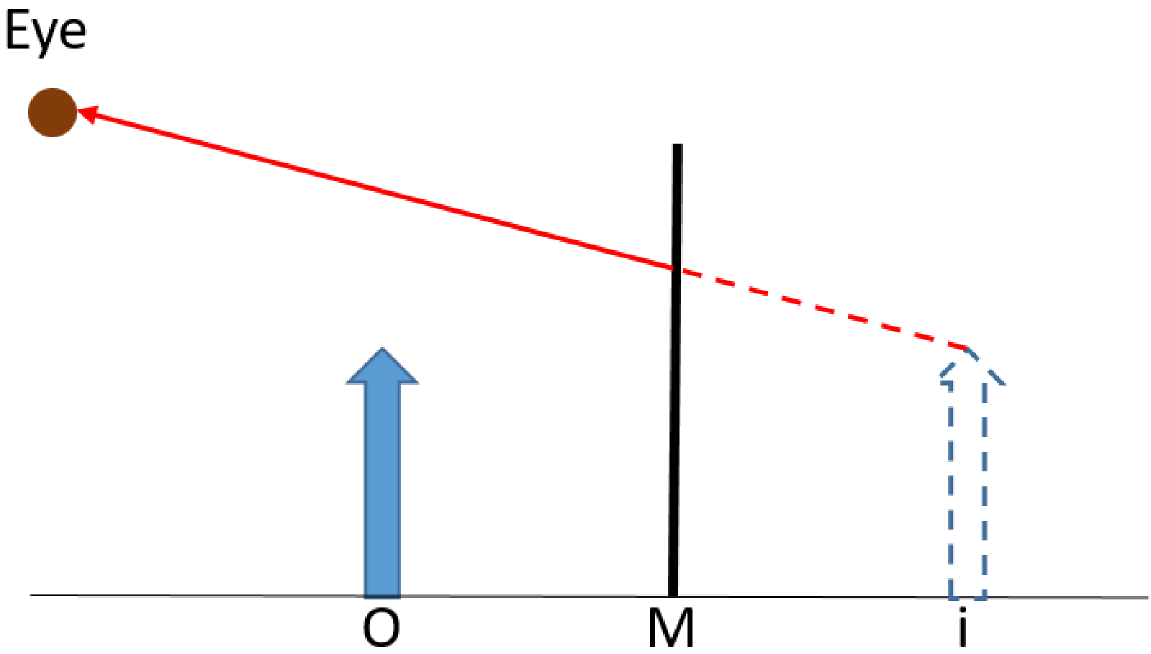


2. We know that a plane mirror always forms a virtual image – that is, an image that forms behind the mirror. We also know that the image formed by a plane mirror is upright, formed at the same distance as the object and is of the same height as the object. We can therefore draw the image behind the mirror accordingly. For the purpose of the example, we denote the image 'i'. Note that the image is drawn in dashed lines, because it exists in the virtual space.

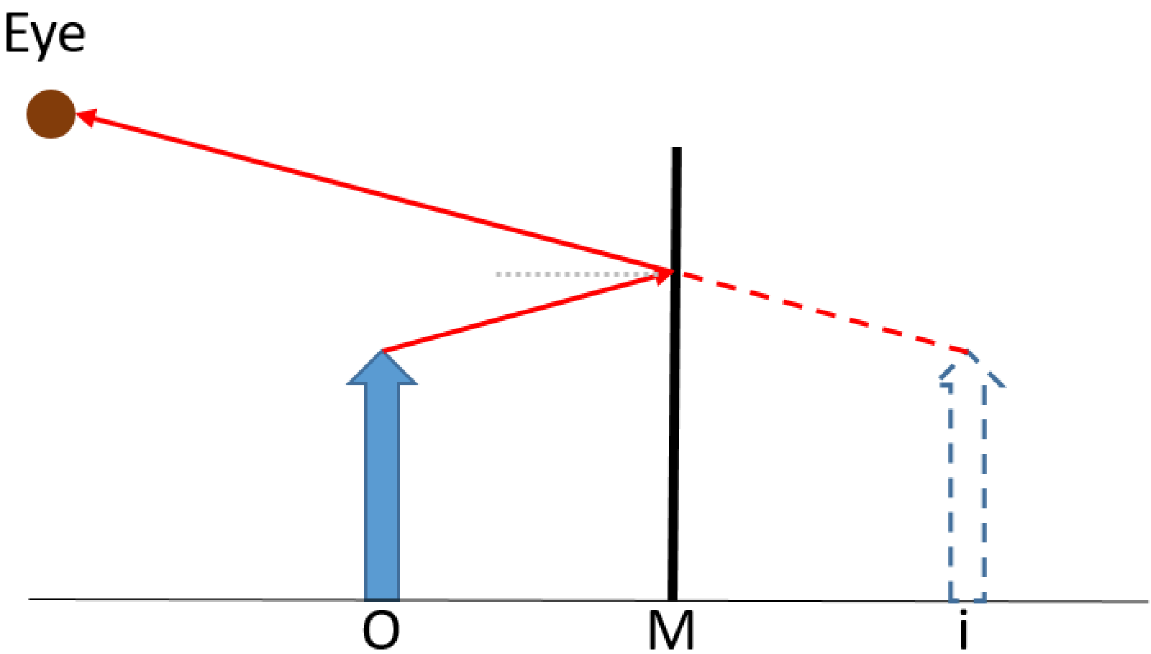


3. An observer is viewing the image, so we know where the line of sight would be for each point on the image. Consider the observer looking at the top of the image. We draw a dashed line from the top of the image to the mirror along the line of sight, because the light ray is *apparently but not actually* coming from that point: it is in the virtual space. The ray on the same side of the mirror as

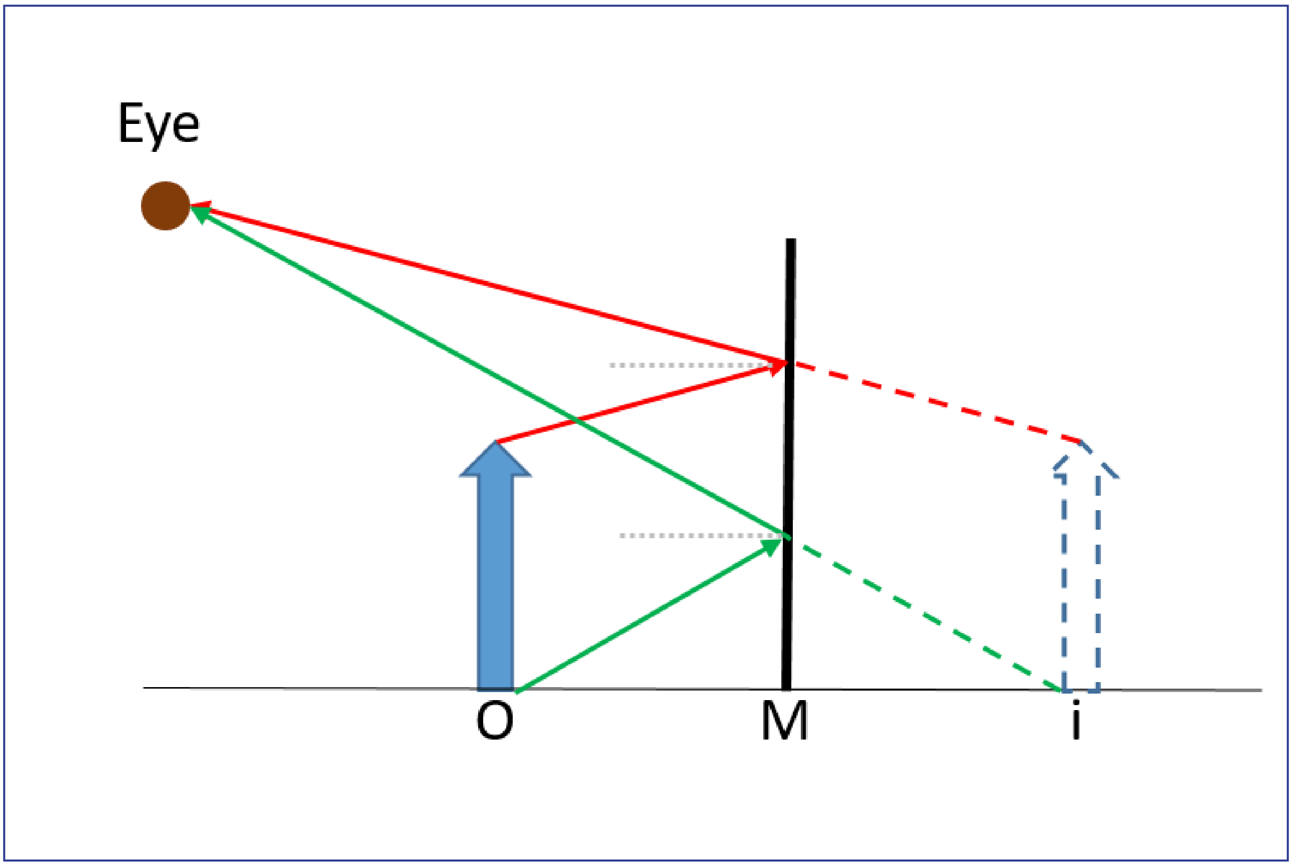
the observer is drawn as a solid line, because it represents the *actual* light ray reflected off the mirror.



4. Having drawn the reflected ray, we can now draw in the incident ray from the top of the object to the mirror. You can check whether you have the directions correct by drawing in a feint normal line and comparing the angle of incidence and angle of reflection: they must be equal.



5. Repeat the process in steps 3 and 4 for another point on the image, such as the bottom of the image.



Ray diagrams for images formed by curved mirrors

To draw ray diagrams for images formed by curved mirrors, we have to define some terminology first, as shown in Figure 3.

- Centre of curvature (C): The centre of the sphere from which the mirror was cut.
- Radius of curvature (R): The radius of the sphere from which the mirror was cut.
- Principal axis (PA) : An imaginary line that runs through the centre of curvature. It is perpendicular to the mirror at the outer most limit of curvature (this point is also called the pole of the mirror).
- Focal point (F): The point halfway between the centre of curvature and the surface of the mirror. This is the point through which all reflected light rays pass (or appear to pass through, in the case of a diverging mirror).
- Focal length (f): The distance from the focal point to the surface of the mirror.

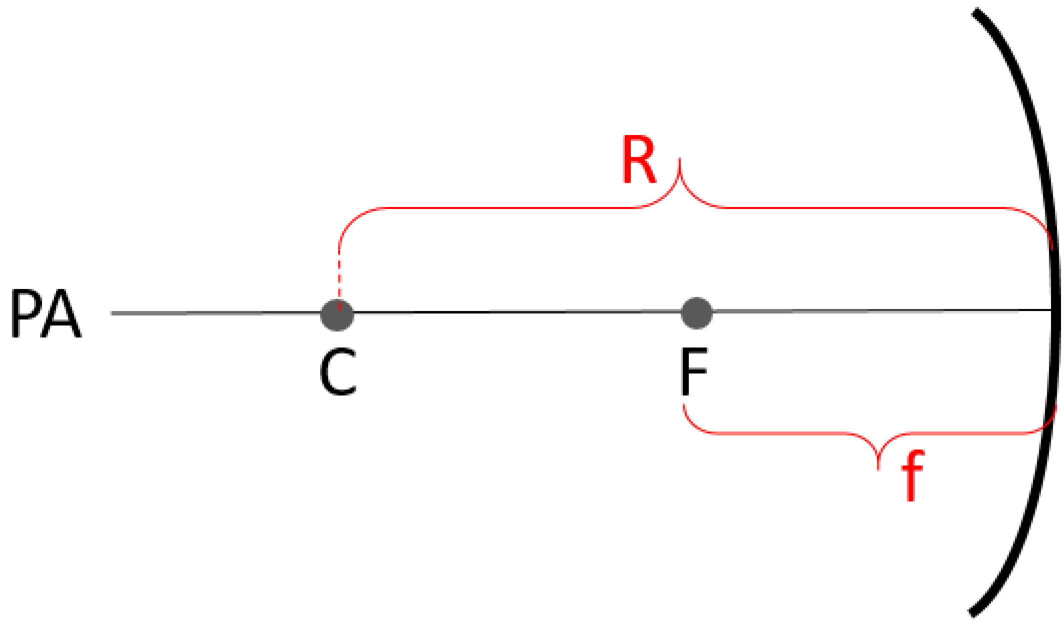


Figure 3: Characteristics of a curved mirror

Remember that the law of reflection always holds when light strikes a mirror, regardless of whether the surface is flat or curved. However, when working with curved mirrors, drawing many incident rays and their associated reflected rays at the correct angles can become tricky. For curved mirrors it is therefore useful to remember three general cases that will always apply:

- Any incident ray parallel to the principal axis will be reflected to pass through the focal point (panel A).
- Any incident ray that passes through the focal point will be reflected parallel to the principal axis (panel B).
- Any incident ray that passes through the centre of curvature will be reflected back through the centre of curvature after striking the mirror's surface (panel C)

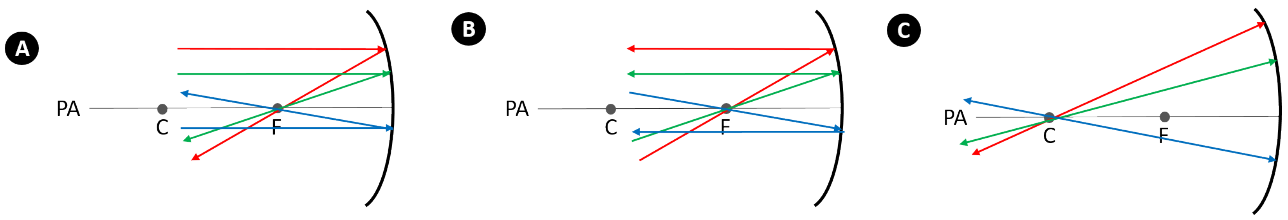


Figure 4: Three general cases of reflection from curved mirrors

We will now look at examples of drawing ray diagrams for both concave and convex mirrors.

Ray diagram for images formed by a concave mirror

The type of image formed by a concave mirror can vary: it can be upright or inverted; real or virtual; magnified or diminished. The type of image formed depends on the position of the object relative to the mirror, which in turn determines whether reflected rays will converge or diverge.

Note

To see how the position of the object affects the image formed by a concave mirror, watch the demonstration called Concave mirror images (Duration: 02.28).

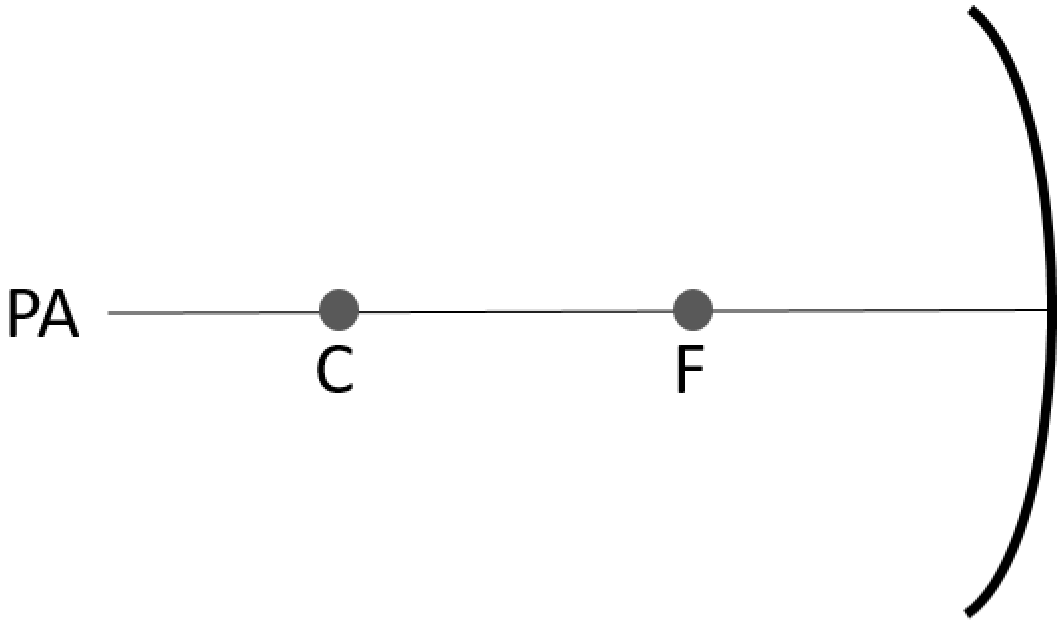
Applying the general principles for drawing a ray diagram for an image formed by a concave mirror will help you understand why different types of images can be formed by concave mirrors.

Example 2.2

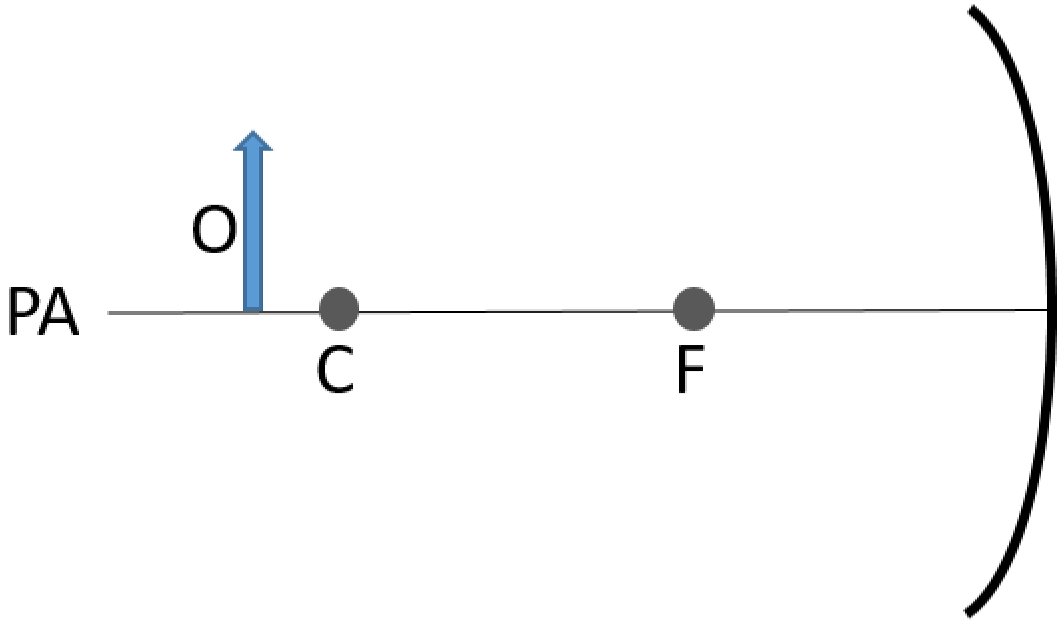
Draw a ray diagram to illustrate an image formed by a concave mirror when the object is placed at a point beyond the centre of curvature.

Solution

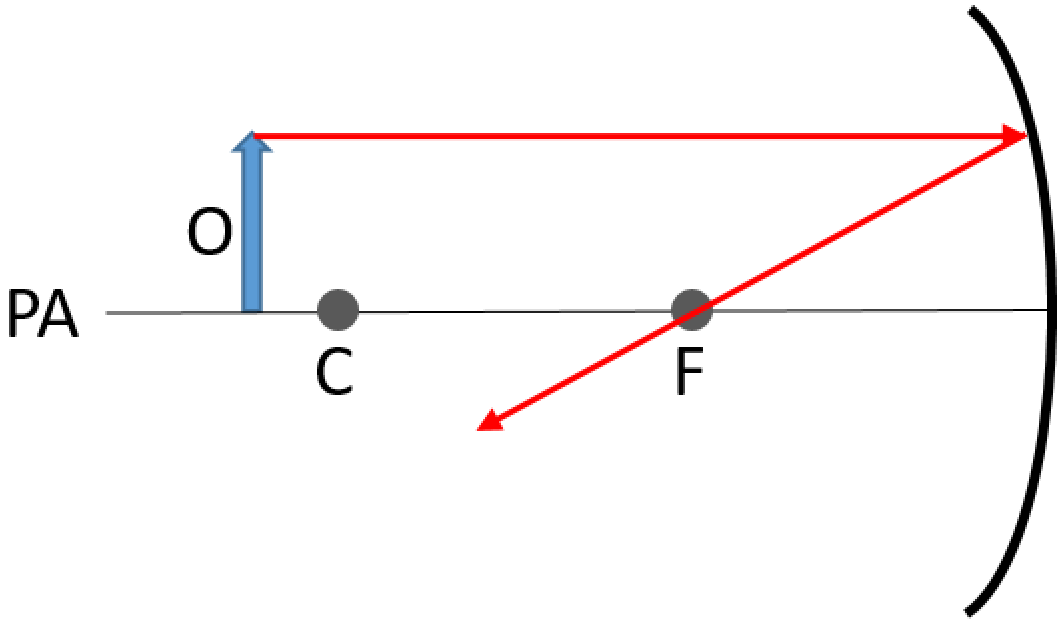
1. First draw the basic components of the diagram: the mirror and principal axis (PA), and also the centre of curvature (C) and focal point (F).



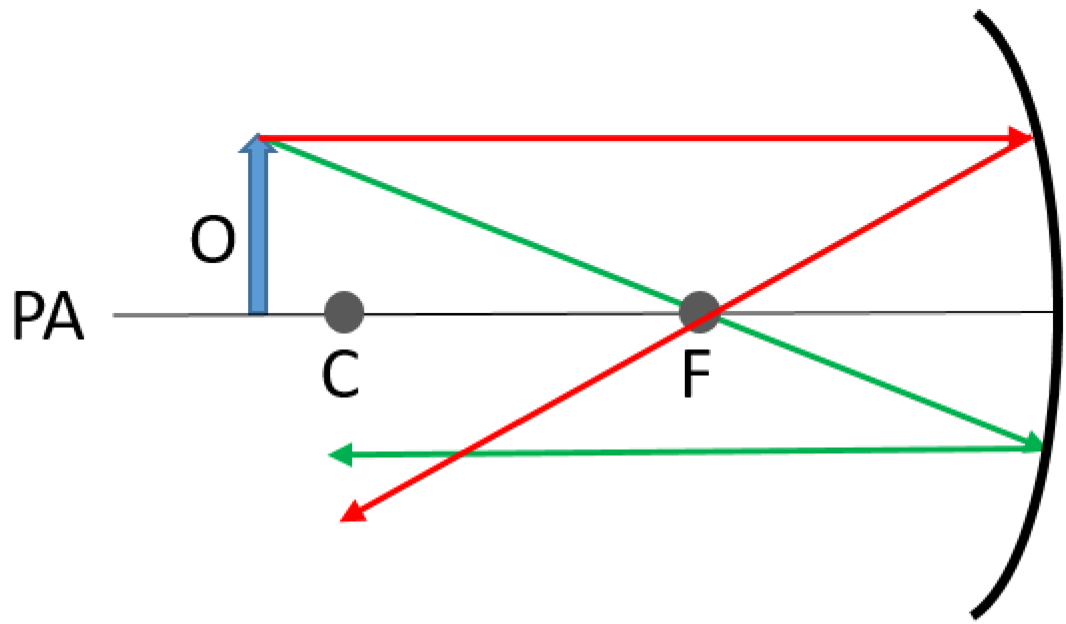
2. Draw an arrow to represent the object (O) at a point beyond C.



3. Draw an incident ray from a point on the object (e.g. the top) towards the mirror, parallel to the principal axis. Then also draw its associated reflected ray. Remember that any incident ray parallel to the principal axis will be reflected to pass through the focal point.

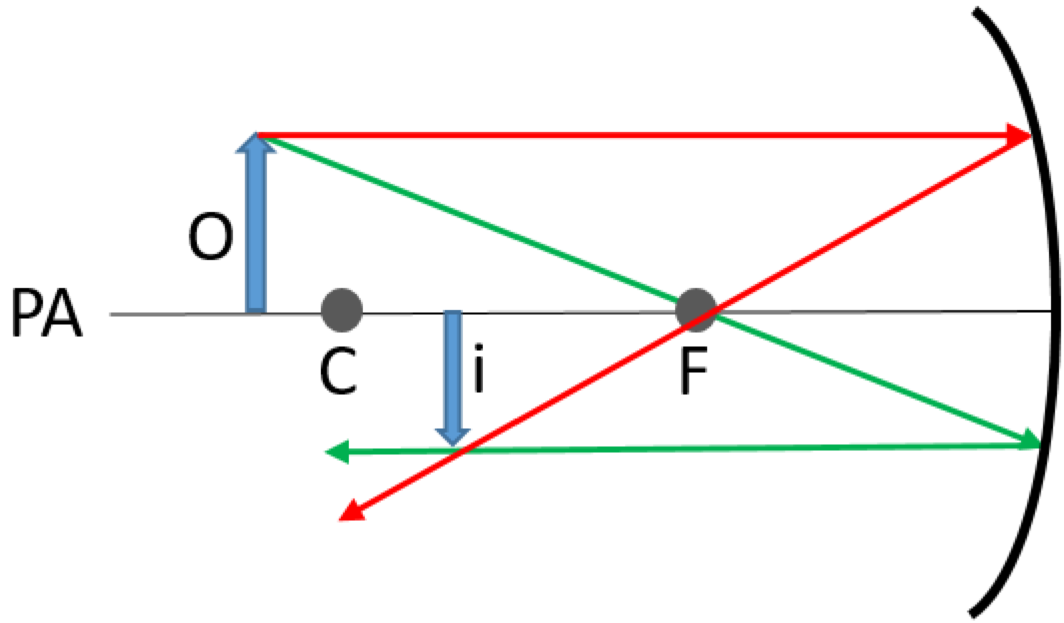


4. Draw another pair of rays from the same point on the object, but this time with the incident ray passing through the focal point. Again, remember that any incident ray passing through the focal point will be reflected parallel to the principal axis.



5. From the diagram in step 4, we can see that the reflected rays converge. The image (i) will be formed at this point of intersection, which is between the centre of curvature and the focal point. Notice that the image is:

- real (it is formed in front of the mirror)
- inverted
- reduced.

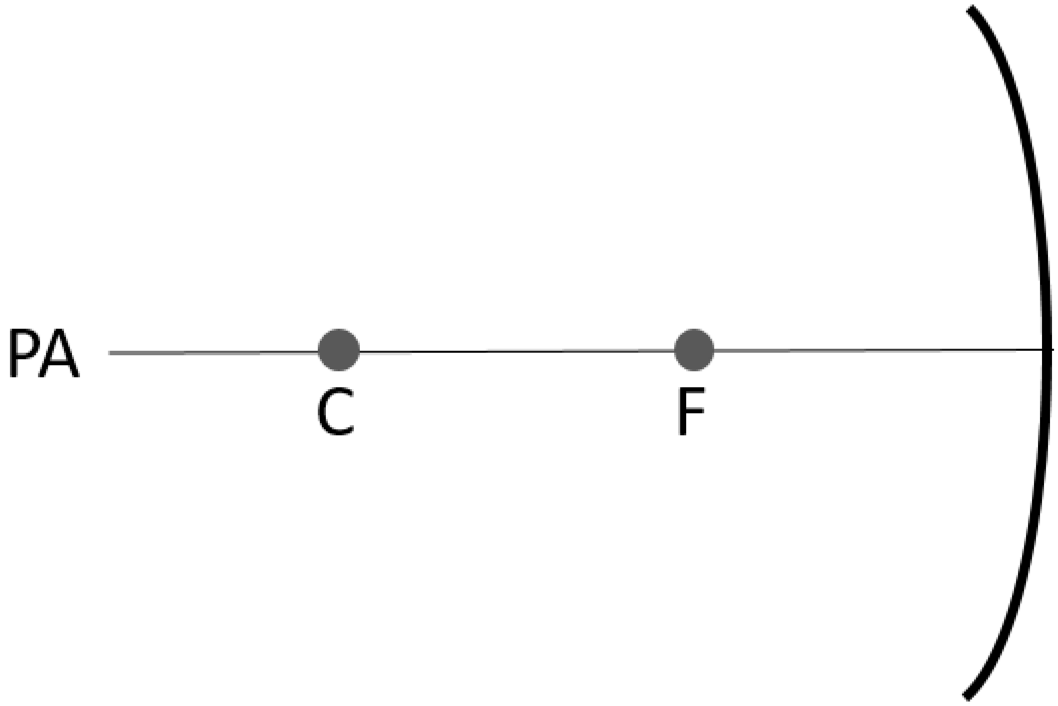


Example 2.3

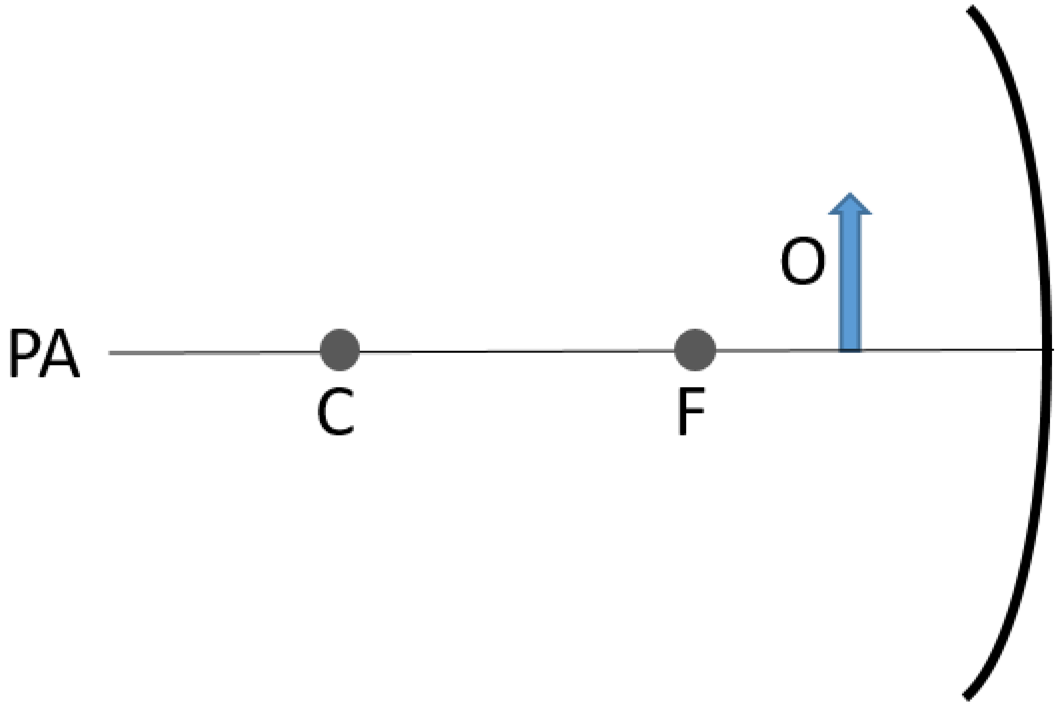
Draw a ray diagram to illustrate an image formed by a concave mirror when the object is placed between the focal point and the mirror.

Solution

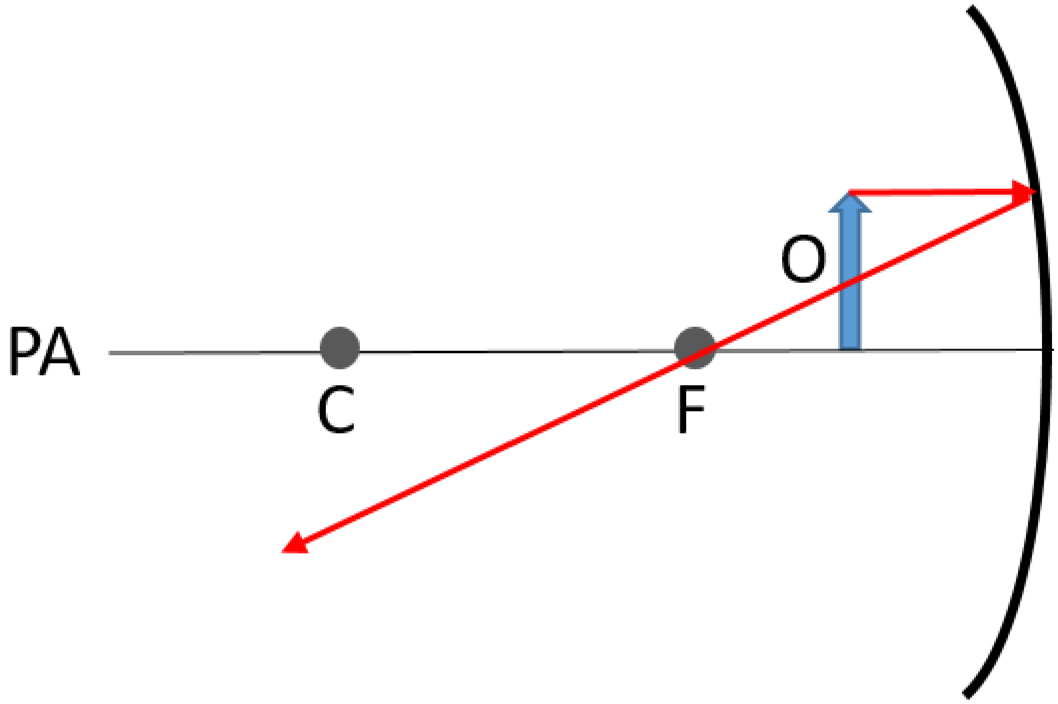
Draw the basic components of the diagram: the mirror and principal axis (PA), and also the centre of curvature (C) and focal point (F).



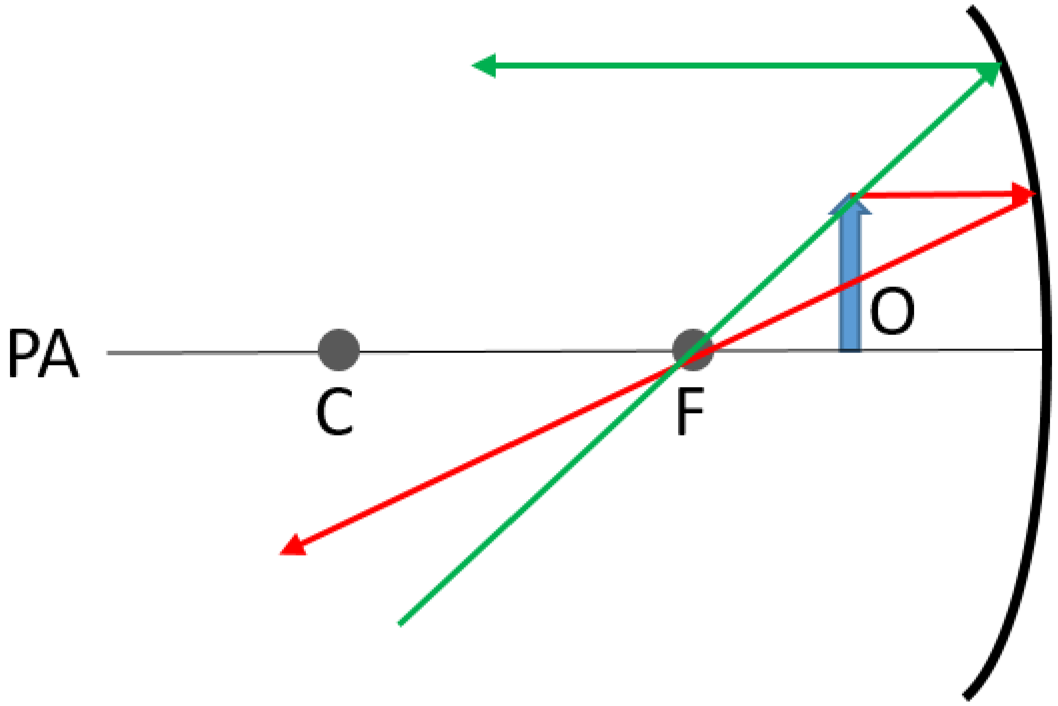
Draw an arrow to represent the object at a position between the focal point and the mirror.



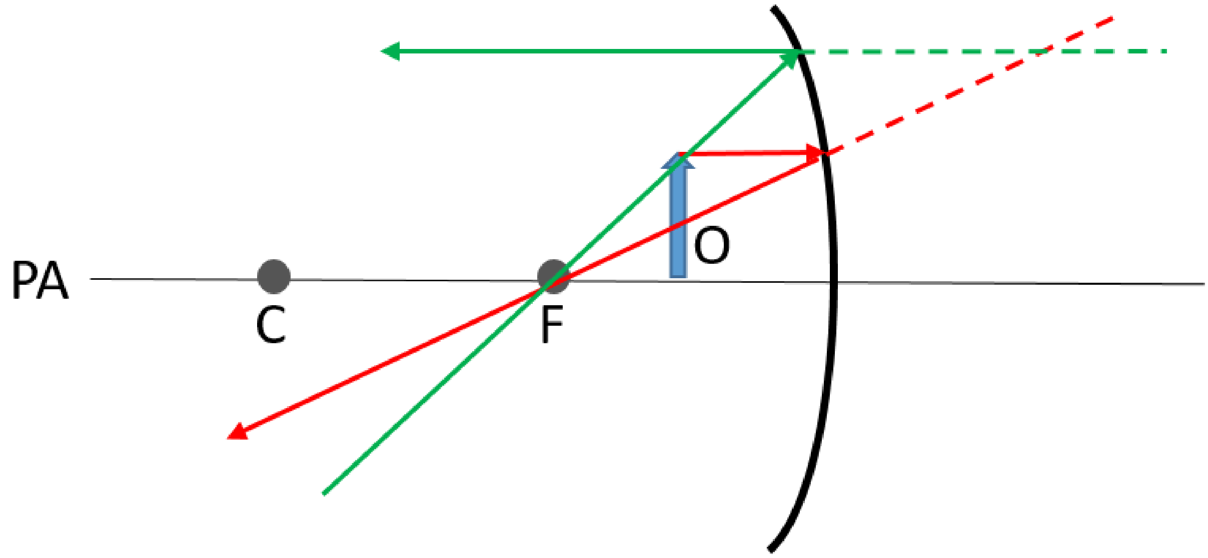
Draw an incident ray from a point on the object (e.g. the top) towards the mirror, parallel to the principal axis. Then also draw its associated reflected ray. Remember that any incident ray parallel to the principal axis will be reflected to pass through the focal point.



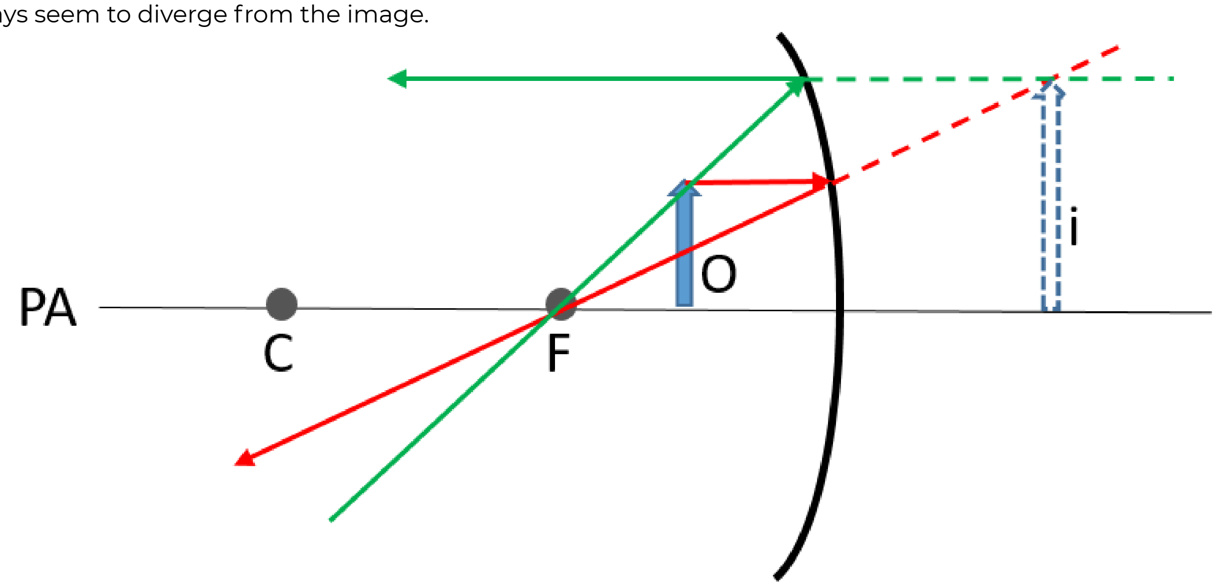
Draw another pair of incident and reflected rays. However, notice that if we were to draw the incident ray passing from the object through the focal point, it would never reach the mirror, and so there would be no reflected ray. A solution is to draw a ray from the object to the mirror, in line with the focal point, and then extending the line backwards. Applying the principle that any incident ray passing through the focal point will be reflected parallel to the principle axis allows us to draw the reflected ray.



Recall that the image forms at the point where the reflected rays intersect. Yet, looking at the diagram in step 4, we see that the reflected rays do not intersect. However, extending the reflected rays backward, behind the mirror, will lead to a point where they do intersect. Notice that because the extensions of the reflected rays are *behind* the mirror – that is, in the virtual space – they are drawn as dashed lines.



Now draw in the image. The image is virtual, magnified and upright, and you can see that the reflected rays seem to diverge from the image.



Drawing ray diagrams for images of objects placed at various positions in front of a concave mirror will show why concave mirrors form varied images. A special case occurs when the object is placed at the focal point, as shown in Figure 5.

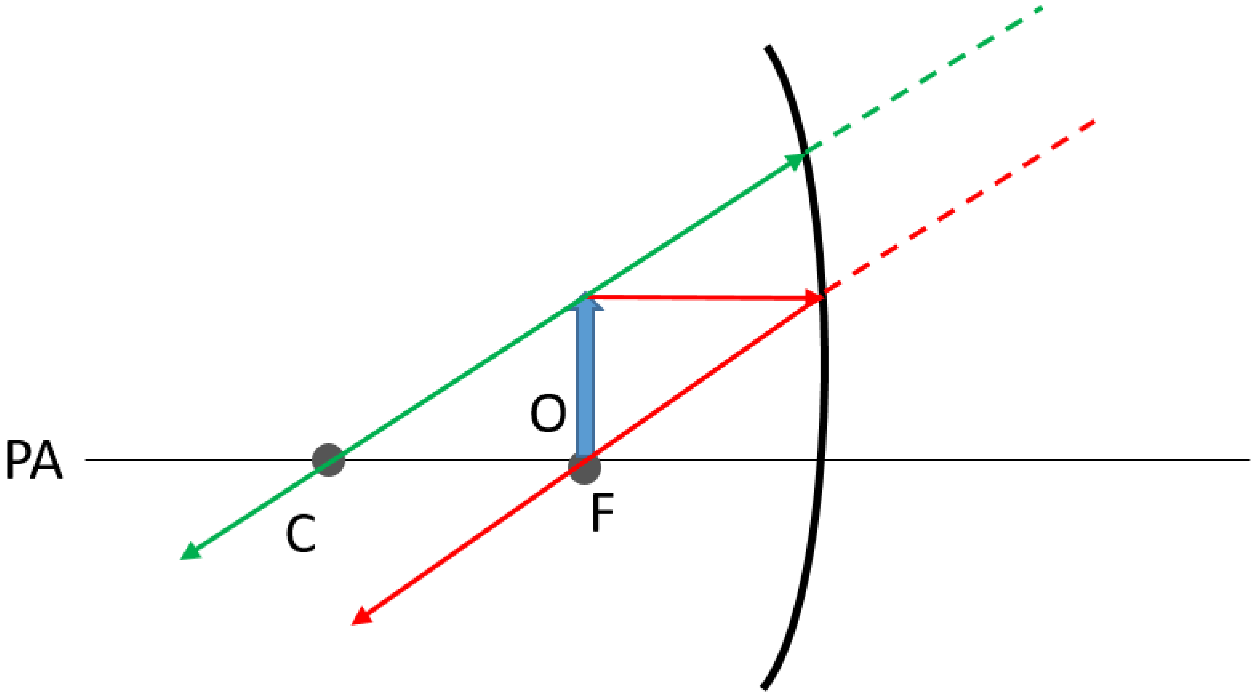
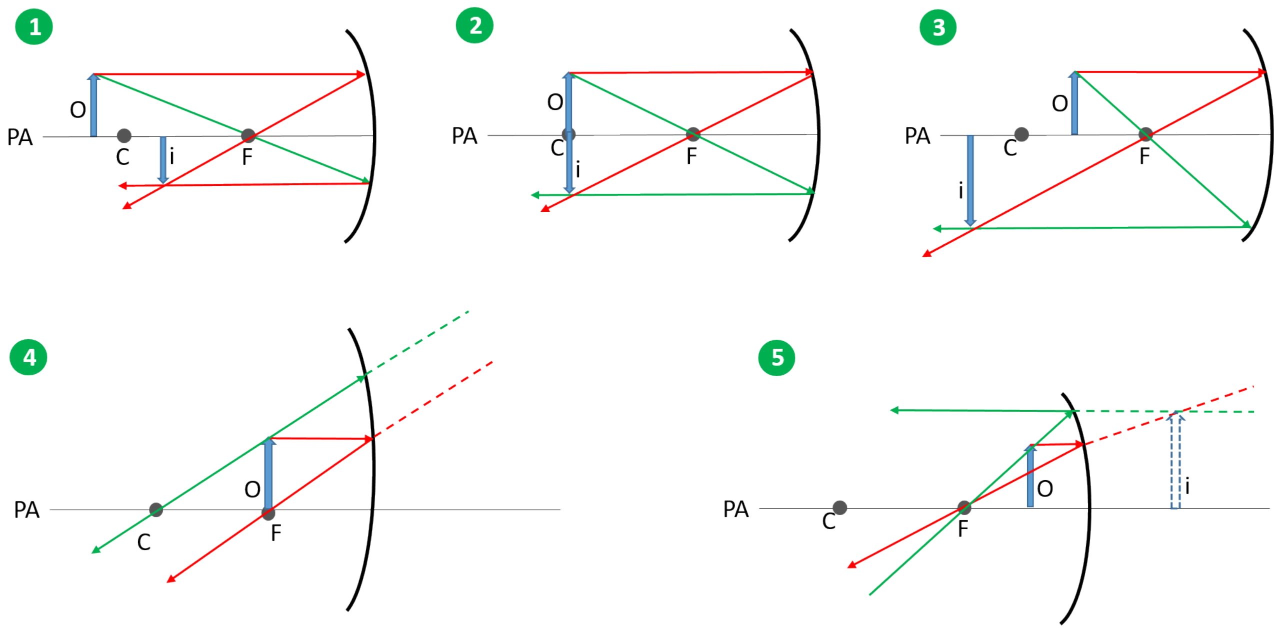


Figure 5: No image is formed when an object is placed at the focal point in front of a concave mirror

In drawing the ray diagram, we start by drawing an incident ray parallel to the principal axis and then its reflected ray passing through the focal point. The second set of rays can be drawn using the general principle that any incident ray passing through the centre of curvature will be reflected along the same path. Extending the reflected rays backwards shows that they remain parallel; they will never intersect. That means, no image will be formed.

The images formed by a concave mirror when an object is placed at various positions in front of the mirror can be summarised as follows , with the ray diagram for each case shown below:

Object position	**Image position**	**Image type**	**Image size**	**Image orientation**
1. Beyond C	Between C and F	Real	Reduced	Inverted
2. At C	At C	Real	Equal to size of object	Inverted
3. Between C and F	Beyond C	Real	Magnified	Inverted
4. At F	No image formed			
5. Between F and mirror	Behind mirror, at a distance that corresponds to a point between C and F	Virtual	Magnified	Upright



Note

To explore ray diagrams for concave mirrors interactively, access this simulation. Set the optical surface to 'mirror'. Note that the point labelled 2f is the same as the centre of curvature (C) in the diagrams shown in this unit.

Ray diagram for images formed by a convex mirrors

The general principles for light reflecting off a convex mirror are the same as for a concave mirror:

- Any incident ray that strikes the mirror parallel to its principal axis will be reflected in line with the focal point.
- Any incident ray that strikes the mirror in line with the focal point will be reflected parallel to the principal axis.

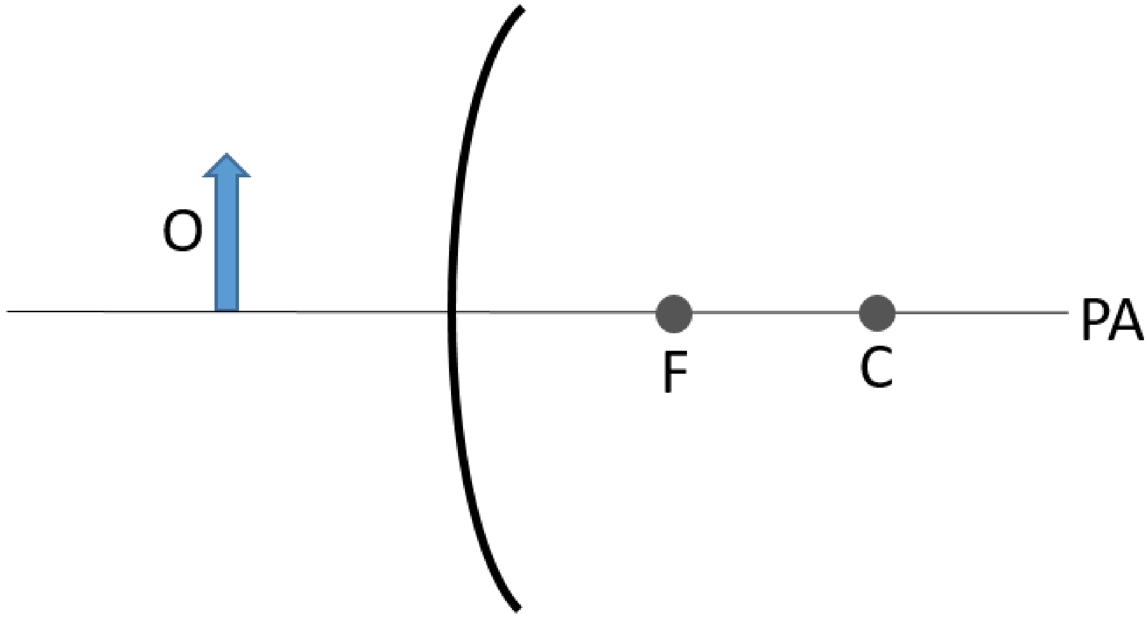
However, in the case of a convex mirror, the centre of curvature and the focal point are located *behind* the mirror, which means reflected rays will diverge. A convex mirror therefore always forms a virtual image that is upright and reduced. You can draw a ray diagram to confirm this.

Example 2.4

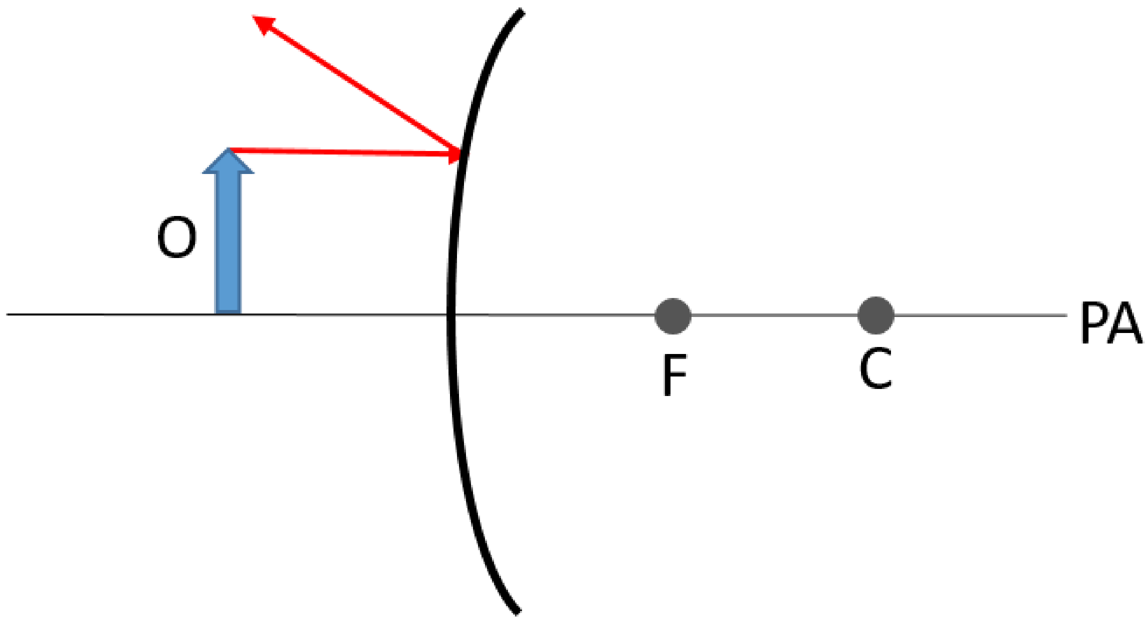
Draw a ray diagram to illustrate an image formed by a convex mirror.

Solution

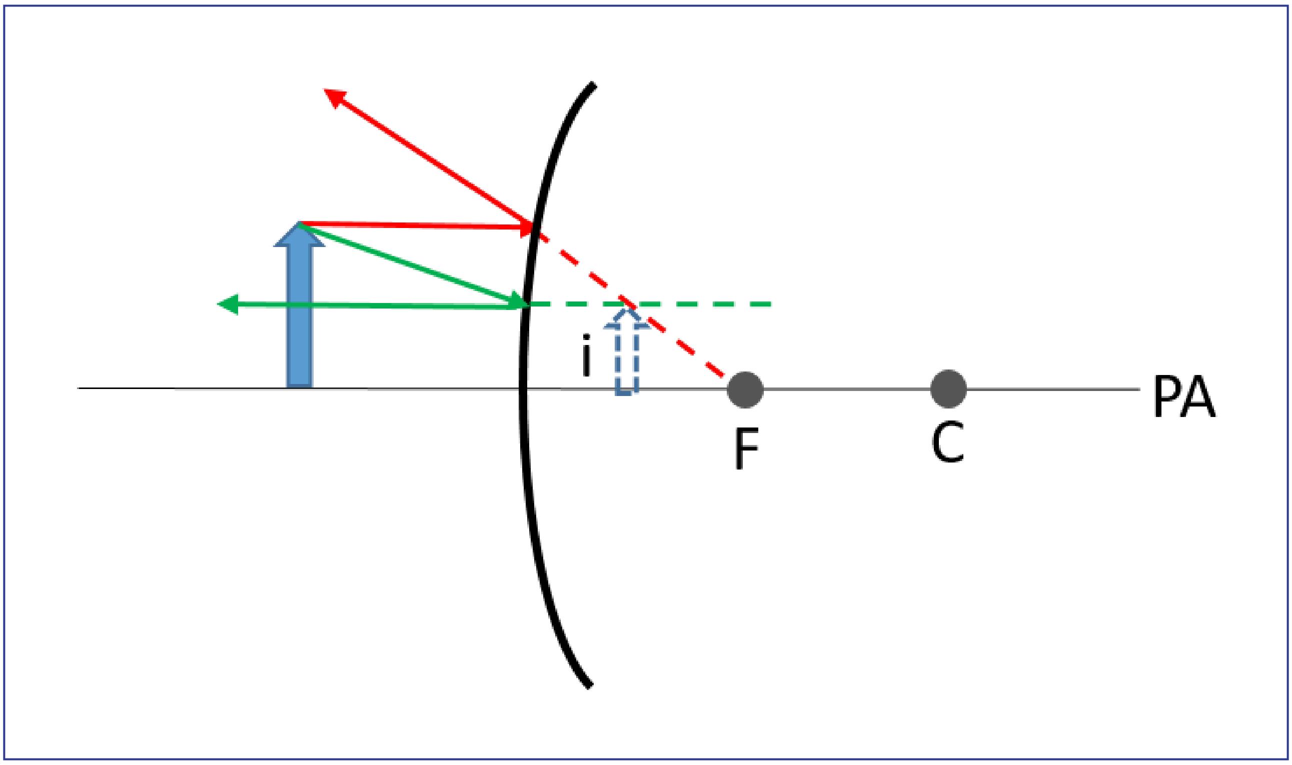
1. Draw the basic components of the diagram: the mirror, the principal axis (PA) and the focal point (F), and place the object in front of the mirror.



2. Draw an incident ray from a point on the object (e.g. the top) towards the mirror, parallel to the principal axis. Then also draw its associated reflected ray. Remember that any incident ray parallel to the principal axis will be reflected to pass through the focal point. Because the focal point is *behind* the mirror – that is, in the virtual space – the extension of the reflected ray is drawn as a dashed line.



3. Then draw an incident ray headed towards the focal point, and its associated reflected ray. Again, extend the reflected ray backwards. The image forms where the reflected rays intersect. It is a virtual image, reduced and upright.



Exercise 2.1

1. Draw a ray diagram to show the image formed of an object that is placed $15\ \mathrm{cm}$ away from a plane mirror. The diagram does not have to be to scale.
2. Use a ray diagram to show that a concave mirror forms a magnified image of an object placed between the centre of curvature and the focal point.
3. Draw a ray diagram to describe the type of image formed of an object reflected in a shiny Christmas tree bauble. The diameter of the bauble is $6\ \mathrm{cm}$ and the object is $20\ \mathrm{cm}$ away from the bauble. The diagram does not have to be to scale.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- A mirror is a shiny reflective surface that is able to form an image of an object in front of it.
- An image is a representation of an object.
- The image location is the point in space where reflected rays intersect or appear to intersect.
- An image formed by a mirror can be: virtual or real; upright or inverted; magnified or reduced.
- The type of image formed by a mirror depends on the shape of the reflective surface, which can be flat or curved. A mirror with a flat reflective surface is called a plane mirror. Curved mirrors can have a convex or concave shape.
- A flat mirror always forms virtual, upright images that are the same height as the object.
- A convex mirror always forms virtual, upright and reduced images.
- A concave mirror can form varied images, depending on the distance of the object in front of the mirror.

- Ray diagrams are useful to help us understand the characteristics of images formed by mirrors.
- To draw ray diagrams for curved mirrors, the centre of curvature and focal point have to be shown.
- Light emanates in all directions from an object. The law of reflection always holds when light strikes a mirror, regardless of whether the surface is flat or curved.
- To make it simpler to draw ray diagrams for an image formed by a curved mirror, it is useful to remember that the following cases will always hold:
  - Any incident ray that travels parallel to the principal axis will be reflected through the focal point.
  - Any incident ray that travels through the focal point towards the surface of the mirror will be reflected parallel to the principal axis.
  - Any incident ray that travels through the centre of curvature will be reflected back through the centre of curvature.

Unit 2: Assessment

Suggested time to complete: 30 minutes

1. The image location of a mirror is:
   A. the point in space where all incident and reflected rays intersect.
   B. the point in space where all reflected rays intersect or appear to intersect.
   C. always in front of the mirror.
   D. always behind the mirror.
2. An object that is $20\ \text{cm}$ high is placed $60\ \text{cm}$ in front of a concave mirror. The mirror has a radius of curvature of $80\ \text{cm}$. Where would the image of the object be formed?
   A. $60\ \text{cm}$ in front of the mirror
   B. Somewhere between $60\ \text{cm}$ and $80\ \text{cm}$ in front of the mirror.
   C. More than $80\ \text{cm}$ in front of the mirror.
   D. $60\ \text{cm}$ behind the mirror.
3. An object in front of a plane mirror will form an image that is:
   A. real and magnified.
   B. virtual and upright.
   C. virtual and inverted.
   D. virtual and magnified.
4. You see an image formed by a mirror that it inverted and magnified. What type of mirror would form this image?
   A. a convex mirror
   B. a concave mirror
   C. a plane mirror
   D. a corner mirror
5. If the radius of curvature of a convex mirror is $10\ \text{cm}$, its focal point will be:
   A. $10\ \text{cm}$ behind the mirror.
   B. $10\ \text{cm}$ in front of the mirror.
   C. $5\ \text{cm}$ in front of the mirror.
   D. $5\ \text{cm}$ behind the mirror.
6.

a. Explain why the rear-view mirror of a car uses a curved mirror rather than a plane mirror.
b. Would it be better to use a concave or a convex mirror in this application? Give a reason for your answer.

7. Draw ray diagrams to compare the images formed by a convex mirror when the same object is placed at a point:
   a. equal to the radius of curvature in front of the mirror.
   b. closer to the mirror than the radius of curvature.
8. Draw ray diagrams to explain why the image formed by concave mirror can be:
   a. virtual or real
   b. magnified or reduced.
9. What type of mirror is shown in each of the following photos? Give a reason for your answer in each case.
   a.

   b.

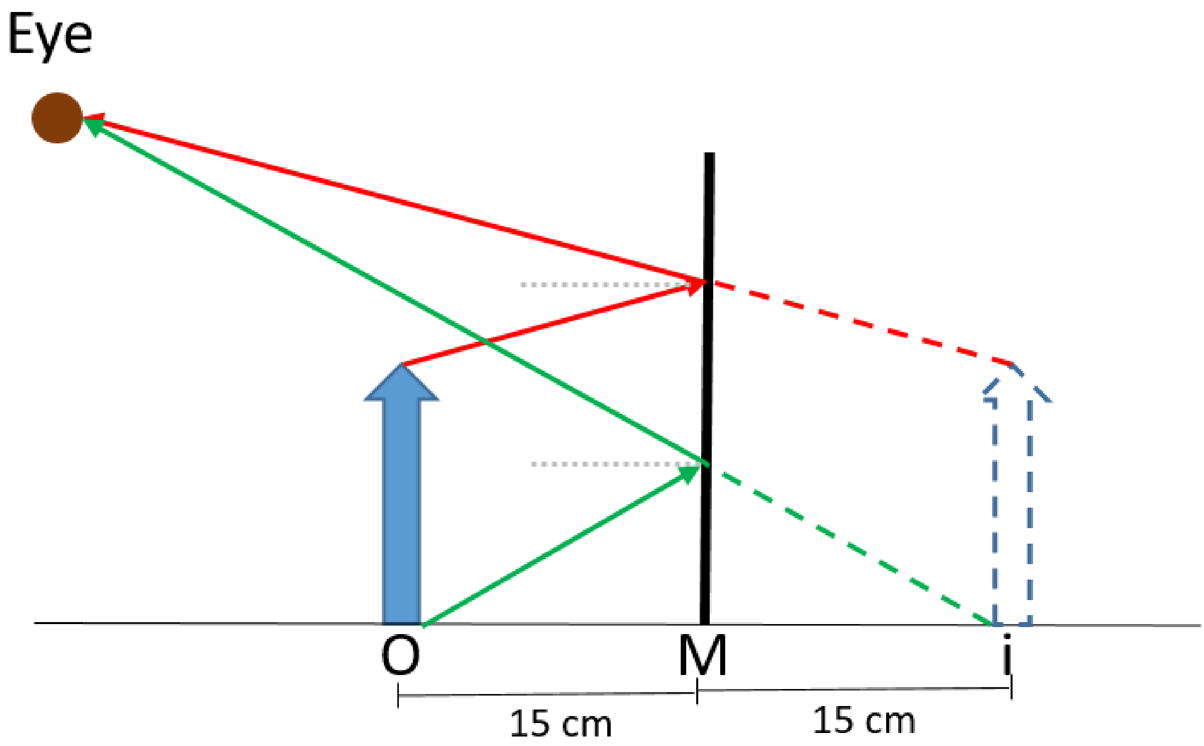
10. Draw a ray diagram to explain what type of image is formed of an object placed $5\ \text{cm}$ in front of a plane mirror.

The full solutions are at the end of the unit.

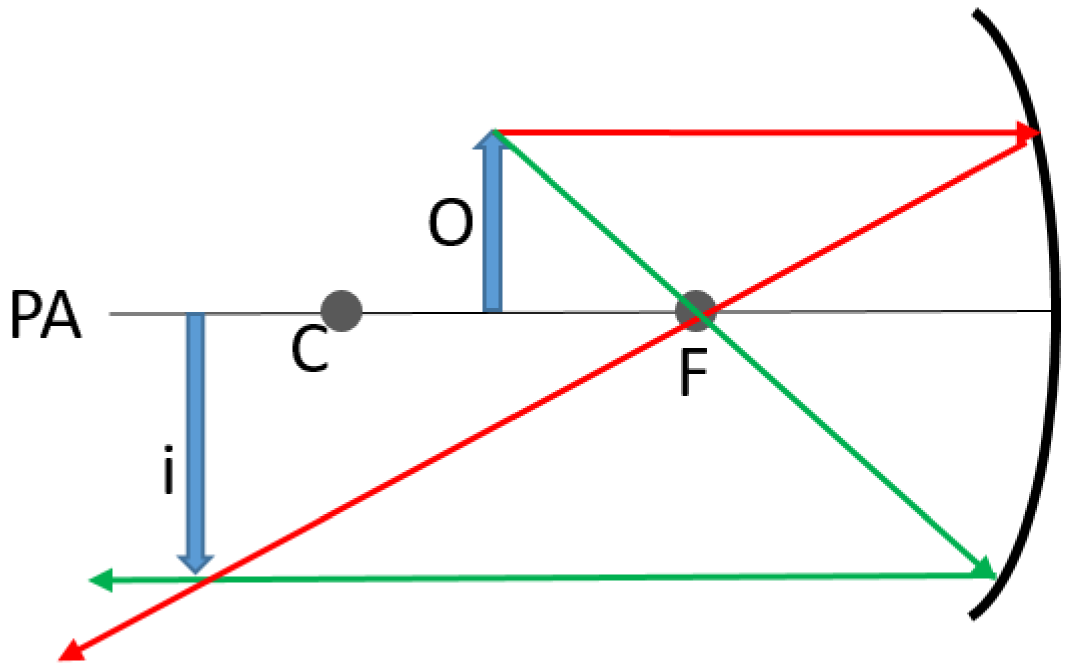
Unit 2: Solutions

Exercise 2.1

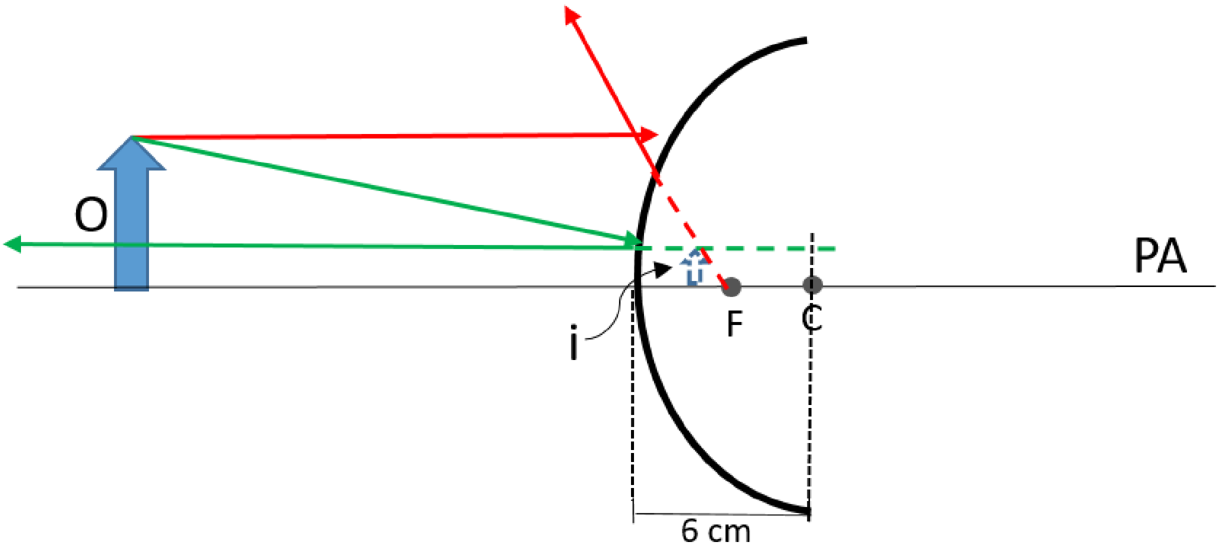
1. The image will be formed behind the mirror, at the same distance as where the object is placed. The image is virtual and upright, and the same height as the object.



2.



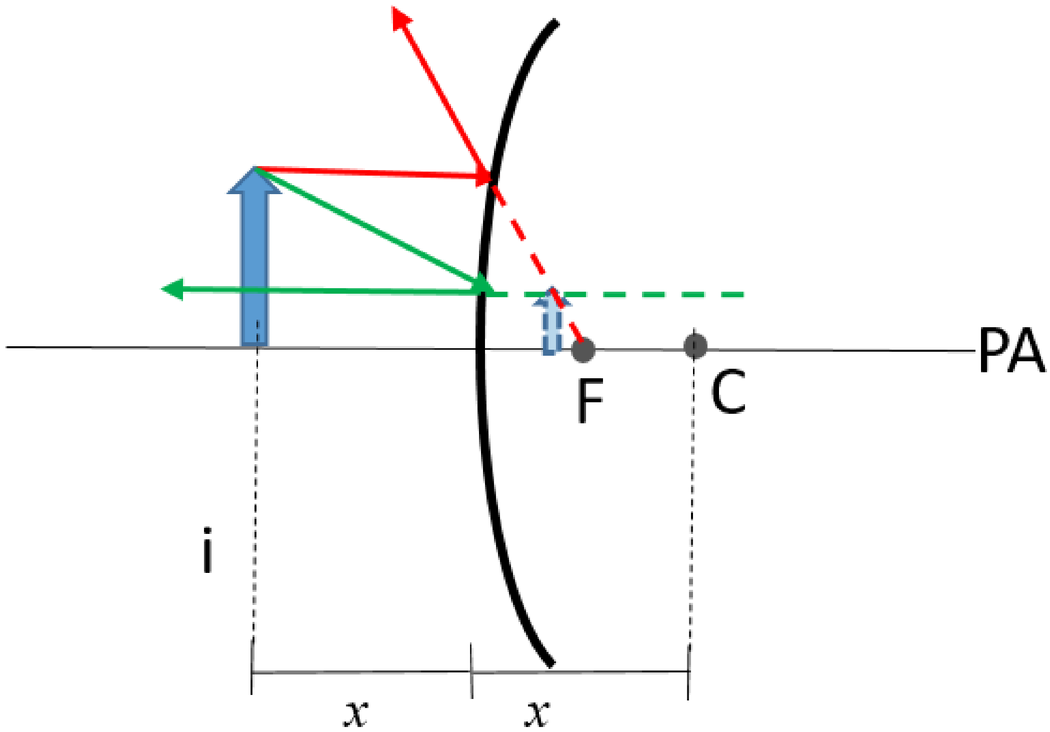
3. The image is virtual, reduced and upright.



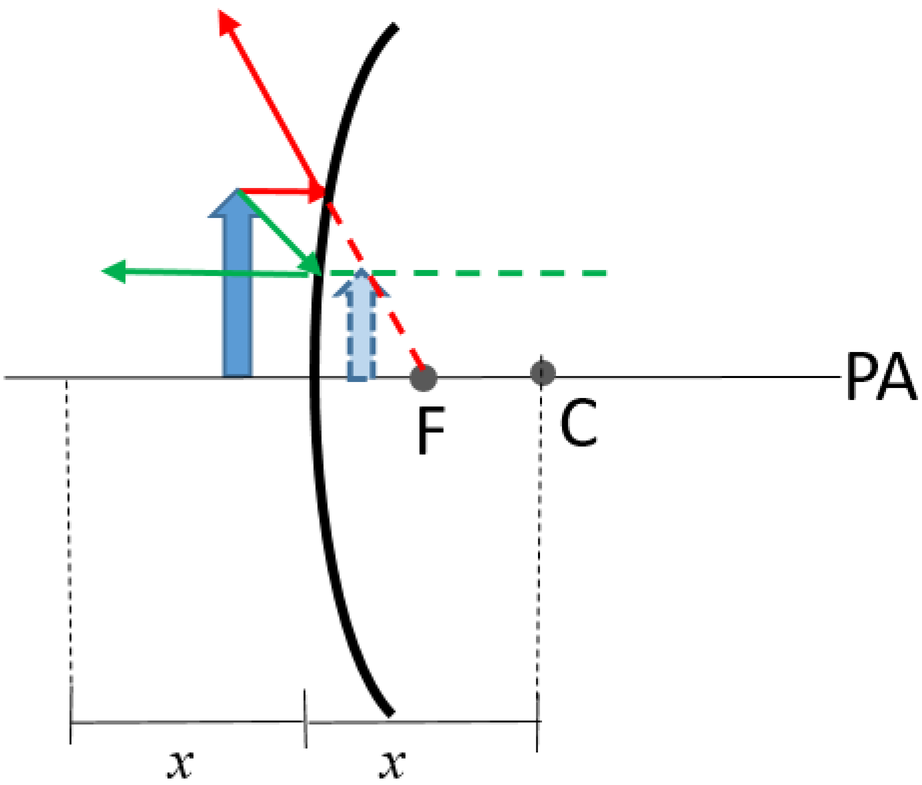
Back to Exercise 2.1

Unit 2: Assessment

1. B.
   An image formed by a mirror is due to the reflection of incident rays, and forms at the point where reflected rays intersect (in the case of a real image) or appears to intersect (in the case of a virtual image).
2. C.
   If the radius of curvature is $80\ \text{cm}$, the focal point would be at $40\ \text{cm}$. An object that is placed at $60\ \text{cm}$ is therefore between the centre of curvature and the focal point, which means the image would be formed beyond the centre of curvature.
3. B.
   A plane mirror always forms virtual, upright images that are the same height as the object.
4. B.
   Convex and plane mirrors always form upright images. A concave mirror can form an inverted magnified image when the object is place between the centre of curvature and the focal point.
5. D.
   The focal point of a curved mirror is midway between the centre of curvature and the surface of the mirror. The focal point of a convex mirror is behind the mirror.
6.
   a. Because a curved mirror allows reduced images to be formed, it can show a wider view than a flat mirror.
   b. A convex mirror would be better, as it always forms an upright image, whereas the images formed by a concave mirror can be either upright or inverted.
7.
   a.



b.

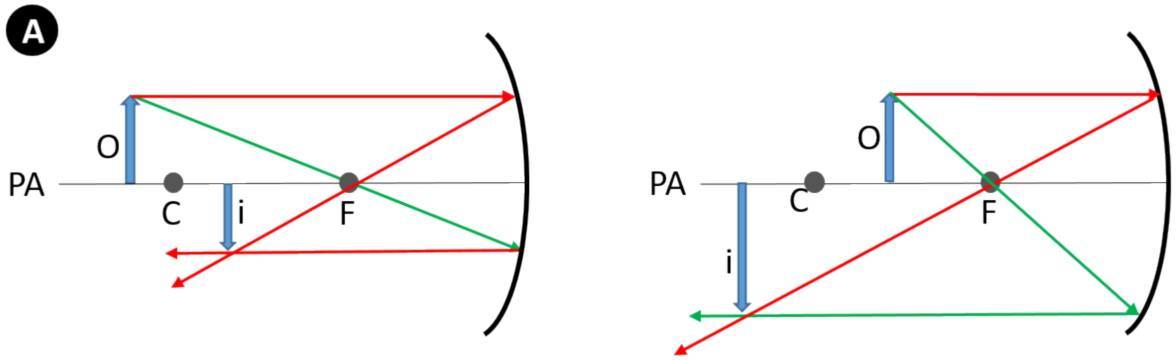


A virtual, upright and reduced image forms in both cases. However, the image size increases to approach the size of the object the closer the object is moved to the surface of the mirror.

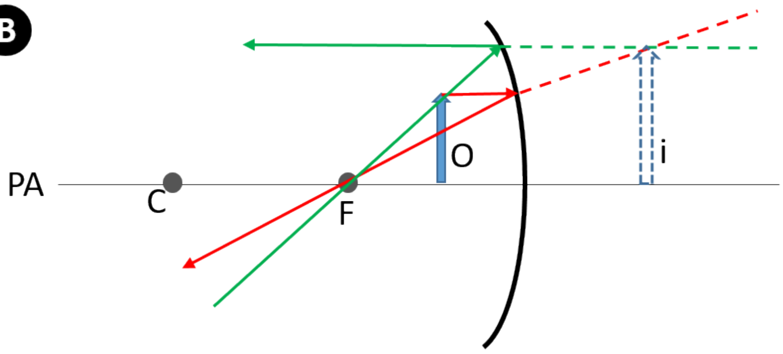
8.

a. A concave mirror will form real images if the object is placed at any point further than the focal length in front of the mirror (panel A). However, a virtual image will form for an object that is placed at any position between the focal point and the surface of the mirror (panel B).

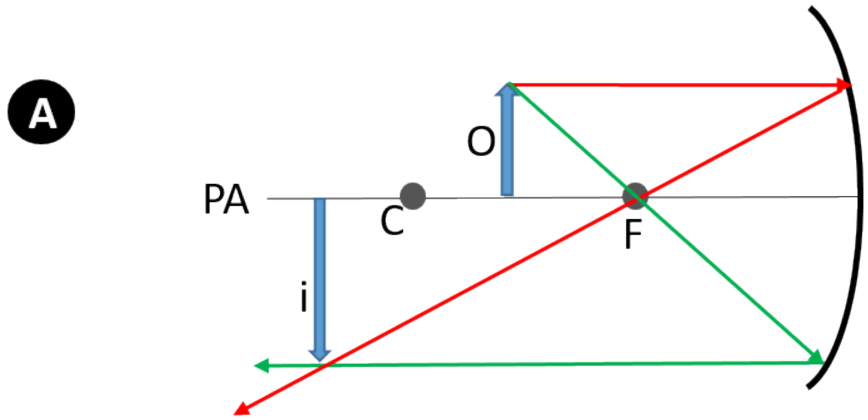
A

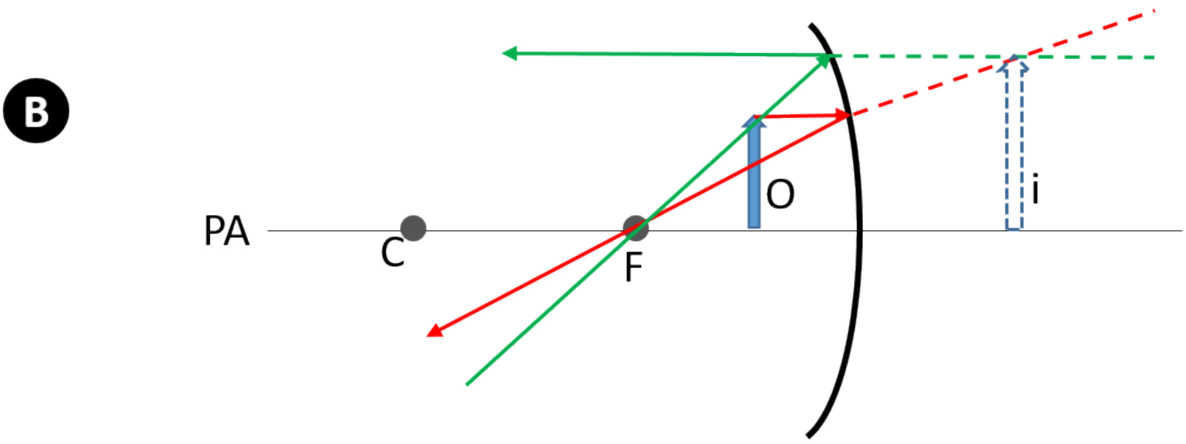


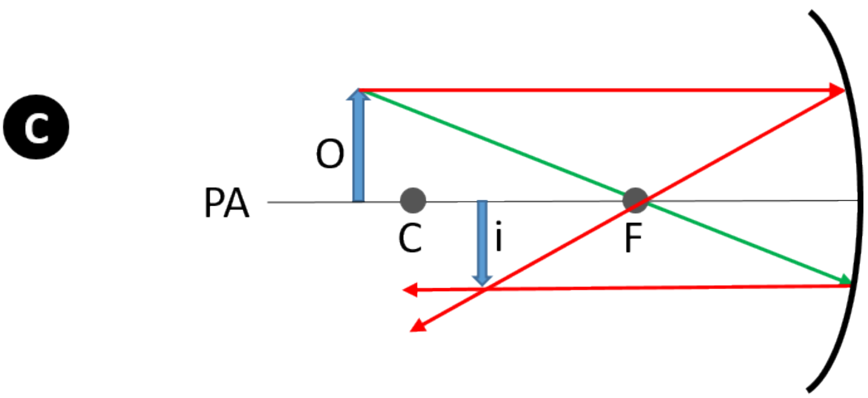
B



b. A concave mirror will form magnified images if an object is placed at any point between the centre of curvature and the focal point, or between the focal point and the surface of the mirror (panels A and B). A reduced image will form for an object placed at any point beyond the centre of curvature (panel C).





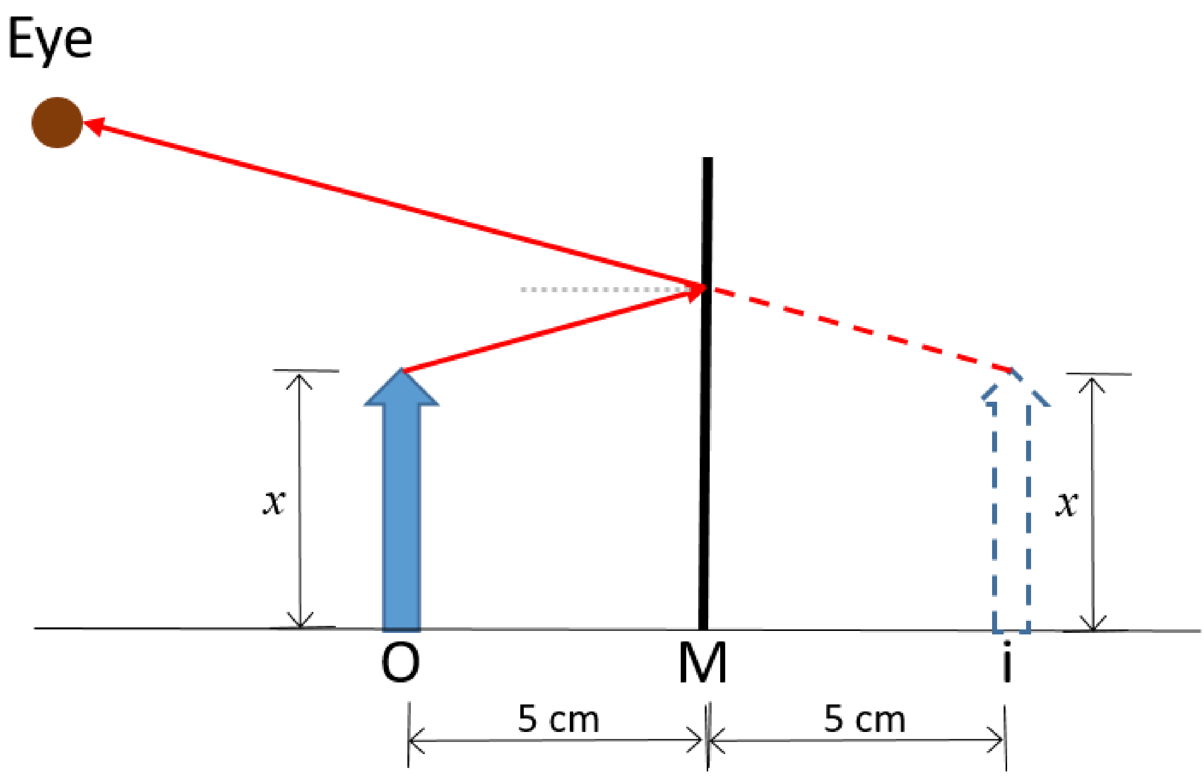


9.

   a. A plane mirror. A virtual, upright image is formed. It appears at the same distance behind the mirror as the object and is of the same height.

   b. The image is formed by a curved mirror, as can be seen from the somewhat distorted view. We see that the image is upright and reduced. We therefore know that it must be a convex mirror shown here, because when upright images are formed by a concave mirror they are always magnified.

10. A plane mirror will form a virtual, upright image of the same height and at the same distance as the object.



Back to Unit 2: Assessment

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SUBJECT OUTCOME VII

MAGNETISM AND ELECTRICITY: IDENTIFY, DESCRIBE AND APPLY PRINCIPLES OF MAGNETISM

Subject outcome

Subject outcome 4.1: Identify, describe and apply principles of magnetism.

Learning outcomes

- Draw and label diagrams showing magnetic field of permanent magnets.
- Describe the effect that poles of permanent magnets have on each other.
- Identify and describe the earth's magnetic field and declination and the working of a compass.
- Apply magnetic phenomena by induction of the earth's magnetic field and refer to iron and steel used in building construction.
- Describe magnetic shielding and its purpose.

Unit 1 outcomes

By the end of this unit you will be able to:

- Draw and label diagrams showing the magnetic field of permanent magnets.
- Describe the effect that poles of permanent magnets have on each other.

Unit 2 outcomes

By the end of this unit you will be able to:

- Identify and describe the Earth's magnetic field.
- Describe magnetic declination.
- Describe the working of a compass.
- Apply magnetic phenomena by induction of the Earth's magnetic field and refer to iron and steel used in building construction.

Unit 3 outcomes

By the end of this unit you will be able to:

- Describe magnetic shielding
- Describe the underlying principles of magnetic shielding
- Describe the purpose of magnetic shielding.

Unit 1: Magnets and magnetic fields

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Draw and label diagrams showing the magnetic field of permanent magnets.
- Describe the effect that poles of permanent magnets have on each other.

What you should know

Before you start this unit, make sure you can:

- identify and apply the principles of forces, as covered in Subject outcome 2.2, Unit 1.

Introduction

This unit[1] is about magnets and magnetic fields. Magnetism is an interaction that allows certain kinds of objects, which are called 'magnetic' objects, to exert forces on each other without physically touching. A magnetic object is surrounded by a magnetic 'field' that gets weaker as one moves further away from the object. A second object can feel a magnetic force from the first object because it feels the magnetic field of the first object. The further away the objects are the weaker the magnetic force will be.

Magnetic fields

A magnetic field is a region in space where a magnet or object made of magnetic material will experience a non-contact, magnetic force.

A moving charged particle has a magnetic field associated with it. One example of a charged particle that occurs in most matter is the electron. Electrons are in constant motion, orbiting the nucleus in the atom which may also be moving, rotating or vibrating.

So electrons inside any object are moving and have magnetic fields associated with them. In most materials these fields point in various directions, so the net magnetic field is zero. For example, in the plastic ball below, the directions of the magnetic fields of the electrons (shown by the arrows) are pointing in different directions and cancel each other out. Therefore, the plastic ball is not magnetic and has no magnetic field.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 15, released under a CC-BY licence

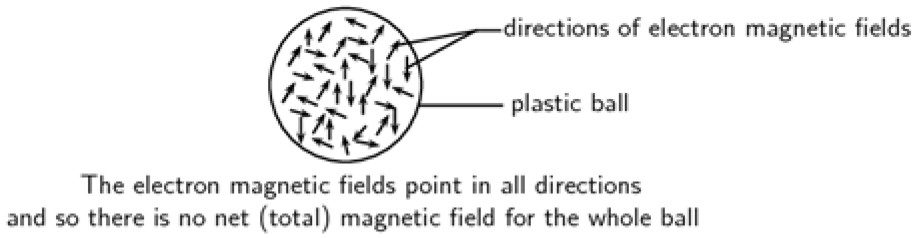


Figure 1: The individual magnetic fields around electrons

In some materials, for example iron, there are regions called domains where the electrons' magnetic fields line up with each other. All the atoms in each domain are grouped together so that the magnetic fields from their electrons point the same way. These materials are called ferromagnetic materials. Figure 2 shows a piece of an iron needle zoomed in to show the domains with the electric fields lined up inside them.

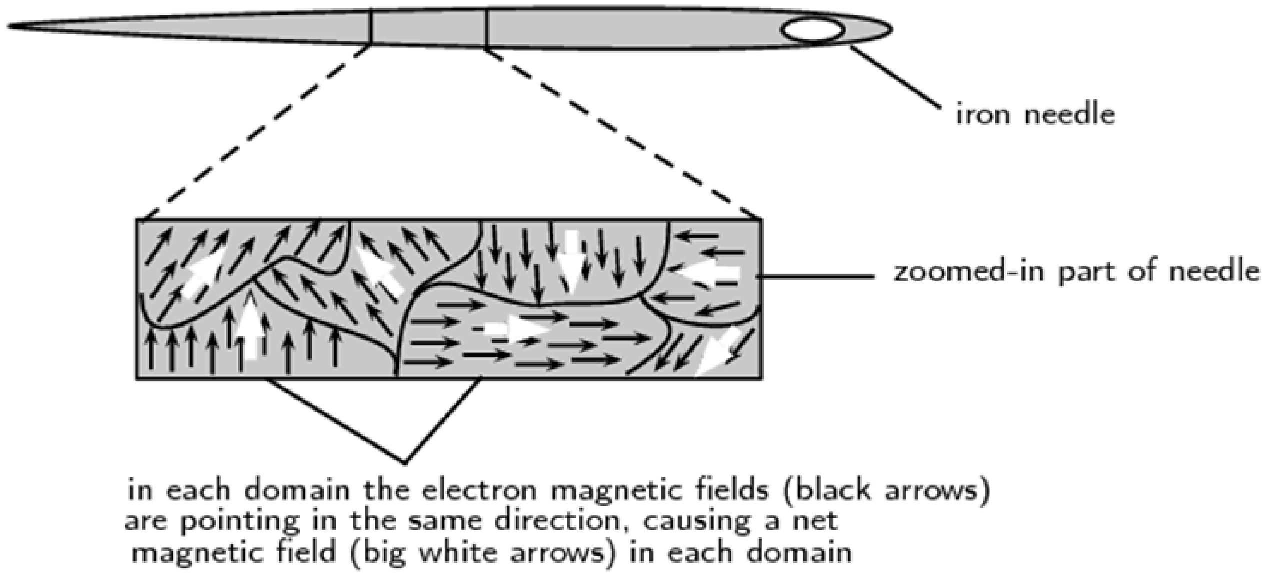


Figure 2: The domains with magnetic fields around electrons, within each domain they point in the same direction

Permanent magnets

In permanent magnets, many domains are lined up, resulting in a *net magnetic field*. Objects made from ferromagnetic materials can be magnetised, for example by rubbing a magnet along the object in one direction. This causes the magnetic fields of most, or all, of the domains to line up in one direction. As a result, the object as a whole will have a net magnetic field. So it then becomes *magnetic*. Once a ferromagnetic object has been magnetised, it can stay magnetic without another magnet being nearby (i.e. without being in another magnetic field). In Figure 3 the needle has been magnetised because the magnetic fields in all the domains are pointing in the same direction.

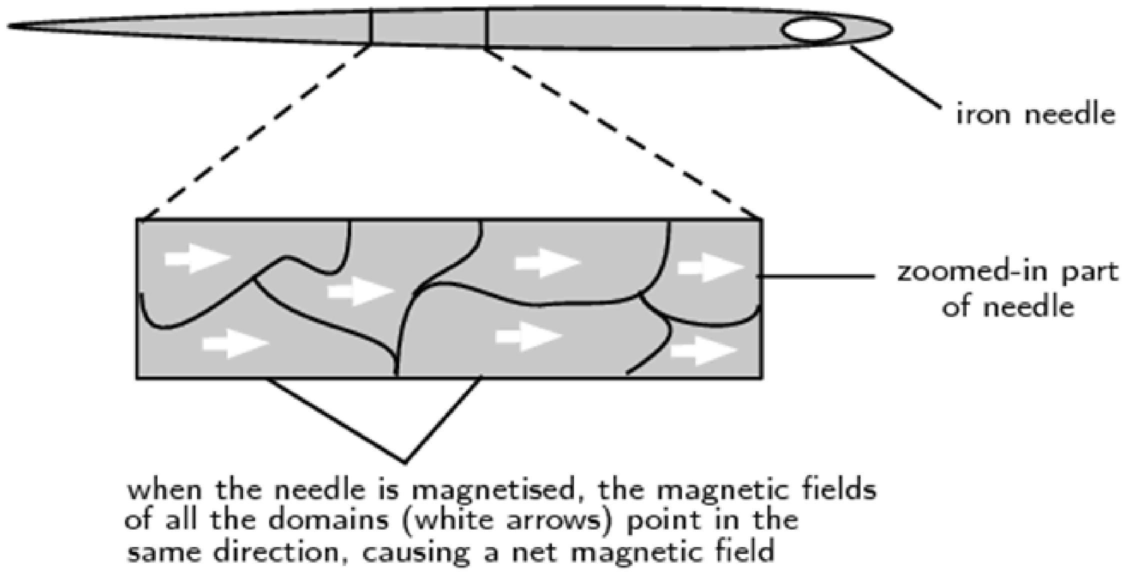


Figure 3: All the domains are now pointing in the same direction

Because the domains in a permanent magnet all line up in a particular direction, the magnet has a pair of opposite poles, called north (usually shortened to N) and south (usually shortened to S). Even if the magnet is cut into tiny pieces, each piece will still have **both** a N and a S pole. These magnetic poles **always** occur in pairs. In nature, we never find a north magnetic pole or a south magnetic pole on its own.

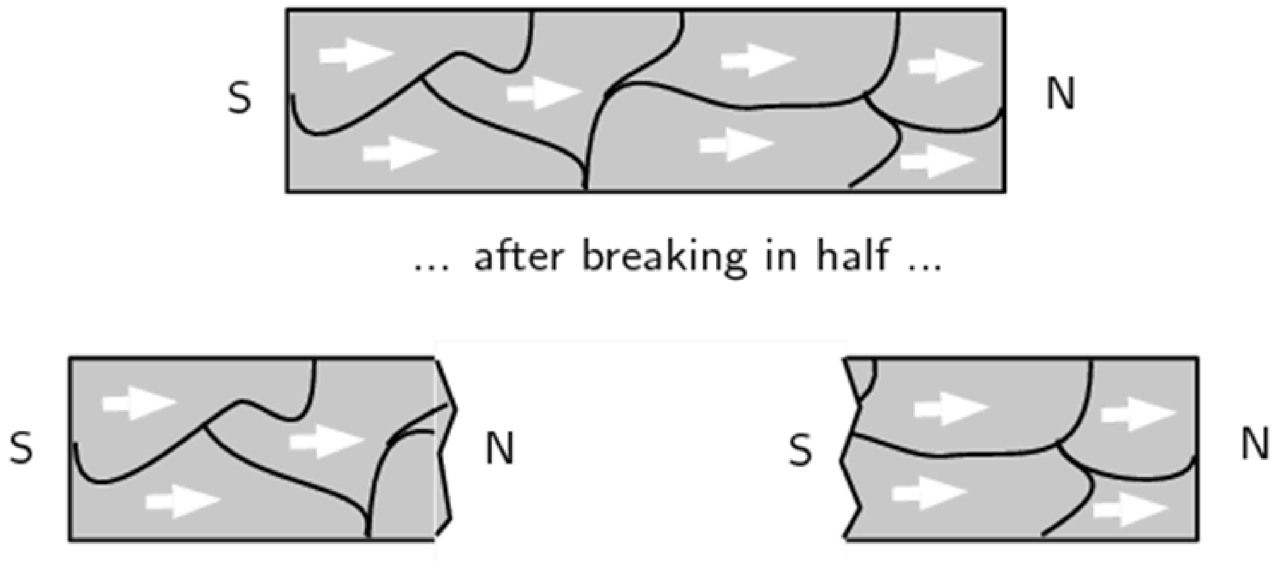


Figure 4: How every magnet has a north and south pole

In nature, positive and negative electric charges can be found on their own, but you *never* find just a north magnetic pole or south magnetic pole on its own. On the very small scale, zooming in to the size of atoms, magnetic fields are caused by moving charges (i.e. the negatively charged electrons).

Like (identical) poles of magnets repel one another whilst unlike (opposite) poles attract. This means that two N poles or two S poles will push away from each other while N poles and S poles will be drawn towards each other.

Do you think the following magnets will repel or be attracted to each other?

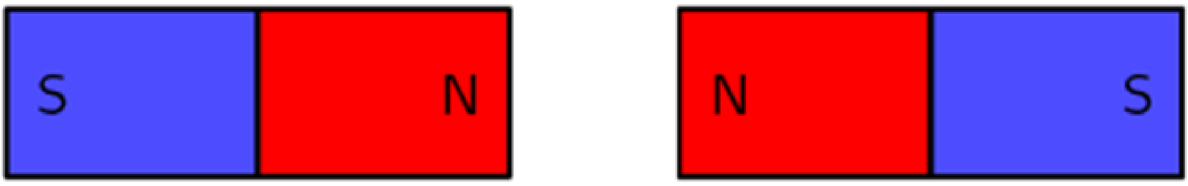


Figure 5: Two magnets with the two north poles facing each other

In Figure 5 you can see two magnets with the N pole of one approaching the N pole of the other. Since both poles are the same, the magnets will repel each other.

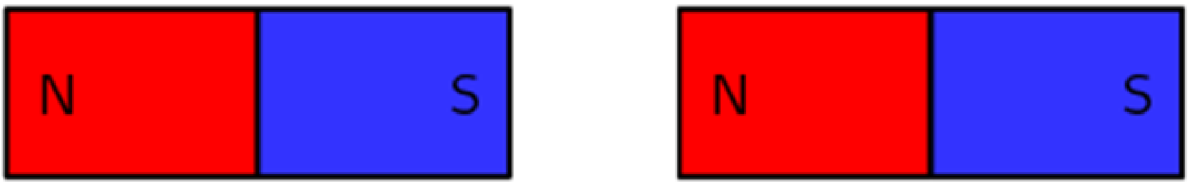


Figure 6: Two magnets with a south pole facing a north pole

In Figure 6 you can see two magnets with the N pole of one approaching the S pole of the other. Since the poles are different, the magnets will be attracted to each other.

Exercise 1.1

1. If all substances contain moving electrons, why are only some substances magnetic?
2. Give a word to describe substances that can be magnetised.
3. Describe how you would position two bar magnets so that they would attract each other.
4. Describe how you would position two bar magnets so that they would repel each other.

The full solutions are at the end of the unit.

Representing magnetic fields

Magnetic fields are invisible, so it is useful to draw diagrams to visualise them. Magnetic field lines are drawn to indicate the strength and direction of the magnetic field. The direction of magnetic field lines is determined by the direction in which a small compass needle will point when placed in the field.

Activity 1.1: Investigate the magnetic field around a bar magnet using a compass

Time required: 5 minutes

What you need:

- an internet connection

What to do:

1. Open the link to the PhET simulation which shows a bar magnet and a small compass. [link:PhET Simulation (colorado.edu)]
2. Begin by dragging the compass around the bar magnet to see the direction the magnetic field points.
3. Note the strength of the magnetic field which is represented by the brightness of the magnetic field icons in the grid pattern around the magnet.
4. Use the magnetic field meter to check the field strength at several points around the bar magnet.
5. Flip the polarity of the magnet and repeat.

What did you find?

The needle of the compass always points outwards from the north pole of the magnet and inwards at the south pole of the magnet. The field is strong near the poles and gets weaker as you move further away from the poles.

Although the magnetic field of a permanent magnet is everywhere surrounding the magnet (in all three dimensions), in a diagram we draw only some of the field lines to represent the field; usually only a two-dimensional cross-section is shown in drawings. Figure 7 shows how the magnetic field around a bar magnet is represented in drawings:

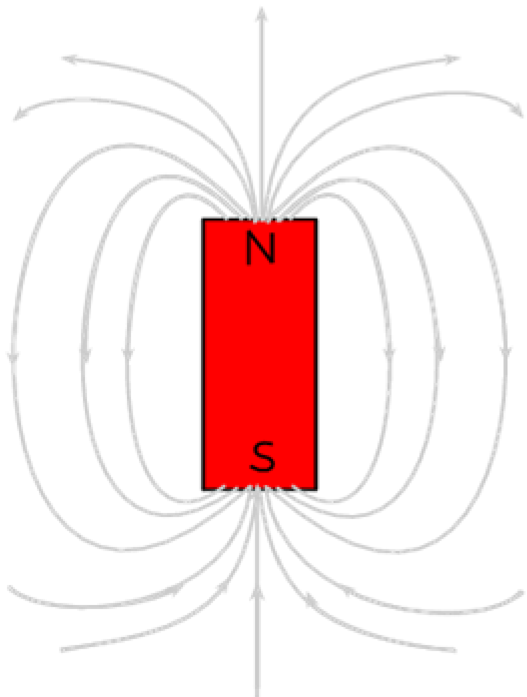


Figure 7: The magnetic field around a bar magnet

Features of magnetic field diagrams:

- The lines must never cross.

- The lines must have arrowheads pointing away from north and towards south.
- In areas where the magnetic field is strong (near the poles), the field lines are closer together. Where the field is weaker (further away from the poles), the field lines are drawn further apart.
- The number of field lines is referred to as the magnetic flux. The magnetic flux is used as a measure of the strength of the magnetic field.

As already stated, opposite poles of a magnet attract each other and bringing them together causes their magnetic field lines to *converge* (come together). Like poles of a magnet repel each other and bringing them together causes their magnetic field lines to *diverge* (bend out from each other).

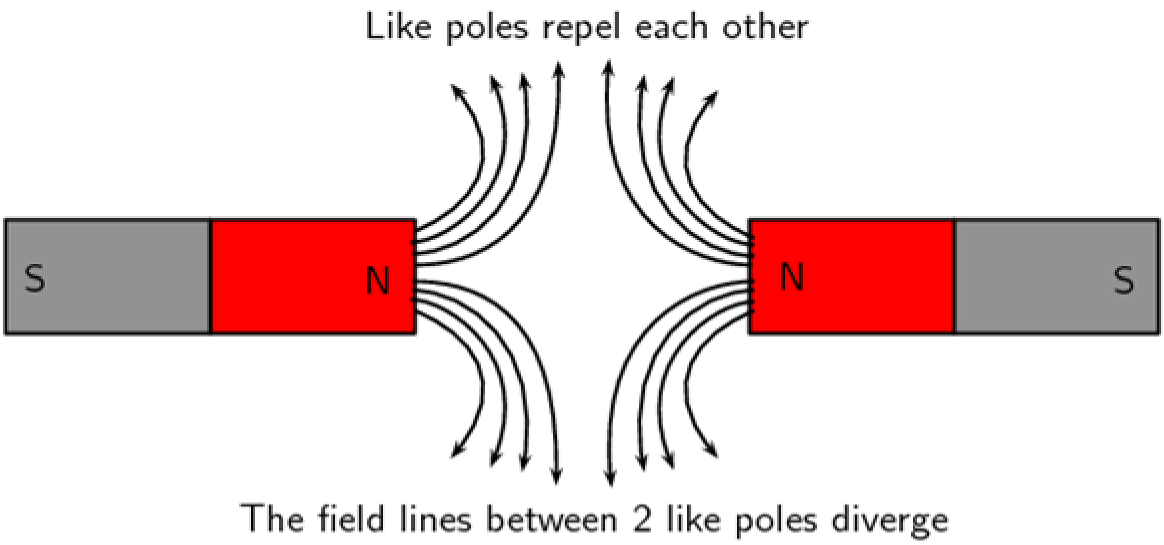


Figure 8: The magnetic field around two bar magnets with north poles facing each other

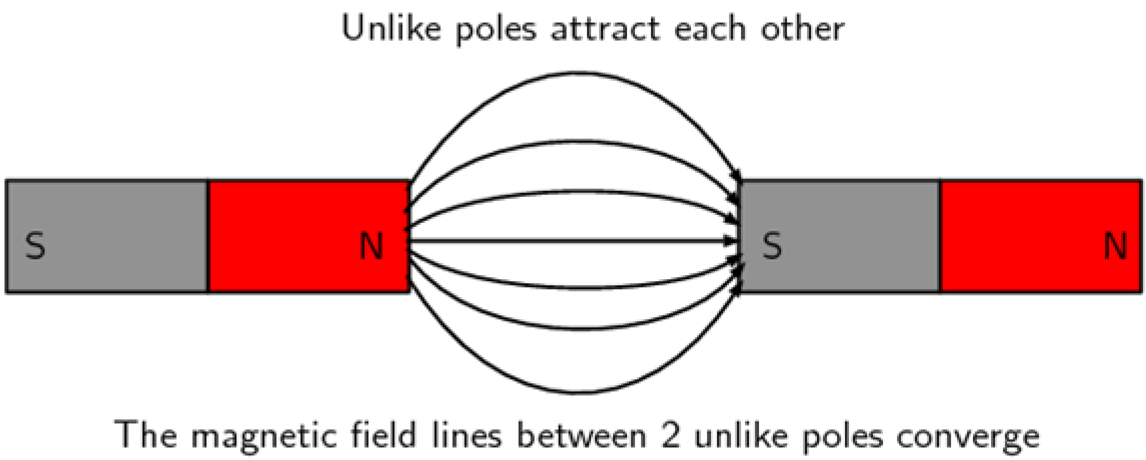


Figure 9: The magnetic field around two bar magnets with a north pole facing a south pole

Note

For further explanation on magnetism, you can watch this video about [Magnetism] by Fuse Schools

(Duration: 3.03).

Summary

In this unit you have learnt the following:

- Magnets have two poles – north and south.
- Some substances can be easily magnetised by aligning the domains; these are called ferromagnetic substances.
- Like poles repel each other and unlike poles attract each other.
- Magnetic field lines are drawn to indicate the direction and strength of a magnetic field.

Unit 1: Assessment

Suggested time to complete: 10 minutes

1. Describe a magnetic field.
2. Explain how a substance can become magnetised.
3. What happens to a magnet if it is cut into pieces?
4. What happens if:
    a. two north poles are brought near each other?
    b. two south poles are brought near each other?
    c. a north pole is brought near a south pole?
5. Draw the magnetic field:
    a. around a single bar magnet
    b. in the area between two magnets with a north pole facing a south pole
    c. in the area between two magnets with two north poles facing each other.

The full solutions are at the end of the unit.

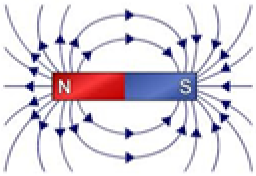
Unit 1: Solutions

Exercise 1.1

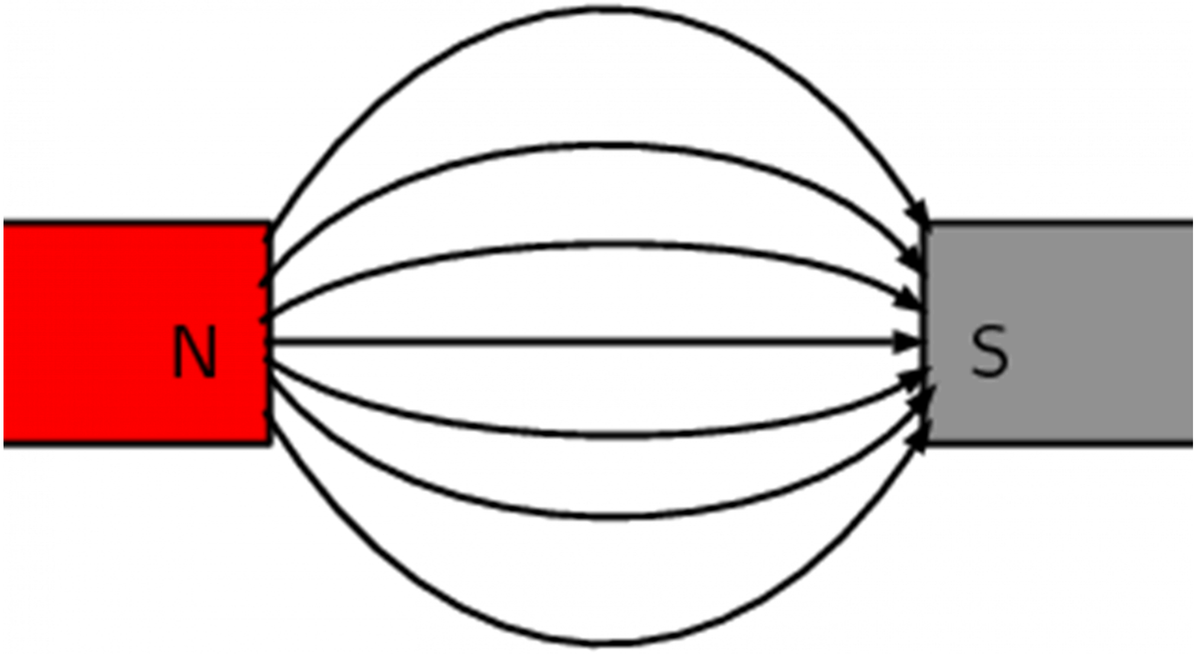
1. In order to have magnetic properties all the domains in the substance have to be aligned (face the same direction). This can only occur in some substances.
2. Ferromagnetic
3. Place the north pole of one magnet facing the south pole of the other magnet.
4. Place two north poles facing each other or two south poles facing each other.

[Back to Exercise 1.1]

Unit 1: Assessment

1. A magnetic field is a region in space where a magnet or object made of magnetic material will experience a non-contact, magnetic force.
2. A magnet is rubbed against the substance and causes all the domains to become lined up in the same direction.
3. Each piece will become a smaller magnet with a north and a south pole.
4.
   a. They will repel each other.
   b. They will repel each other.
   c. They will attract each other.
5.
   a.
   

   b.



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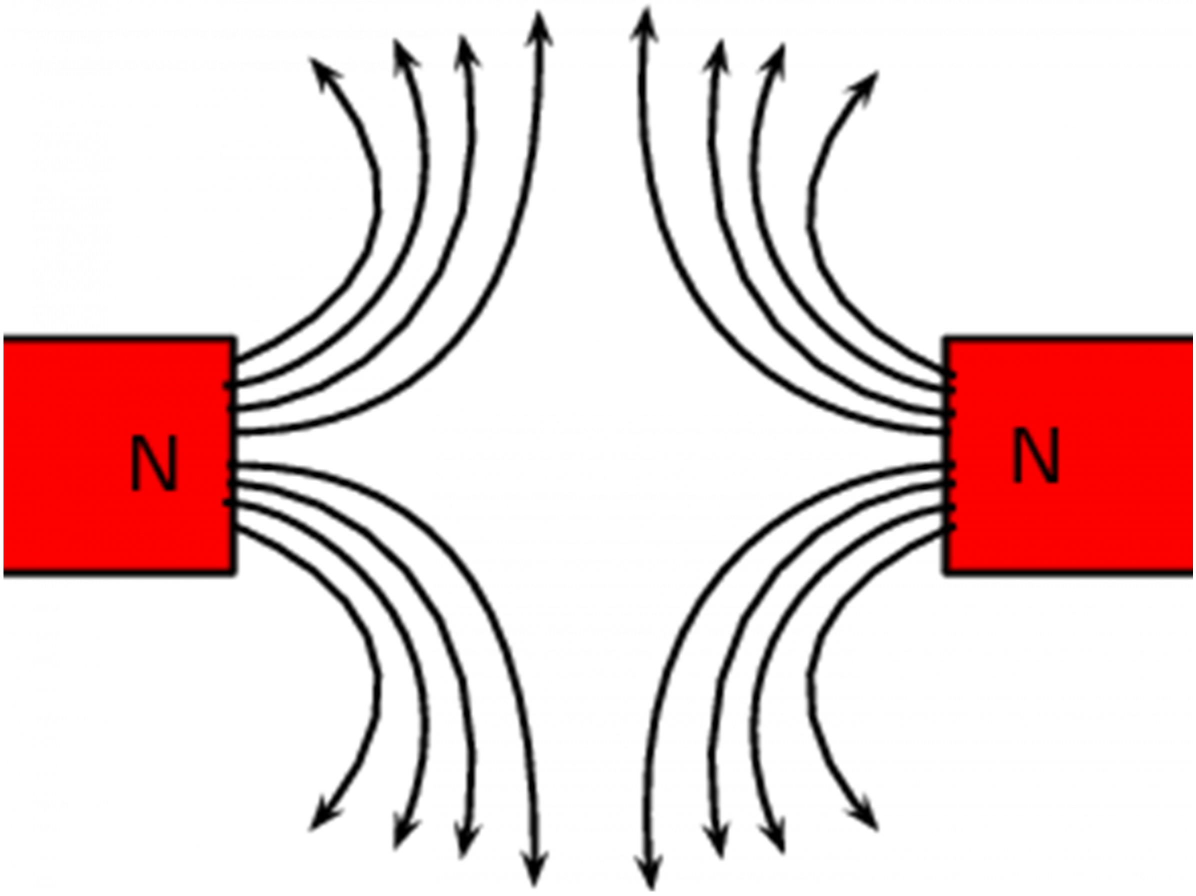

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Unit 2: The Earth's magnetic field

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Identify and describe the Earth's magnetic field.
- Describe magnetic declination.
- Describe the working of a compass.
- Apply magnetic phenomena by induction of the Earth's magnetic field and refer to iron and steel used in building construction.

What you should know

Before you start this unit, make sure you:

- Understand the principles of magnets and magnetic fields, as covered in Subject outcome 4.1, Unit 1.

Introduction

The Earth behaves like a giant bar magnet and as such there is a magnetic field present around it. The Earth's magnetic field is thought to be caused by flowing liquid metals in the outer core of the planet which causes electric currents and a magnetic field.

The Earth's magnetic field and magnetic declination

In Figure 1 you can see a representation of the Earth's magnetic field, which is very similar to the magnetic field of a giant bar magnet shown in Figure 2. The Earth has two magnetic poles, a north and a south pole just like a bar magnet.

In addition to the magnetic poles the Earth also has two geographic poles. The two geographic poles are the points on the Earth's surface where the line of the Earth's axis of rotation meets the surface. To visualise this, you could take any round fruit (lemon, orange, etc.) and stick a pencil through the middle so it comes out the other side. Turn the pencil, the pencil is the axis of rotation and the geographic poles are where the pencil enters and exits the fruit. We call the geographic north pole true north.

The Earth's magnetic field has been measured very precisely and scientists have found that the position of the magnetic poles do not correspond exactly to the geographic poles.

So, the Earth has two north poles and two south poles: two geographic poles and two magnetic poles.

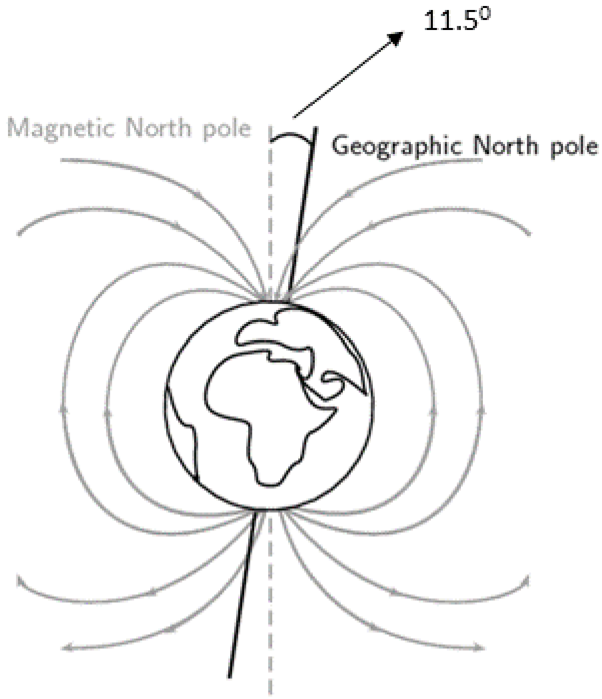


Figure 1: A representation of the Earth's magnetic field

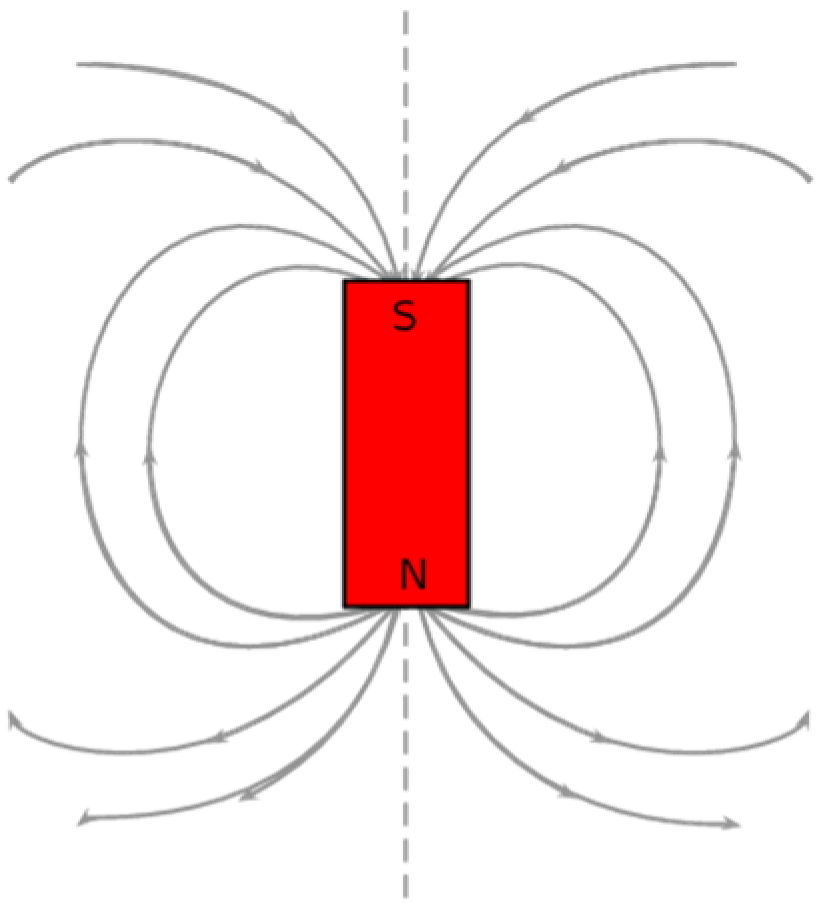


Figure 2: The magnetic field of a magnet

In Figure 1 you can see that the direction of magnetic north and true north are not identical. The geographic north pole is about 11.5° away from the direction of the magnetic north pole (which is where a compass will point). This difference is referred to as magnetic declination. However, the magnetic poles shift slightly all the time.

Another interesting thing to note is that if we think of the Earth as a big bar magnet, and we know that magnetic field lines always point from *north* to *south*, then the compass tells us that what we call the *magnetic north* pole is actually the *south pole* of the 'bar magnet' within the earth!

Activity 2.1: Investigate the Earth's magnetic poles with a compass simulation

Time required: 5 minutes

What you need:

- an internet connection

What to do:

1. Open the PhET simulation. [link: https://phet.colorado.edu/sims/cheerpj/faraday/latest/faraday.html?simulation=magnet-and-compass]
2. Tick the checkbox for 'Show planet Earth'.
3. Move the compass and note the direction of the magnetic field at several points.

What did you find?

The compass shows that the direction of the magnetic field around the Earth is outwards at the geographic south pole and inwards at the geographic north pole.

How a compass works

A compass is an instrument that is used to find the direction of a magnetic field. A compass consists of a small metal needle which is magnetised itself and which is free to turn in any direction. The point of the needle is the north pole of the magnet. Therefore, when in the presence of a magnetic field, the needle lines up in the same direction as the field.

Compasses are mainly used in navigation to find direction on the Earth. This works because the Earth's magnetic field is similar to that of a bar magnet (see Figures 1 and 2). The compass needle (a north pole) aligns with the Earth's magnetic field direction and points towards the south of the Earth's magnetic field. This direction is referred to as north (N). Once you know where north is, you can figure out any other direction.

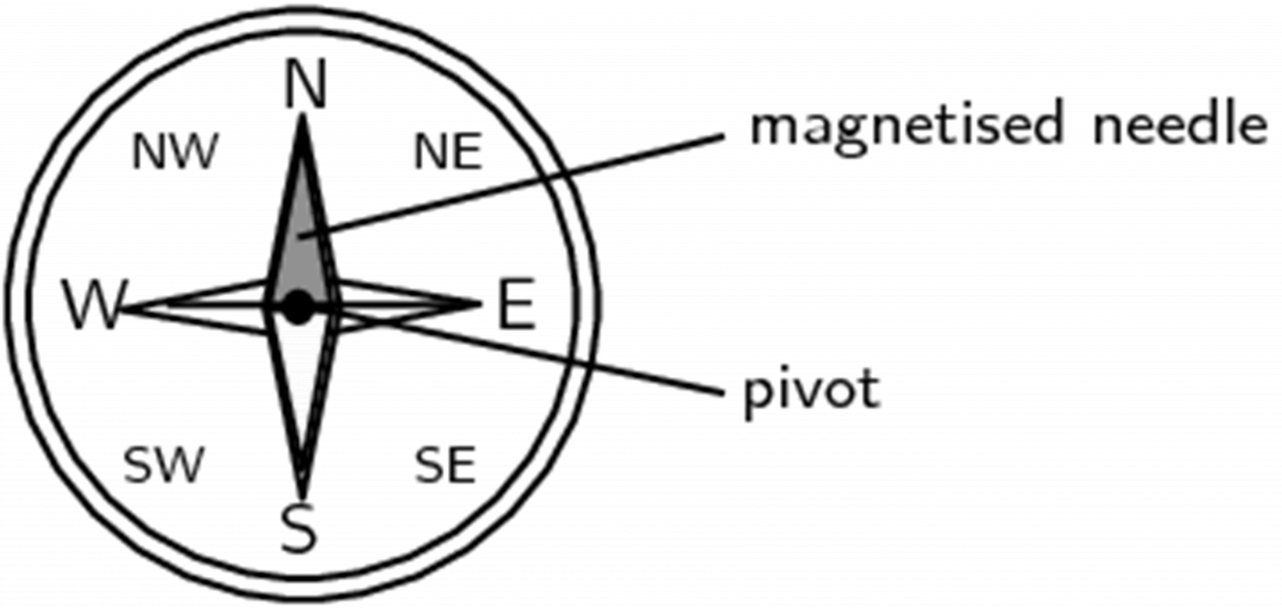


Figure 3: A basic compass

Exercise 2.1

1. What causes the earth to have a magnetic field?
2. Why is the earth's geographic north not the same as its magnetic north?
3. Why does a compass needle point towards the earth's magnetic north pole?

The full solutions are at the end of the unit.

The importance of the magnetic field to life on Earth

The Earth's magnetic field is very important for humans and other animals on Earth because it protects us from being bombarded by high energy charged particles which are emitted by the Sun. The stream of charged particles (mainly positively charged protons and negatively charged electrons) coming from the sun is called the solar wind. When these particles come close to the Earth, they are deflected by the Earth's magnetic field and cannot shower down to the surface where they can harm living organisms. Astronauts in space are at risk of being exposed to radiation from the solar wind because they are outside the zones where the charged particles are trapped.

The region above Earth's atmosphere in which charged particles are affected by the Earth's magnetic field is called the magnetosphere. Relatively often, in addition to the usual solar wind, the sun may eject a large bubble of material (protons and electrons) with its own magnetic field. Sometimes these bubbles travel towards the Earth where their magnetic fields can join with Earth's magnetic field. When this happens a huge amount of energy is released into the Earth's magnetosphere, causing a geomagnetic storm. These storms cause rapid changes in the Earth's magnetosphere which in turn may affect electric and magnetic systems on the Earth such as power grids, cell phone networks, and other electronic systems.

Other effects caused by the Earth's magnetic field are the spectacular northern and southern lights, which are also called the aurora borealis and the aurora australis respectively. When charged particles from the solar wind reach the Earth's magnetosphere, they spiral along the magnetic field lines towards the north and south poles. If they collide with particles in the Earth's atmosphere, they can cause red or green lights which stretch across a large part of the sky and this is called the aurora.

Figure 4: Aurora borealis photographed in Alaska

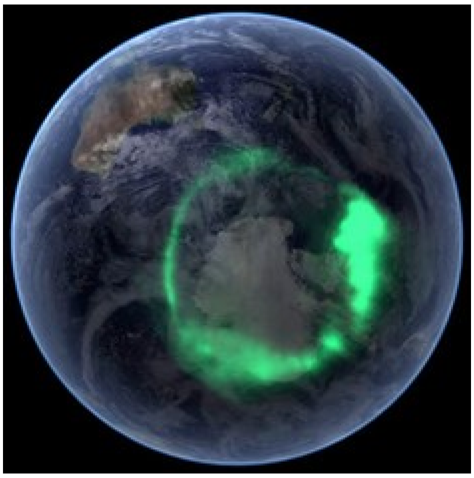


Figure 5: Aurora australis photographed from space

As this only happens close to the north and south poles, we cannot see the aurorae from South Africa. However, people living in the high northern latitudes in Canada, Sweden, and Finland, for example, often see the northern lights.

Some animals can detect magnetic fields, which helps them orientate themselves and navigate. Animals that can do this include pigeons, bees, monarch butterflies, sea turtles and certain fish.

Iron can be easily magnetised when placed in a magnetic field. This property needs to be considered when it is used in building construction. As steel is more difficult to magnetise, it is more often used for building construction.

Note

Watch the Fuse School Video on the Earth's magnetic field and compasses, which summarises the concepts covered in this unit (Duration: 3.42).

Summary

In this unit you have learnt the following:

- The Earth has a magnetic field.
- A compass can be used to find the magnetic north pole and help us find our direction.
- The magnetic north pole does not correspond precisely with the geographic north pole – this difference is called magnetic declination.
- The Earth's magnetic field protects us from being bombarded by high energy charged particles which are emitted by the sun.
- The aurorae are effects of the Earth's magnetic field.

Unit 2: Assessment

Suggested time to complete: 15 minutes

1. Draw a diagram showing the magnetic field around the Earth, and indicate the poles of a bar magnet within the Earth.
2. Explain the difference between the geographical north pole and the magnetic north pole of the Earth.
3. Explain how a compass works.
4. Explain why the Earth's magnetic field has a protective effect for the planet.
5. Describe the effects of a geomagnetic storm in the magnetosphere.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

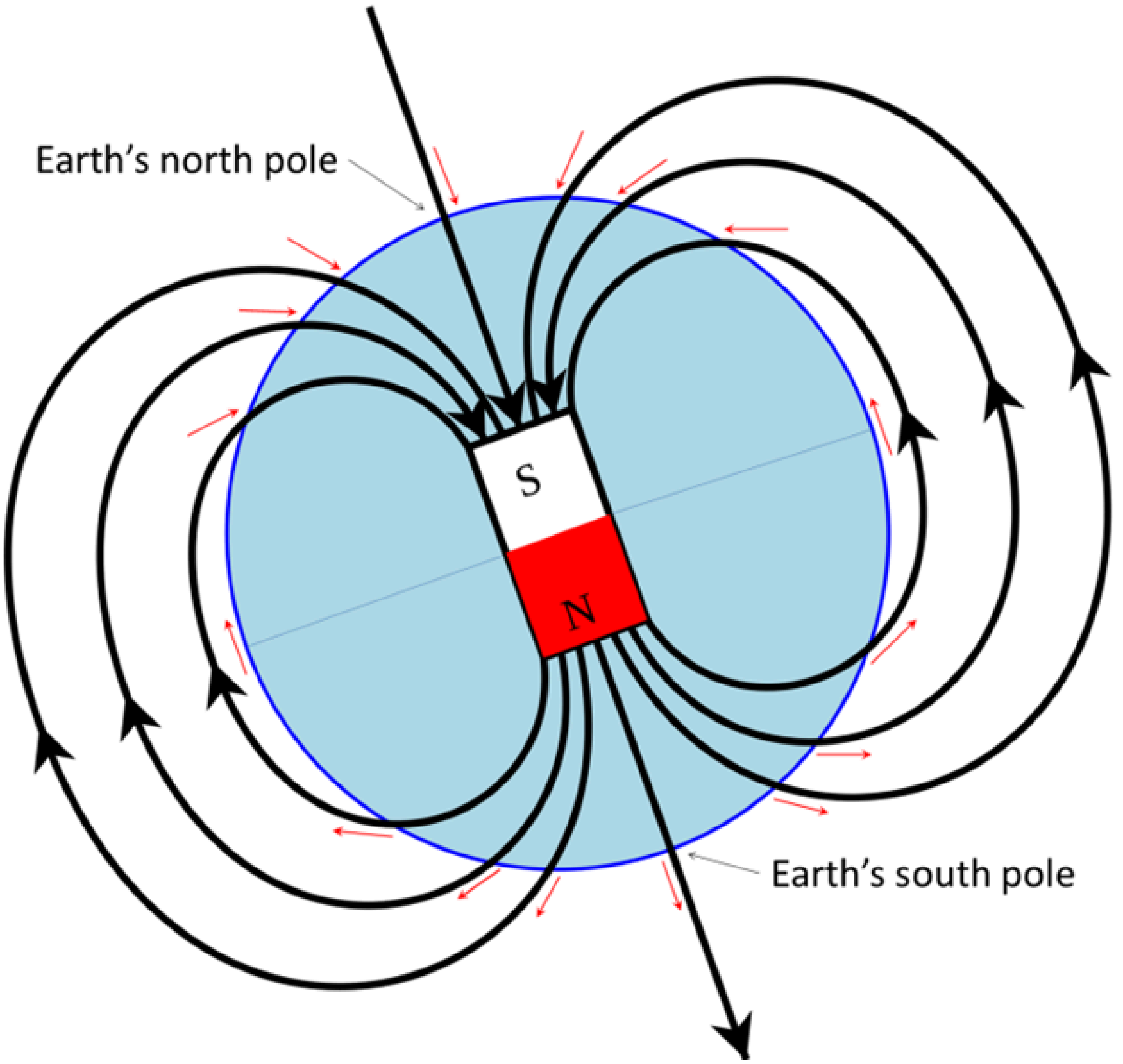
1. The Earth's magnetic field is thought to be caused by flowing liquid metals in the outer core of the planet which causes electric currents and a magnetic field.

2. This is because of the declination (tilt of the axis) of the earth. The northmost point of the earth (the geographic north pole) is about 11.5^{o} away from the direction of the magnetic north pole.
3. The compass needle is a north pole of a magnet, so it aligns with the Earth's magnetic field direction and points towards the south of the Earth's magnetic field.

Back to Exercise 2.1

Unit 2: Assessment

1.



2. The geographic north pole is the point on the Earth that is furthest north or where the line of axis of rotation meets the surface. Whereas the magnetic north pole is where the magnetic field lines of the Earth's magnetic field converge.
3. A compass has a needle made of a magnet. The north pole of the magnet is the point of the needle. It will therefore be attracted towards the south pole of the Earth's magnetic field. This direction is called north (N), and all other directions can then be determined once north is known.
4. The Earth is continually bombarded by streams of charged particles released from the sun which can damage living organisms. These particles are deflected by the Earth's magnetic field.
5. Geomagnetic storms cause rapid changes in the magnetosphere which can affect magnetic and electric systems like power grids, cell phone networks and electronics.

Back to Unit 2: Assessment

Media Attributions

Unit 3: Magnetic shielding

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Describe magnetic shielding
- Describe the underlying principles of magnetic shielding
- Describe the purpose of magnetic shielding.

What you should know

Before you start this unit, make sure you:

- Understand the principles of magnets and magnetic fields, as covered in Subject outcome 4.1, Unit 1.
- Understand the principles of the Earth's magnetic field, as covered in Subject outcome 4.1, Unit 2.

Introduction

Magnetic shielding is the practice of reducing the magnetic field in a space by blocking the field with barriers made of conductive or magnetic materials. Shielding is typically applied to enclosures to isolate electrical devices from their surroundings, and to cables to isolate wires from the environment through which the cable runs. This can be done with several materials, including sheet metal, metal mesh, ionized gas, or plasma. The purpose is most often to prevent magnetic fields from interfering with electrical devices.

How does it work?

Instead of attempting to stop these magnetic field lines, magnetic shielding re-routes them around an object. This is done by surrounding the device to be shielded with a magnetic material. Magnetic permeability describes the ability of a material to be magnetised. If the material used has a greater permeability than the objects inside, the magnetic field will tend to flow along this material, avoiding the objects inside. Thus, the magnetic field lines are redirected.

The most effective shielding material available is mu-metal — an alloy of 77% nickel, 16% iron, 5% copper and 2% chromium — which is then heated in a hydrogen atmosphere to increase its permeability. As mu-metal is extremely expensive, other alloys with similar compositions are sold for shielding purposes, usually in rolls of foil.

Activity 3.1: Investigate which materials can act as a magnetic shield

Time required: 30 minutes

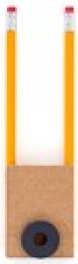
What you need:

- three round ceramic magnets (rectangular magnets will also work)
- two pieces of cardboard of equal size, about 5 x 7 centimetres
- two pencils, 7 cm or longer
- five or six paper clips
- a wood craft stick (ice cream stick), a plastic straw, or any other non-metallic material
- a steel knife
- a hot-glue gun and glue (alternatively, you can use rubber bands)

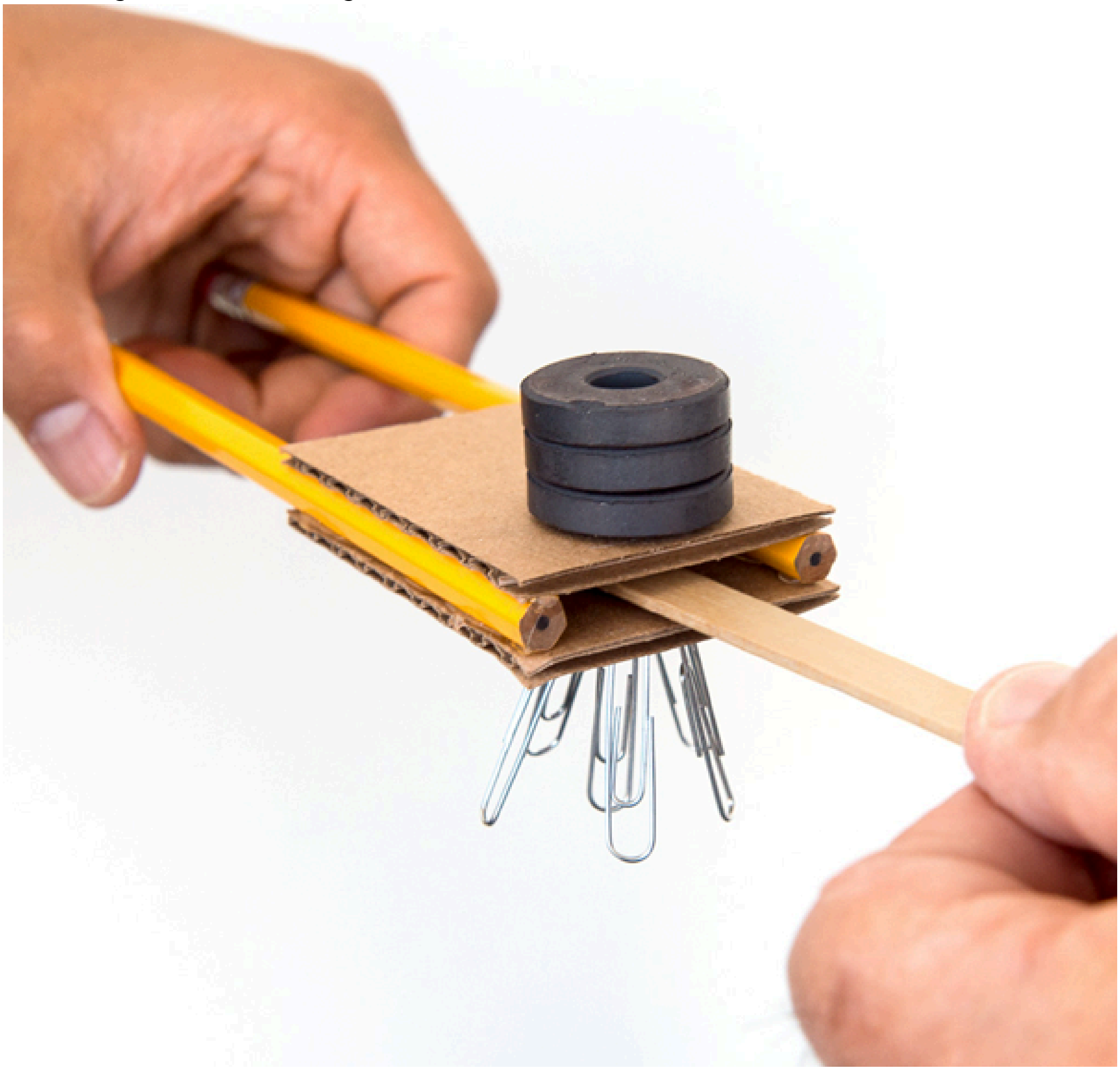
What to do:

You will test different materials to see which of them gather magnetic lines of force and act as magnetic shields, and which allow magnetic lines of force to pass through them.

1. Make a cardboard-pencil sandwich: Attach the pencils to one piece of cardboard, placing the pencils parallel to each other and close to the opposite edges of the cardboard (see the photo below). Glue the second piece of cardboard to the pencils so that you end up with a cardboard-pencil-cardboard sandwich.
2. Secure one of the magnets to the top piece of cardboard with hot glue. Centre the magnet near one of the edges (see the photo below).



3. Add two more magnets on top of the first one so that they are held in place by magnetic attraction. Do not glue them!
4. Hold your shielding sandwich with the magnets on top. Lift the paper clips one at a time from the bottom side and notice what happens (see the photo below). The paper clips should be attracted to the magnet and so will hang from the bottom of the cardboard sandwich.



5. As you add more paper clips, notice what happens. If you add them carefully, they will arrange themselves so that they are evenly spaced.
6. Insert the craft stick or plastic straw into the shielding sandwich, move it around, and notice what happens. The paper clips should be unaffected.

7. Now insert the flat blade of a steel knife into the shielding sandwich, move it from side to side, and notice what happens. Do the paper clips fall off? Try experimenting with different materials, such as various metallic coins, to see what makes the paper clips fall off.

What did you find?

The magnetic-field lines from the magnet pass through the cardboard, the air, and other materials like the craft stick and straw. Materials that allow magnetic lines of force to pass through them are called nonpermeable because magnetic fields do not form within them.

In contrast, the metal knife acts as a magnetic shield, meaning the field lines coming from the pole of the magnet do not pass through it. Instead, they are gathered in, travel down the metal, and re-enter the magnet at the other pole. Materials that gather magnetic lines of force are said to be permeable, because they support the formation of magnetic fields within those materials. Only magnetic materials are permeable and can be used for shielding.

Where is magnetic shielding used?

Magnetic shielding is often used in hospitals, where devices such as magnetic resonance imaging (MRI) equipment generates powerful magnetic flux. Shielded rooms are constructed to prevent this equipment from interfering with surrounding instruments or meters. Similar rooms are used in electron beam exposure rooms where semiconductors are made, or in research facilities using magnetic flux.

Smaller applications of magnetic shielding are common in home theatre systems. Speaker magnets can distort a cathode ray tube (CRT) television picture when placed close to the set, so speakers intended for that purpose are shielded. It is also used to counter similar distortion on computer monitors. Shielding using superconducting magnets is being researched as a means of shielding spacecraft from cosmic radiation.

Summary

In this unit you have learnt the following:

- Magnetic shielding blocks magnetic fields by using barriers made of materials that can be magnetised.
- The magnetic field lines are redirected by the shielding material creating a space that is free of magnetic force.
- Magnetic shielding has practical applications in everyday life.

Unit 3: Assessment

Suggested time to complete: 10 minutes

1. Explain the concept of magnetic shielding and its purpose.
2. Which of these materials would make an effective magnetic shield: iron or cardboard? Explain the underlying principle of how the shielding takes place.
3. Would nickel be effective for magnetic shielding? Explain your answer.
4. Describe three practical applications of magnetic shielding in a real-world context.

The full solutions are at the end of the unit.

Unit 3: Solutions

Unit 3: Assessment

1. Magnetic shielding is the practice of reducing the magnetic field in a space by blocking the field with barriers made of conductive or magnetic materials which redirect the field. The purpose is most often to prevent magnetic fields from interfering with electrical devices.
2. Iron is easily magnetised whereas cardboard cannot be magnetised. Any magnetic field present will tend to flow through the iron and avoid objects on the other side of the iron shield.
3. Yes. Shielding can only be accomplished by using a magnetically permeable substance and nickel can be magnetised easily.
4.
    - Rooms for MRI equipment – these prevent the strong magnetic field generated by this equipment from interfering with other equipment in hospitals.
    - TVs, computer monitors or home theatre systems – these prevent the magnetic fields from speaker magnets distorting the pictures.
    - Shielding using superconducting magnets is being researched as a means of shielding spacecraft from cosmic radiation.

Back to Unit 3: Assessment

Media Attributions

SUBJECT OUTCOME VIII

MAGNETISM AND ELECTRICITY: IDENTIFY, DESCRIBE, AND APPLY PRINCIPLES OF ELECTROSTATICS (STATIC ELECTRICITY)

Subject outcome

Subject outcome 4.2: Identify, describe, and apply principles of electrostatics (static electricity).

Learning outcomes

- Identity two kinds of charge and describe how an object becomes charged.
- Define the law of conservation of charge.
- Identify and predict the distribution of charge over the surface of a conductor (spherical and non-spherical).
- Identify and predict action between electric charges, the attraction between charged and uncharged objects and action of highly charged points.
- Identify and describe electrostatic induction.
- Apply the principle of discharge to a charged rod using ions in a flame and ions in the atmosphere and atmospheric electricity and the use of a lightning conductor.

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify two kinds of charge.
- Describe how an object becomes charged.
- Define the law of conservation of charge.

Unit 2 outcomes

By the end of this unit you will be able to:

- Identify and predict the distribution of charge over the surface of a conductor (spherical and non-spherical).

- Identify and predict action between electric charges, the attraction between charged and uncharged objects and action of highly charged points.
- Identify and describe electrostatic induction.

Unit 3 outcomes

By the end of this unit you will be able to:

- Apply the principle of discharge to:
  - charged rod using ions in a flame
  - ions in the atmosphere
  - atmospheric electricity and the use of a lightning conductor.

Unit 1: What is charge?

LEIGH KLEYNHANS

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify two kinds of charge.
- Describe how an object becomes charged.
- Define the law of conservation of charge.

What you should know

Before you start this unit, make sure you can:

- Identify and apply the principles of forces, as covered in Subject outcome 2.2, Unit 1.

Introduction

In this unit[1] you will learn what 'charge' is and what it means when we say an object is or becomes charged.

Electrostatics is the study of electric charge which is at rest or static (not moving). In this unit we will look at some of the basic principles of electrostatics as well as the principle of conservation of charge.

What is charge?

All objects surrounding us (including people!) contain large amounts of electric charge. There are two types of electric charge: **positive** charge and **negative** charge. If the same amounts of negative and positive charge are found in an object, there is *no net charge*, and the object is electrically **neutral**. If there is more of one type of charge than the other on the object, then the object is said to be **electrically charged**. Figure 1 below shows what the distribution of charges might look like for a neutral, positively charged and negatively charged object.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 16, released under a CC-BY licence

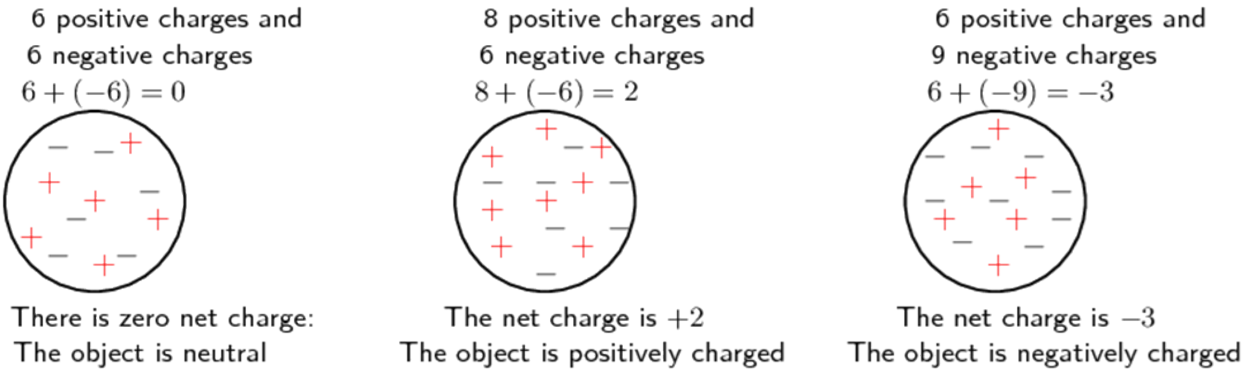


Figure 1: The distribution of charges in neutral, positively and negatively charged objects

Positive charge is carried by the protons in material and negative charge by electrons. The overall charge of an object is usually due to changes in the number of electrons.

To make an object:

- **positively charged**, electrons are removed making the object electron deficient.
- **negatively charged**, electrons are added giving the object an excess of electrons.

So in practise what happens is that the number of positive charges (protons) remains the same and the number of negative charges (electrons) changes:

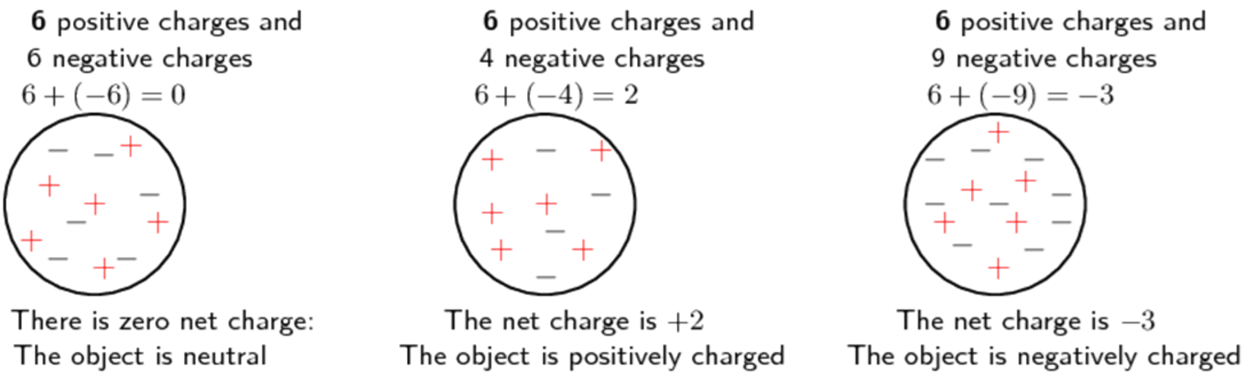


Figure 2: Changes in the number of electrons determines whether an object becomes positively or negatively charged

Note

We represent the positive charge with a + and the negative charge with a –. These symbols illustrate the balance and changes that occur, not the actual number or location of the positive and negative charges. The charges are spread throughout the material and the real change happens by increasing or decreasing electrons on the surface of the materials.

How does an object become charged?

Objects may become charged in many ways, including coming into contact with or being rubbed by other objects. This means that they can gain or lose negative charge. For example, charging happens when you rub your feet against the carpet. When you rub your feet against the carpet, negative charge is transferred to you from the carpet. The carpet will then become positively charged by the same amount.

Another example is to take two neutral objects such as a plastic ruler and a cotton cloth. To begin with, the two objects are neutral (i.e. have the same amounts of positive and negative charge).

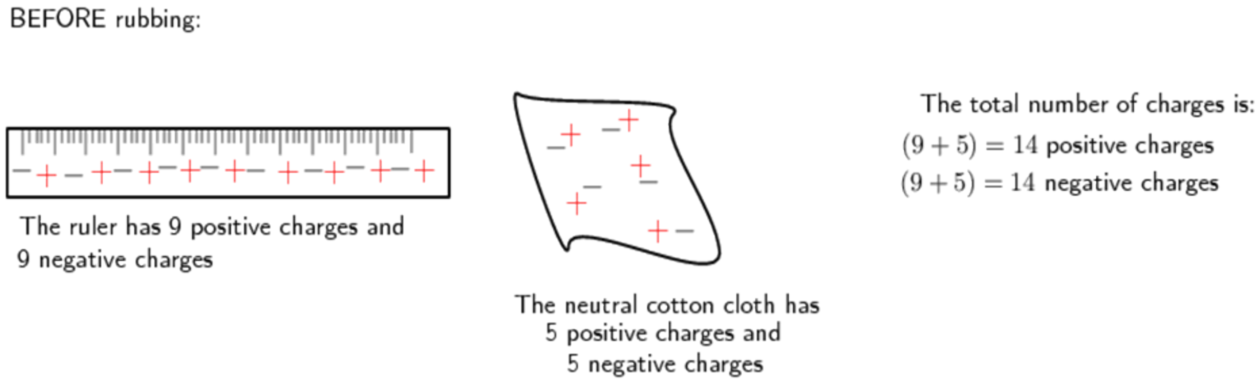


Figure 3: A ruler and piece of cotton cloth before rubbing – both are neutral

Now, if the cotton cloth is used to rub the ruler, negative charge is transferred from the cloth to the ruler. The ruler is now negatively charged (i.e. has an excess of electrons) and the cloth is positively charged (i.e. is electron deficient). If you count up all the positive and negative charges at the beginning and the end, there are still the same amount, i.e. total charge has been conserved!

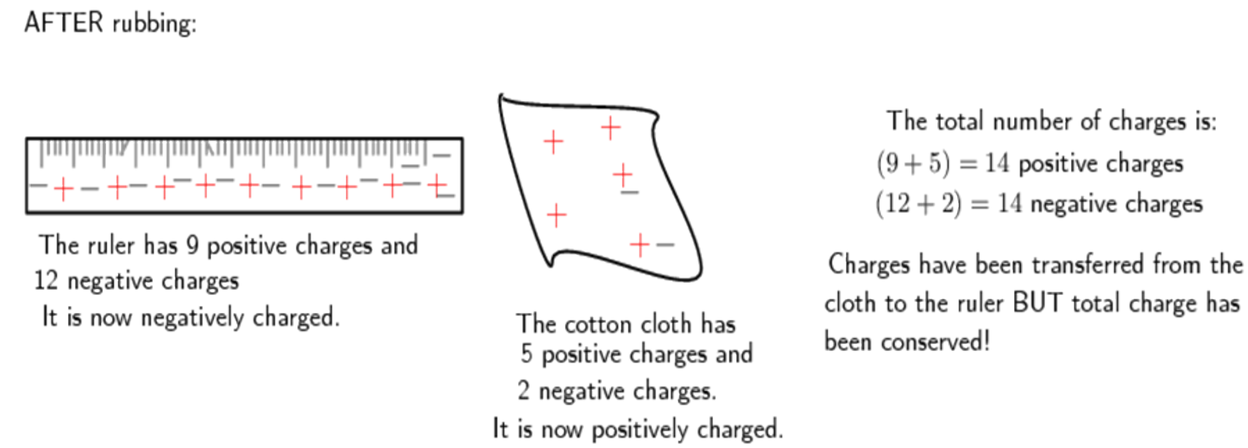


Figure 4: A ruler and piece of cotton cloth after rubbing

What determines the direction in which the negative charges move?

You now know that two objects made of different materials can be electrically charged by rubbing them against each other. But which one will gain electrons and become negatively charged, and which one will lose electrons and become positively charged?

During the rubbing process, the atoms from the different substances interact. The substance with atoms with a greater electron affinity attracts some electrons from the other substance (with less electron affinity) to itself. On separation, the objects will have opposite electrostatic charges.

The triboelectric series compares abilities of substances to lose or gain electrons by friction.

Figure 5: Extract from the triboelectric series

Example 1.1

Use the triboelectric series to determine which object will become positively charged and which will become negatively charged, when wood is rubbed with nylon.

Solution

Step 1: Find the two substances on the table.

Step 2: The substance higher up on the table tends to lose electrons, so it will become positively charged.

Step 3: The substance lower down on the table tends to gain electrons, so it will become negatively charged.

Step 4: By comparison, the answer to this question will be:

- nylon will become positively charged
- wood will become negatively charged.

Activity 1.1: Investigate how objects becomes charged

Time required: 10 minutes

What you need:

- internet access

What to do:

1. Open the following link to the Physics Classroom to play 'Name that charge'.

2. Follow the instructions and complete the activity.

What did you find?

Objects can become charged by friction. The direction in which the negative charges move (electrons) is determined by the relative electron affinity between the two substances. Electrons will move from the substance with the lesser electron affinity into the substance with the greater electron affinity.

Exercise 1.1

For the pairs of substances below determine the charge on each when rubbed together and then separated:

1. Cat fur and amber
2. Ebonite and silk
3. Glass and human hair
4. Steel and wood

The full solutions are at the end of the unit.

The law of conservation of charge

In all the examples we have looked at charge was not created or destroyed. It moved from one material to another. The total amount of positive charge and the total amount of negative charge in the whole system remained constant. It was merely the redistribution of the negative charges that resulted in one object becoming positively charged and the other becoming negatively charged.

This concept is referred to as the law of conservation of charge.

Summary

In this unit you have learnt the following:

- There are two kinds of charge: positive and negative.
- Positive charge is carried by protons in the nucleus of atoms.
- Negative charge is carried by electrons.
- Objects become charged because of a change in the number of electrons.
- Friction causes electrons to move from one substance to another.
- Objects can be positively charged, negatively charged or neutral.
- Objects that are neutral have equal numbers of positive and negative charge.
- Charge is neither created nor destroyed, it can only be transferred.

Unit 1: Assessment

Suggested time to complete: 10 minutes

1. Name the two kinds of charge and the sub-atomic particles responsible for each?
2. Choose the correct answer to the following multiple-choice questions:
    a. Objects become positively charged when:
        A. they gain electrons
        B. they gain protons

C. they lose electrons
D. they lose protons

b. When amber is rubbed with cotton cloth:
A. electrons move from the cotton cloth to the amber
B. electrons move from the amber to the cotton cloth
C. protons move from the cotton cloth to the amber
D. protons move from the amber to the cotton cloth

c. When human hair is rubbed with silk:
A. the human hair becomes positively charged
B. the human hair remains neutral
C. the human hair becomes negatively charged
D. the silk becomes positively charged

d. Electrons will be most likely to move from:
A. plastic wrap to amber
B. steel to ebonite
C. glass to Teflon®
D. nylon to silk

3. Explain what happens when an object becomes charged by friction.
4. Given that silicon has a greater electron affinity compared to aluminium, explain:
   a. how you could charge two objects made of these substances.
   b. the charge that develops on the aluminium, in terms of the movement of electrons.
5. State the law of conservation of charge.

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1. cat fur – positive; amber – negative
   (cat fur has a greater tendency to lose electrons compared to amber according to the triboelectric series)
2. ebonite – negative; silk – positive
   (ebonite has a greater tendency to gain electrons compared to silk according to the triboelectric series)
3. glass – positive; human hair – negative
   (glass has a greater tendency to lose electrons compared to human hair according to the triboelectric series)
4. steel – positive; wood – negative
   (steel has a greater tendency to lose electrons compared to wood according to the triboelectric series).

Back to Exercise 1.1

Unit 1: Assessment

1. Positive – protons
   Negative – electrons
2.
   a. C
   b. A (use the triboelectric series)
   c. A (use the triboelectric series)
   d. C (these two substances exhibit the greatest difference in their electron affinity)
3. During the rubbing process, electrons will move from the substance with lesser electron affinity to the substance with greater electron affinity.
4.
   a. You can rub the two substances together.
   b. The aluminium will lose electrons and therefore become positively charged.
5. The net charge of an isolated system remains constant.

Back to Unit 1: Assessment

Media Attributions

Unit 2: Interaction of charge

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Identify and predict the distribution of charge over the surface of a conductor (spherical and non-spherical).
- Identify and predict action between electric charges, the attraction between charged and uncharged objects and action of highly charged points.
- Identify and describe electrostatic induction.

What you should know

Before you start this unit, make sure you can:

- Identify the two types of charge.
- Describe how objects become charged, as covered in Subject outcome 4.2, Unit 1.

Introduction

In this unit[1] you will learn about the arrangement of charge on a conductor and an insulator, how charged and uncharged objects interact and the principle of electrostatic induction.
Charged particles or objects with an overall net charge exert forces on one another. The force exerted by non-moving (static) charges on each other is called the electrostatic force.

The electrostatic force

The basic rule of electrostatics is that like charges experience a repulsive force and unlike charges experience an attractive force.

In other words, like charges repel each other while opposite charges attract each other.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 16, released under a CC-BY licence

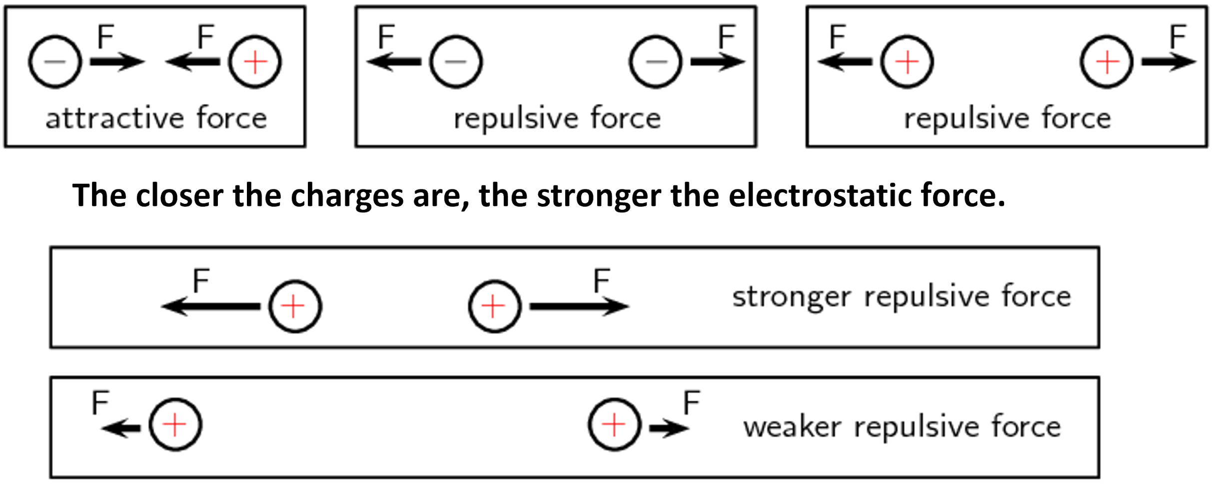
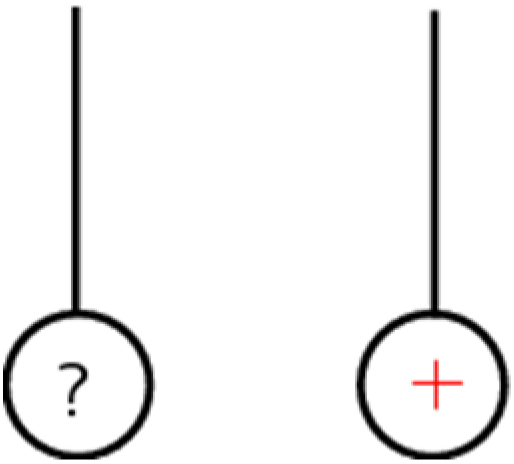


Figure 1: The rule of electrostatics

Exercise 2.1

Two charged hollow metal spheres hang from strings and are free to move as shown in the picture below. The right hand sphere is positively charged. The charge on the left hand sphere is unknown.



The left sphere is now brought close to the right sphere.

1. If the left sphere swings towards the right hand sphere, what can you say about the charge on the left sphere and why?
2. If the left sphere swings away from the right sphere, what can you say about the charge on the left sphere and why?

The full solutions are at the end of the unit.

Note

Watch this video of a static electricity science demonstration to see electrostatic forces in action (Duration: 1.45).

Charge distribution

Some materials allow electrons to move relatively freely through them (e.g. most metals, and the human body). These materials are called conductors.

Other materials do not allow the charge carriers, the electrons, to move through them (e.g. plastic, and glass). The electrons are bound to the atoms in the material. These materials are called non-conductors or insulators.

If an excess of charge is placed on an insulator, it will stay where it is put and there will be a concentration of charge in that area of the object. However, if an excess of charge is placed on a conductor, the electrons will repel each other and spread out over the outer surface of the object.

If the conductor has a spherical shape, the excess electrons will spread uniformly over the surface of the sphere. However, for conductors with irregular shapes, there is a concentration of charge near the point or points of the object.

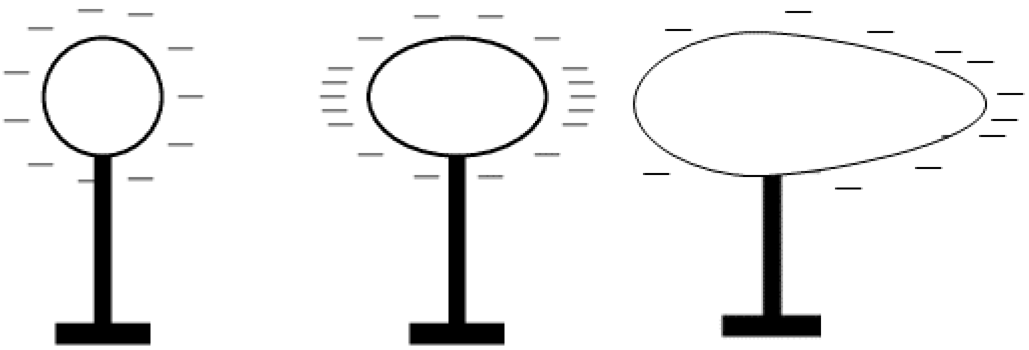


Figure 2: Distribution of charge in spherical and non-spherical objects

In non-spherical objects, the collection of charge where the object is narrower can allow charge to leak off the conductor if the point is sharp enough. It is for this reason that buildings often have a lightning rod on the roof to remove any charge the building has collected. This minimises the possibility of the building being struck by lightning.

This is also the reason why it is safe to be inside a car during a lightning storm. The excess charge in the lightning will spread out on the outer surface of the (metal) car and therefore the inside will be safe. This concept is called a Faraday cage.

This “spreading out” of charge would not occur if we were to place the charge on an insulator since charge cannot move in insulators.

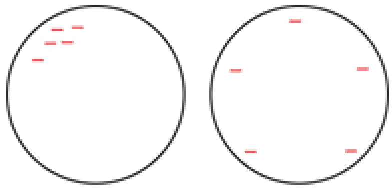


Figure 3: Charge distribution on an insulator and a conductor

Interaction between charged and uncharged objects

Unlike conductors, the electrons in insulators (non-conductors) are bound to the atoms of the insulator and cannot move around freely through the material. However, a charged object can still exert a force on a neutral insulator due to a phenomenon called polarisation or electrostatic induction.

If a positively charged rod (B in Figure 4 below) is brought close to a neutral insulator such as a polystyrene ball (A in Figure 4 below), it can attract the bound electrons to move round to the side of the atoms which is closest to the rod and cause the positive nuclei to move slightly to the opposite side of the atoms. This process is called polarisation. Although it is a very small (microscopic) effect, if there are many atoms and the polarised object is light (e.g. a small polystyrene ball), it can add up to enough force to cause the object to be attracted onto the charged rod. Remember, that the polystyrene is only polarised, not charged. The polystyrene ball is still neutral since no charge was added or removed from it. The picture shows a not-to-scale view of the polarised atoms in the polystyrene ball.

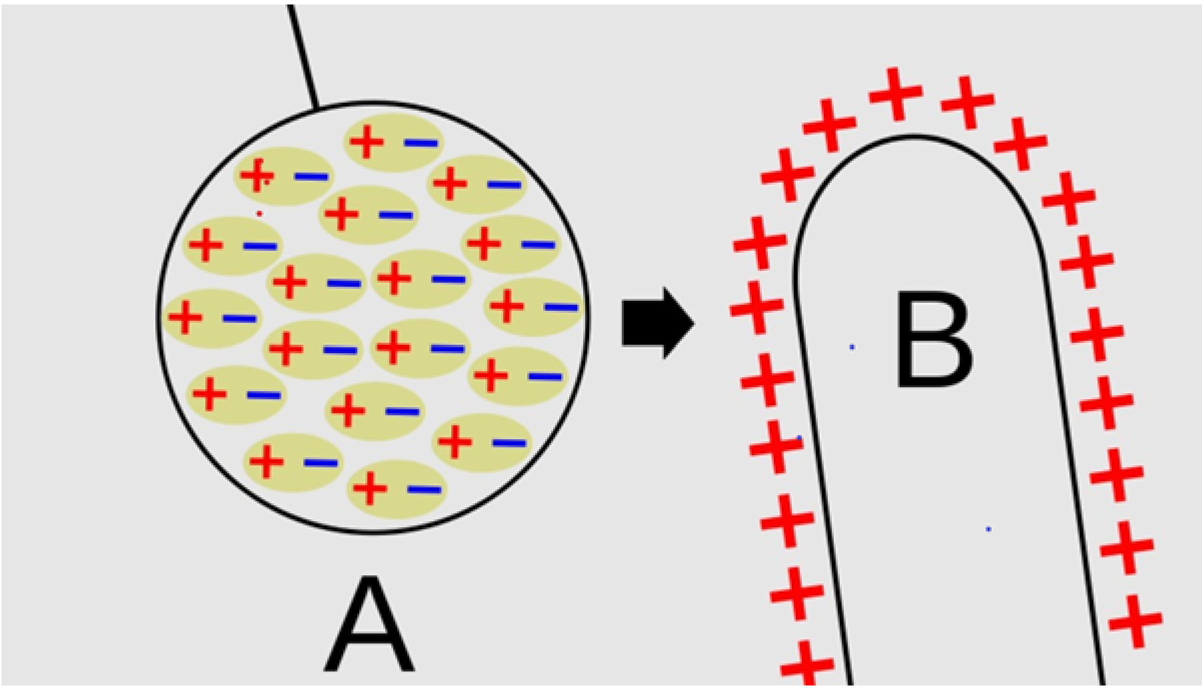


Figure 4: Polarisation of a polystyrene ball by a positively charged rod

Some materials are made up of molecules that are already polarised. These are molecules that have a more positive and a more negative side but are still neutral overall. Just as a polarised polystyrene ball can be attracted to a charged rod, these materials are also affected if brought close to a charged object.

Activity 2.1: Polarising an aluminium can

Time required: 10 minutes

What you need:

- internet access

What to do:

1. Open the link to the Physics Classroom.
2. Play with the simulation, moving the rods about the screen and observing the behaviour of charges within the can.
3. Describe what must happen inside the aluminium can in order for it to be attracted to a positively charged and to a negatively charged object.

What did you find?

The neutral aluminium can becomes polarised when a positively charged or negatively charged rod is held near it. The polarisation causes the side of the can near the rod to have an opposite charge to the rod itself. The can and the rod then experience an attractive force.

Note

Watch this static electricity demonstration to consolidate your understanding of the interaction of charged objects and electrostatic induction (polarisation) (Duration: 10.34).

Summary

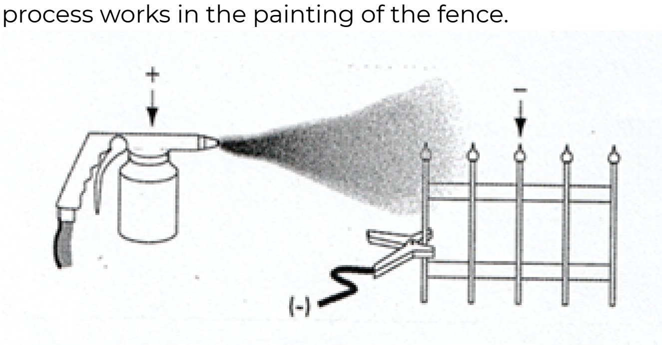
In this unit you have learnt the following:

- Charged objects exert electrostatic forces on each other.
- Like charges repel and unlike charges attract.
- Excess charge on a conductor that is spherical will distribute evenly around the outer surface.
- Excess charge on a conductor with an irregular shape will concentrate in the narrower areas forming highly charged points.
- Charged objects can interact with uncharged objects creating a force of attraction because of electrostatic induction or polarisation.

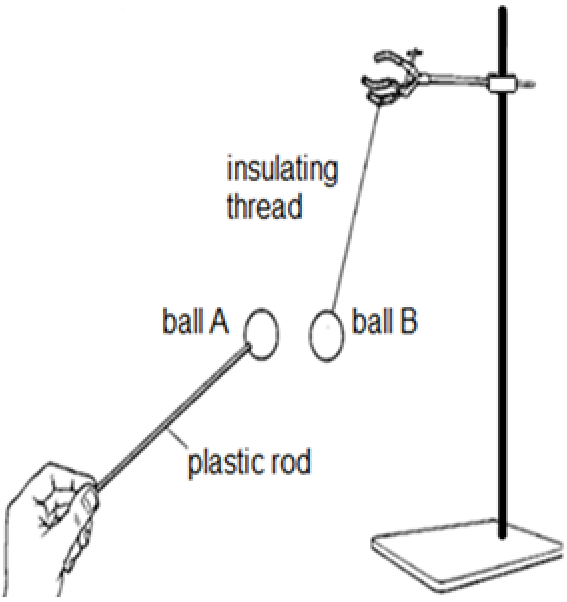
Unit 2: Assessment

Suggested time to complete: 15 minutes

1. Complete the sentence: The electrostatic force between like charges is ________, while between unlike charges it is _______.
2. Two positively charged metal balls are placed 20 cm apart.
   a. Explain what will happen.
   b. If the balls are now placed 10 cm apart, explain what will happen.
3. A Perspex ruler is positively charged by rubbing it with a piece of cloth. It is then held over small pieces of paper.
   a. Describe what will happen.
   b. Give the term for this phenomenon.
   c. Explain the observation.
4. Explain how a stream of water can be attracted to a charged rod.
5. Spray painting makes use of electrostatic forces. Study the diagram below and explain how the process works in the painting of the fence.

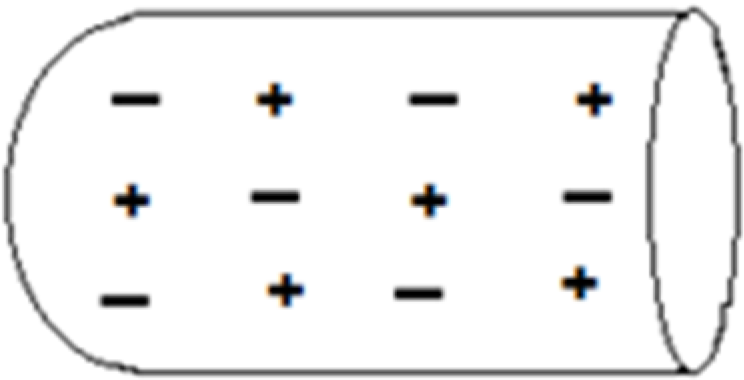


6. Two identical light balls, A and B, are shown below. The diagram shows what happens when ball A is brought near ball B and held still. Which combination of charges on the balls would **NOT** produce the result shown?



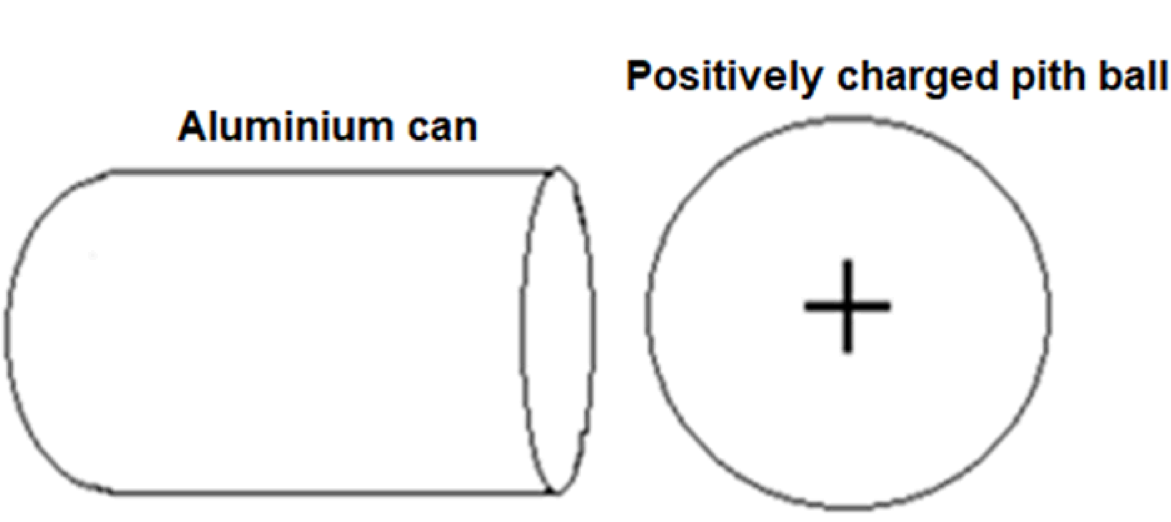
	Ball A	Ball B
A	positive	neutral
B	negative	neutral
C	positive	positive
D	negative	positive

7. The diagram below represents a neutral can. The positive and negative signs are a simple representation of the spread of charge on the surface of the can.



The can is placed next to a positively charged pith (lightweight) ball as shown below. This changes the position of some of the charges on the surface of the can due to polarisation.

a. Draw the resulting representation of the positive and negative charges on the surface of the can.



b. Explain how they can become polarised.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. The charge is negative. Unlike charges attract, so it needs to have an opposite charge to the right-hand sphere.
2. The charge is positive. Like charges repel, so it needs to have the same charge as the right-hand sphere.

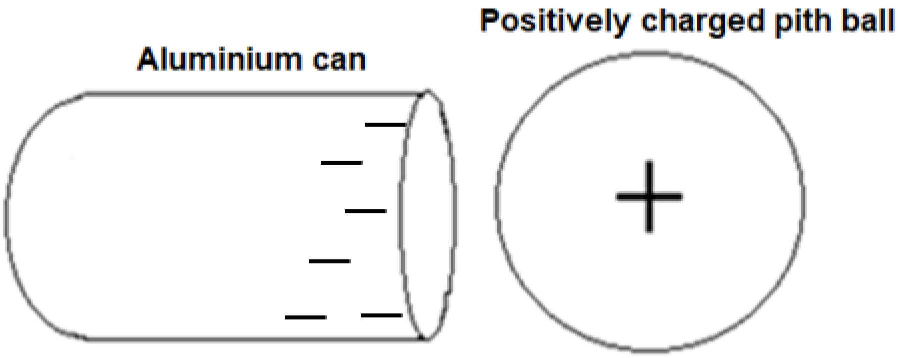
Back to Exercise 2.1

Unit 2: Assessment

1. The electrostatic force between like charges is repulsive, while between unlike charges it is attractive.
2.
   a. They will repel each other because the electrostatic force between like charges is repulsive.
   b. They will repel each other with a stronger force because electrostatic forces increase when the distance between the charged objects decreases.
3.
   a. The pieces of paper will be attracted to the ruler.
   b. Polarisation or electrostatic induction.
   c. The positively charged ruler causes the electrons (negative charges) in the paper to move slightly towards the ruler, inducing a negative charge on the side of the paper nearest the ruler. As a result there is an attractive force because unlike charges attract.
4. The molecules of water are polar (they have a positively charged side and a negatively charged side). If a charged rod is held near a stream of water, the oppositely charged side of the water molecules will be attracted towards the rod.
5. The metal fence is connected to the negative terminal of a battery so that it becomes negatively charged. The spray gun is connected to the positive terminal of the battery, so it becomes positively

charged. The droplets of paint will become positively charged as they leave the spray gun. Because the droplets have like charges, they will repel each other and form a mist. The opposite charge of the fence attracts the paint droplets, and this prevents wastage.

6. C: Like charges will repel. Charged objects can attract neutral objects by electrostatic induction.
7.
   a.



   b. The positively charged pith ball attracts the electrons in the metal can and, because it is a conductor, the electrons can move freely and collect at the side nearest to the pith ball.

Back to Unit 2: Assessment

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Unit 3: Electrostatics in practice

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Unit outcomes

By the end of this unit you will be able to:

- Apply the principle of discharge to:
  - a charged rod using ions in a flame
  - ions in the atmosphere
  - atmospheric electricity and the use of a lightning conductor.

What you should know

Before you start this unit, make sure you can:

- Identify the two types of charge.
- Describe how objects become charged, as covered in Subject outcome 4.2, Unit 1.
- Describe how charged objects interact and explain polarisation, as covered in Subject outcome 4.2, Unit 2.

Introduction

You have learnt how objects can become charged. In this unit you will learn how charged objects can revert to being neutral by the process of discharging.

The principle of discharge

Excess charge can build up in objects as a result of friction. This is happening all the time in objects around us. When objects become highly charged, the excess electrons will want to move into another object so that they can move apart from each other. The most common way this can happen is when the charged object touches another object. Electrons can also jump across a relatively small gap between objects. This can be observed as a spark.

There are also other ways in which discharging can take place and these are explained below.

Discharging using ions in a flame

In dry conditions a charged ebonite rod or polythene rod will retain its charge for a long time. If the rod is to be discharged it may be done most effectively by passing it through the air above a flame. In a flame the gas molecules are vibrating very rapidly. Frequent collisions occur, and this friction causes electrons to be knocked off from some molecules. Molecules that have lost electrons are called positive ions. At the same time some of the free electrons may attach themselves to neutral molecules, and so form negative ions. When a charged rod is moved through the ionised air above a flame, ions of the opposite charge are attracted to the rod, and the charge on the rod becomes neutralised.

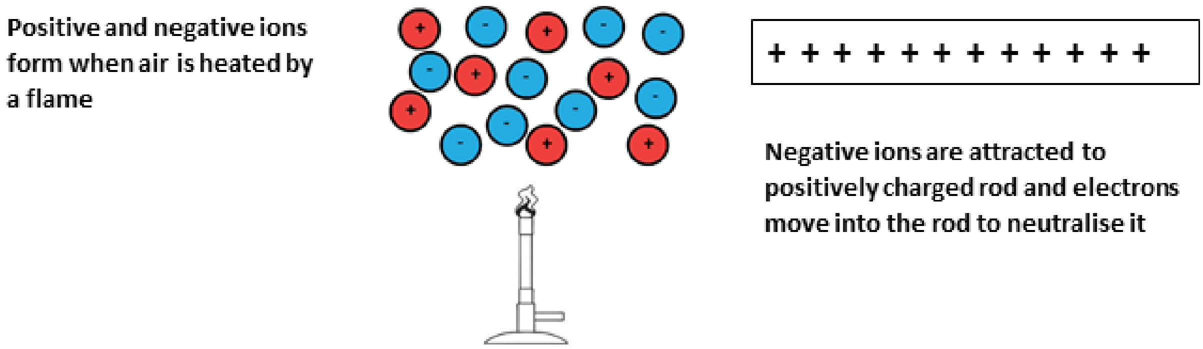


Figure 1: Discharging a positively charged rod using a flame

Note

Watch this video which shows the electrostatic discharge of two balloons using a flame (Duration: 1.25).

Discharging using ions in the atmosphere

Ionisation by the process described above is only one way of producing gaseous ions. Various experiments have shown that the atmosphere contains ions which have been produced by radiation from radioactive minerals in the Earth's crust, by ultraviolet light from the sun and by the so-called cosmic radiation which enters the Earth's atmosphere from outer space.

The presence of these ions in the atmosphere explains why a charged conductor will slowly lose its charge over a period of time even when mounted on a good insulator. The charge on the conductor is gradually neutralised by ions of opposite sign which are attracted towards it out of the surrounding air.

Discharging by means of lightning

Lightning is caused by an imbalance of electric charge between the Earth and a thundercloud. Friction in the cloud causes positively and negatively charged particles to form. The positively charged particles rise above the negatively charged ones hence polarising the cloud. This in turn polarises the Earth beneath the cloud; the Earth's surface is now positively charged.

Figure 2: Lightning strike over Johannesburg

Air is normally a very effective insulator, but in the presence of a highly charged cloud, and the high build-up of charge on the ground (i.e. a high potential difference), its insulating properties break down. The air molecules become ionised.

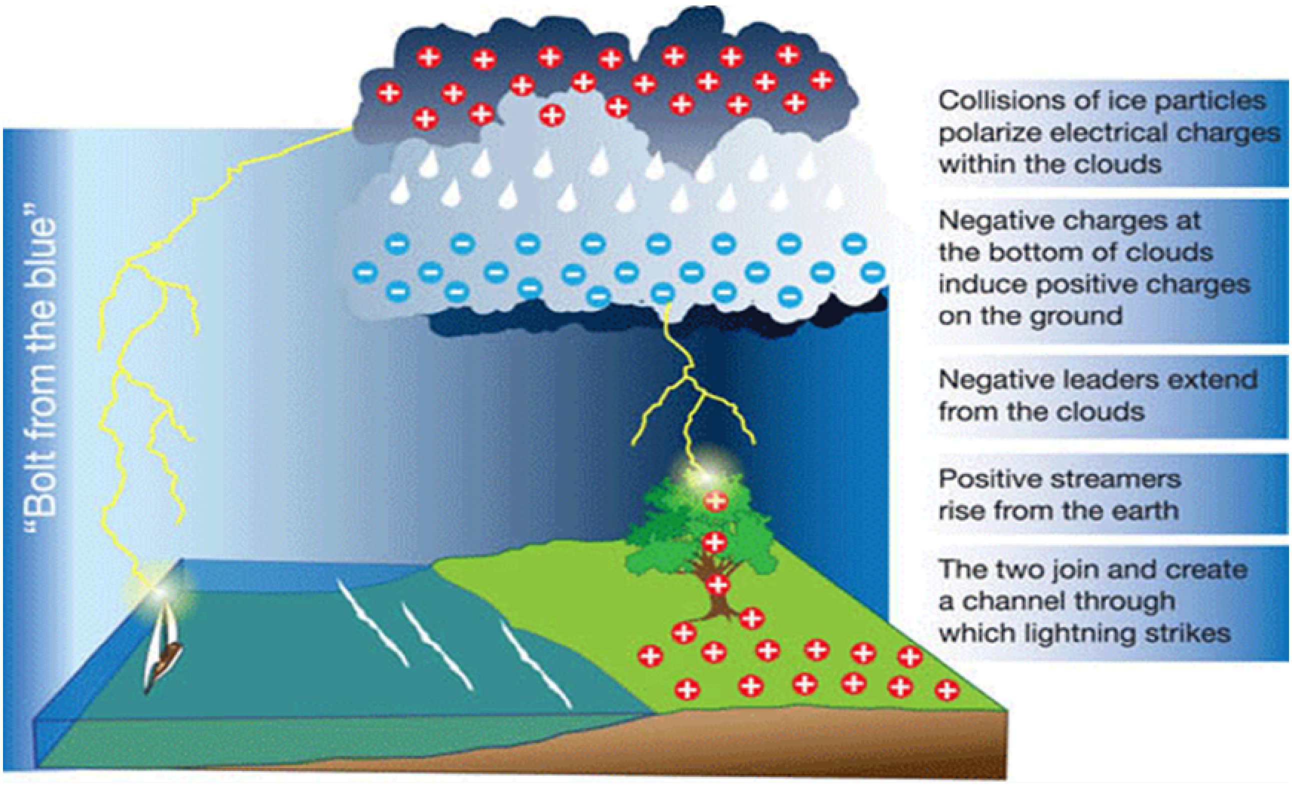


Figure 3: The build-up of charge and discharging during a lightning strike.

A lightning strike begins when a passage of electric charge from the cloud to the Earth meets an upward surge of charge (streamer) from the Earth to the cloud. This establishes the link from cloud to Earth.

Once that link is established the bolt of lightning strikes. In fact, there are multiple lightning strikes, happening milliseconds apart from each other. They happen so fast that we experience only the overall effect of all the strikes as 'one' bolt of lightning.

As the lightning streams through the air, the air heats up rapidly. Pressure waves form when the hot air expands, and these pressure waves create a shockwave that we call thunder.

Protection against lightning

Buildings and houses are protected from lightning by lightning conductors. These conductors can be steel rods placed on the roofs of buildings and connected to the ground by a piece of copper wire. They can also be steel rods placed on the ground near buildings. Streamers are much more likely to form from these higher points than the buildings and so the lightning will strike the rods. The charge then flows quickly towards the Earth. That is why people inside buildings are not harmed. The buildings with rods on them are said to be earthed or grounded.

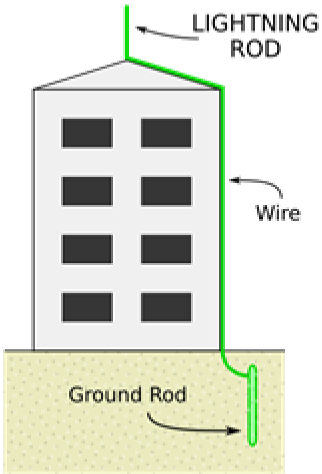


Figure 4: A lightning rod on a building

Note

Watch a video on lightning by clicking on the QR code or this link (Duration: 4.49).

Summary

In this unit you have learnt the following:

- Charged objects can become neutral by losing their charge in the process of discharging.
- Discharging can occur by contact or through ionised gas particles in the air.
- Lightning is the discharge of a build-up of charge in clouds.
- Lightning conductors can make buildings safer from lightning strikes by providing a pathway for excess charge to return to the Earth.

Unit 3: Assessment

Suggested time to complete: 15 minutes

1. Explain what is meant by 'discharging'.
2. A negatively charged rod is discharged by passing it through a flame. Explain how this process occurs.
3. Why does a charged object eventually lose its charge even if it is placed on an insulating stand?
4. Charge separates in thunderclouds. Provide a word for this 'separation of charge'.
5. Copy the diagram below, and draw in the charge distribution on the cloud, ground, the building, the tree and the girl, just before lightning strikes.

6. Explain, using bullet points, how lightning develops.
7. Explain how a lightning conductor protects a building.

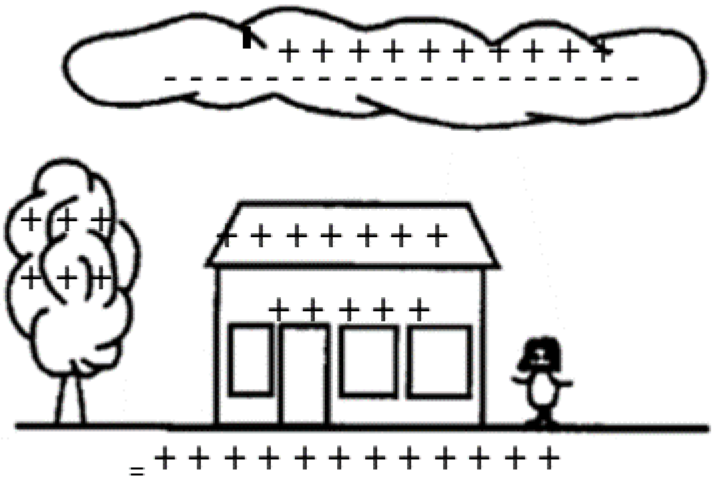
The full solutions are at the end of the unit.

Unit 3: Solutions

Unit 3: Assessment

1. Discharging occurs when a charged object gains or loses sufficient electrons to become neutral again.
2. The flame ionises the air (causes some molecules to lose electrons and some to gain electrons). The positive ions will be attracted to the negatively charged rod and remove excess electrons in the rod. The rod will therefore be neutralised.

3. There are ions in the atmosphere (from radioactive materials in the Earth, UV radiation from the sun or cosmic radiation from outer space). A charged object will attract oppositely charged ions to it. Electrons will then move from the ions to the object, or from the object to the ions. In this way the object will lose its excess charge and become neutral.
4. Polarisation
5.



6. Friction of water particles in clouds cause them to become charged.
   - The cloud becomes polarised – positively charged particles move to the top and negatively charged particles move to the lower area of the cloud.
   - The polarised cloud induces polarisation of the surface of the Earth, so it becomes positively charged.
   - Negative charge streams from the base of the cloud meet positive streams from the Earth (or objects on the Earth).
   - The two streams join forming a channel for a powerful discharge – this is a lightning bolt.
7. Metal rods are placed on the roofs of buildings and connected to the ground by a piece of copper wire. Because the rods are pointed and higher than the building, streamers are much more likely to form from this point than from the building. The lightning will therefore strike the rod. The charge then flows in the copper wire quickly towards the ground and the building will be protected.

Back to Unit 3: Assessment

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SUBJECT OUTCOME IX

MAGNETISM AND ELECTRICITY: IDENTIFY, DESCRIBE AND APPLY PROPERTIES OF ELECTRICITY IN AN ELECTRIC CIRCUIT

Subject outcome

Subject outcome 4.3: Identify, describe and apply properties of electricity in an electric circuit).

Learning outcomes

- Define and calculate electrical current.
- Differentiate between the two types of current (AC and DC).
- Describe and identify resistance in terms of length, cross-sectional area and type of material.
- Determine and describe the relationship between load (total resistance) and current.
- Define electrical potential difference (voltage) and emf and give examples of sources.
- Determine potential charge when cells are grouped and potential division in a series circuit.
- Describe the reason for electrical safety and earthing.

Unit 1 outcomes

By the end of this unit you will be able to:

- Define electrical current.
- Calculate electrical current.
- Differentiate between the two types of current, namely alternating current (AC) and direct current (DC).

Unit 2 outcomes

By the end of this unit you will be able to:

- Describe resistance in an electric circuit.
- Describe how the following properties of a conducting material affect resistance:

- length
- cross-sectional area
- type of material.

- Determine the relationship between load (total resistance} and current, and describe the general principle.

Unit 3 outcomes

By the end of this unit you will be able to:

- Define electrical potential difference (voltage) and emf.
- Give examples of sources of potential difference and emf.
- Determine potential change when cells are grouped.
- Determine potential division in a series circuit.

Unit 4 outcomes

By the end of this unit you will be able to:

- Describe the reason for electrical safety and earthing.

Unit 1: Electric current

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Unit outcomes

By the end of this unit you will be able to:

- Define electrical current.
- Calculate electrical current.
- Differentiate between the two types of current, namely alternating current (AC) and direct current (DC).

What you should know

Before you start this unit, make sure you can:

1. Identify the charge carriers in an atom, as covered in Subject outcome 4.2, Unit 1.
2. Identify the basic components of an electrical circuit and how they are connected. If you need to revise this, go to this virtual circuit building simulation to build some circuits. Use the buttons on the left (see Figure 1) to change between working with either pictures or symbols.

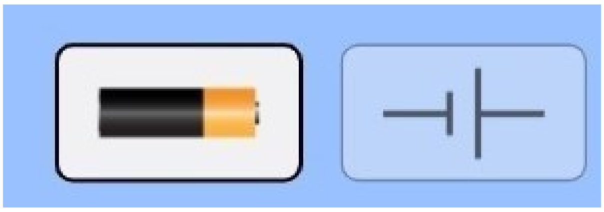

Figure 1: Buttons to change between working with either pictures or symbols

Introduction

You have learnt about static electricity where charged particles (electrons) can move from one object into another giving objects an overall charge. In this unit[1] you will learn about current electricity. This is when a continuous flow of charge can be created using a circuit made of conducting wires and an energy source.

Electrical current

You have learnt that conductors, like a piece of copper wire, contain free electrons that can move randomly because they are not firmly bound to the nuclei of individual atoms. If these free electrons are forced to move in one direction, a current is created. To do this a closed circuit and a source of energy (for example a battery) is required. The strength of the current will be determined by the voltage of the battery and the resistance of the components in the circuit.

Think of charges being pushed around the circuit by the battery, there are charges in the wires but unless there is a battery, they do not move in one direction through the wire.

When one charge moves the charges next to it also move. Imagine if you had a tube of marbles like in Figure 1 below, or a train and its carriages.

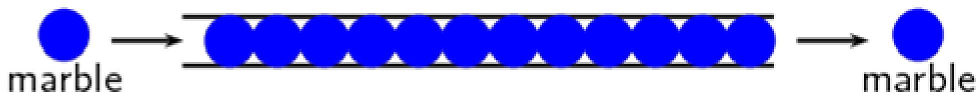

Figure 2: Analogy of electric current using marbles in a tube

If you push one marble into the tube one must come out the other side, if a train locomotive moves then all the carriages move immediately because they are connected. This is the same for charges in the wires of a circuit. The idea is that if a battery starts to drive charge in a circuit then all the charges start moving instantaneously.

The definition of current is how much charge flows past a point in a circuit per second, or the rate at which charge moves past a fixed point in a circuit. A large current, such as that used to start a truck engine, moves a large amount of charge in a small amount of time, whereas a small current, such as that used to operate a hand-held calculator, moves a small amount of charge over a long period of time.

An ammeter is an instrument used to measure the rate of flow of electric current in a circuit. In order to measure g the current flowing *through* a circuit component, the ammeter must be connected in series with the measured circuit component.

1. Parts of the text in this unit were sourced from [Siyavula Physical Science Gr 10 Learner's Book, Chapter 16](), released under a CC-BY licence

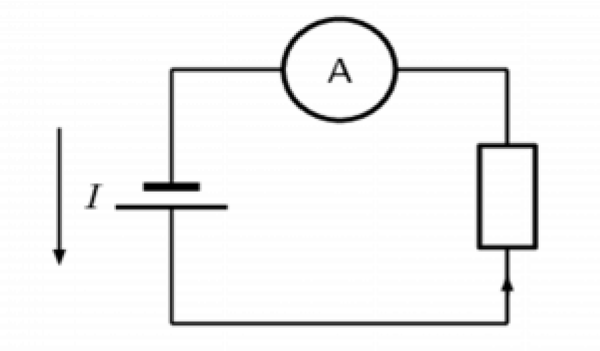

Figure 3: An ammeter and a circuit diagram showing the symbol for an ammeter

Calculating electrical current

Electrons are very small and move very fast, so measuring how many individual charges (electrons) are moving past a point per second would result in large numbers that are not user-friendly. For this reason, charge is measured in groups or packages of electrons using the units called Coulombs.

$1 \text{ Coulomb} = 6.24 \text{ x } 10^{24} \text{ electrons}$

The rate at which these packages of electrons move past a point in a circuit can be calculated using the following formula:

$$I = \frac{Q}{\Delta t}$$

Where:
I is the current measured in amperes (A)
Q is the charge measured in Coulombs (C)
$\triangle t$ is the time measured in seconds (s)

The unit for current is the ampere or amp (A) though it is often given in milliamperes (mA) and must be converted: $1\ 000 \text{ mA} = 1 \text{ A}$

Example 1.1

45 C of charge passes a point in a circuit in one second. Calculate the current.

Solution

Step 1: We are given an amount of charge (Q) and a time(Δt) and asked to calculate the current (I). We know that current is the rate at which charge moves past a fixed point in a circuit, so we have all the information we need. We have quantities in the correct units already.

Step 2: Apply the principle.

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{45}{1} \\ &= 45 \text{ A} \end{aligned}$$

Step 3: State the answer with units.

The current will be 45 A

Example 1.2

An amount of charge equal to 53 C moves past a fixed point in a circuit in 2 s. What is the current?

Solution

Step 1: We are given the amount of charge (Q) and the time (Δt) and asked to calculate the current (I). We know that current is the rate at which charge moves past a fixed point in a circuit, so we have all the information we need. We have quantities in the correct units already.

Step 2: Apply the principle.

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{53}{2} \\ &= 26.6 \text{ A} \end{aligned}$$

Step 3: State the answer with units.

The current will be 26.5 A

Exercise 1.1

1. The table below gives the charge that passes through a lightbulb in a circuit, and the time it takes for that charge to pass through the bulb. Calculate the current through that bulb in five different circuits. Show all your calculations correctly laid out. You may need to convert to the correct units first.

Circuit	Charge	Time
1	$1.0\ \mathrm{C}$	$20\ \mathrm{s}$
2	$300\ \mathrm{mC}$	$2\ \mathrm{s}$
3	$0.9\ \mathrm{C}$	$3\ \mathrm{s}$
4	$200\ \mathrm{mC}$	$4\ \mathrm{s}$
5	$24\ \mathrm{C}$	$2\ \mathrm{min}$

2. The table below gives the charge that passes through a lightbulb in a circuit, and the current in the circuit. Calculate the time it takes for the given charge to pass through the bulb in five different circuits. Show all your calculations correctly laid out. You may need to convert to the correct units first.

Circuit	Charge	Time
1	$1.0\ \mathrm{C}$	$2\ \mathrm{A}$
2	$0.5\ \mathrm{C}$	$0.5\ \mathrm{A}$
3	$0.6\ \mathrm{C}$	$300\ \mathrm{mA}$
4	$0.2\ \mathrm{C}$	$0.4\ \mathrm{A}$
5	$1,5\ \mathrm{C}$	$0,02\ \mathrm{A}$

3. The table below gives the current that runs through a lightbulb in five different circuits, and the time the current runs for. Calculate the amount of charge that passes through the bulb in that time. Show all your calculations correctly laid out. You may need to convert to the correct units first.

Circuit	Charge	Time
1	$2\ \mathrm{A}$	$20\ \mathrm{s}$
2	$0.5\ \mathrm{A}$	$2\ \mathrm{s}$
3	$300\ \mathrm{mA}$	$3\ \mathrm{s}$
4	$0.4\ \mathrm{A}$	$4\ \mathrm{s}$
5	$0.2\ \mathrm{A}$	$2\ \mathrm{min}$

The full solutions are at the end of the unit.

Two types of current

There are two types of current based on the charge flow through the circuit:

- direct current (DC) and
- alternating current (AC).

In direct current (DC), the electric charge (current) only flows in one direction. By convention, this is described as the flow of positive charge from the positive terminal of a battery to the negative terminal and is referred to as conventional current flow. In fact, it is negative charges (electrons) that are flowing from the negative terminal to the positive terminal. Watch the video at the end of this unit which explains this conundrum!

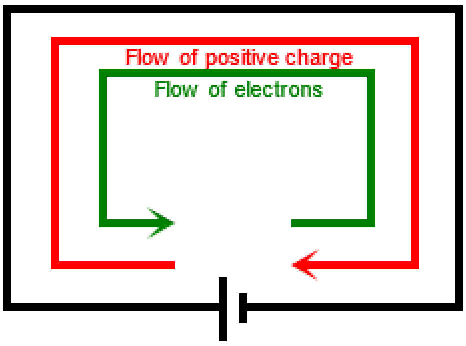

Figure 4: The conventional current flow (red arrow) and flow of electrons (green arrow)

Electric charge in alternating current (AC), on the other hand, changes direction at regular intervals. The source of energy for alternating current is not batteries, but electrical generators which use motion and magnetism to create a voltage. The voltage generated in AC circuits reverses at regular intervals (the positive and negative terminals swop around) and as a result, the current also changes direction in corresponding time intervals.

Whether a circuit has AC or DC will not affect the measurement or calculation of the current.

Most digital electronics or any battery-powered devices use DC. Most homes are wired for AC, as the source of the electricity is from a power station. Most home appliances are designed to run off AC. If you want to use a device that is designed to use DC you will need to convert AC to DC, before you plug it into a wall socket. Fortunately, these devices have built-in components called rectifiers which are able to make the conversion.

AC also has some useful properties, such as being able to increase or decrease voltage levels with a single component (a transformer), which is why AC was chosen as the primary means to transmit electricity over long distances.

Note

Watch this video explaining electrical current to consolidate the concepts covered in this unit (Duration: 18.44).

Summary

In this unit you have learnt the following:

- Current is the rate at which charges move in a circuit.
- Charge can be calculated using the formula $Q = \frac{I}{\Delta t}$
- Direct current is when charges flow in one direction only.
- Alternating current is when charges reverse their direction at regular intervals.

Unit 1: Assessment

Suggested time to complete: 25 minutes

1. Define electric current.
2. Explain the difference between static electricity and current electricity.
3. Give the units in which the following are measured:
   a. current
   b. charge
4. An electric current of $10\ \text{A}$ flows in a circuit for one minute. Calculate the electrical charge which flows past a point in the conductor during this time.
5. Calculate the amount of current passing a point in a conductor when $2\ 400\ \text{C}$ takes 5 minutes to pass this point.
6. 95 electrons move past a fixed point in a circuit in one tenth of a second, what is the current in the circuit?
7. How many electrons move through a fixed point in a circuit in $10\ \text{s}$ if the current is $6\ \text{A}$?
8. What is the current, in milliamperes, produced by the solar cells of a pocket calculator through which $4\ \text{C}$ of charge passes in $4\ \text{hrs.}$?
9. A total of $600\ \text{C}$ of charge passes through a flashlight in $0.5\ \text{hrs.}$ What is the average current?
10. What is the current when a typical charge of $0.25\ \text{C}$ moves from your finger to a metal doorknob in one millisecond?
11. A large lightning bolt had a $20\ 000\ \text{A}$ current and moved $30\ \text{C}$ of charge. What was its duration?
12. The $200\ \text{A}$ current through a spark plug moves $0.003\ \text{mC}$ of charge. How long does the spark last?
13. Explain the difference between direct and alternating current.

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1.

	Circuit 1	**Circuit 2**	**Circuit 3**	**Circuit 4**	**Circuit 5**
$I = \frac{Q}{\Delta t}$	$= \frac{1}{20}$	$= \frac{0.3}{2}$	$= \frac{0.9}{3}$	$= \frac{0.2}{4}$	$= \frac{24}{120}$
	$= 0.05\ \text{A}$	$= 0.15\ \text{A}$	$= 0.3\ \text{A}$	$= 0.05\ \text{A}$	$= 0.2\ \text{A}$

Notes: In circuits 2 and 4 the current needs to be converted from mA to A by dividing by 1000. In circuit 5, the time needs to be converted from minutes to seconds by multiplying by 60.

2.

	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5
$\Delta t = \frac{Q}{I}$	$= \frac{1.0}{2}$	$= \frac{0.5}{0.5}$	$= \frac{0.6}{0.3}$	$= \frac{0.2}{0.4}$	$= \frac{1.5}{0.02}$
	$= 0.5\ \text{s}$	$= 1\ \text{s}$	$= 2\ \text{s}$	$= 0.5\ \text{s}$	$= 75\ \text{s}$

Note: In circuit 3 the current must be converted from mA to A by dividing by 1000.

3.

	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5
$Q = I \text{ x } \Delta t$	$= 2 \text{ x } 20$	$= 0.5 \text{ x } 2$	$= 0.3 \text{ x } 0.3$	$= 0.4 \text{ x } 0.4$	$= 0.2 \text{ x } 120$
	$= 40\ \text{C}$	$= 1\ \text{C}$	$= 0.9\ \text{C}$	$= 1.6\ \text{C}$	$= 24\ \text{C}$

Note: In circuit 3 the current needs to be converted from mA to A by dividing by 1000. In circuit 5 the time needs to be converted from minutes to seconds by multiplying by 60.

Back to Exercise 1.1

Unit 1: Assessment

1. Current is the rate at which charge moves through a fixed point in a circuit OR current is how much charge passes a particular point in a circuit per second.
2. Static electricity occurs when electrons move from one object into another object creating two objects of opposite charge and how these charged objects interact to create a force between them. Current electricity is the continuous flow of electrons in a conductor in a closed circuit because of energy supplied by a power source.
3.
   a. Amperes
   b. Coulombs
4. Convert minutes to seconds: 1 minute = 60 seconds
$$\begin{aligned} Q &= I \times \Delta t \\ &= 10 \times 60 \\ &= 600\ \text{C} \end{aligned}$$
5. Convert minutes to seconds: 5 minutes = 300 seconds
$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{2\ 400}{300} \\ &= 8\ \text{A} \end{aligned}$$
6. The charge of 95 electrons must be calculated first:
$$1\ \text{C} = 6.24 \times 10^{18} \text{ electrons. Then the charge on 1 electron} = \frac{1}{6.24} \times 10^{18} = 1.6 \times 10^{-19}\ \text{C}$$

$$Q_{95} \text{ electrons} = 95 \times 1.6 \times 10^{-19} = 1.52 \times 10^{-17} \text{ C}$$

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{1.52 \times 10^{-17}}{0.1} \\ &= 1.52 \times 10^{-16} \text{ A} \end{aligned}$$

7.

$$\begin{aligned} Q &= I \text{ x } \Delta t \\ &= 6 \text{ x } 10 \\ &= 60 \text{ C} \end{aligned}$$

$$\begin{aligned} \text{no. of electrons} &= \frac{Q}{\text{charge on one electron}} \\ &= \frac{60}{1.6 \text{ x } 10^{-19}} \\ &= 3.75 \text{ x } 10^{20} \text{ electrons} \end{aligned}$$

8. Convert time in hrs. to seconds. $4 \text{ x } 60 \text{ x } 60 = 14\ 400 \text{ s}$

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{4}{14\ 400} \\ &= 2.78 \text{ x } 10^{-4} \text{A} \end{aligned}$$

Convert to milliamperes: $2.78 \text{ x } 10^{-4} \text{ x } 1\ 000 = 0.28 \text{ mA}$

9. Convert time from hours to seconds: $0.5 \text{ x } 60 \text{ x } 60 = 1800 \text{ s}$

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{600}{1800} \\ &= 0.33 \text{ A} \end{aligned}$$

10. Convert one ms to seconds: $1 \text{ ms} = 0.001 \text{ s}$

$$\begin{aligned} I &= \frac{Q}{\Delta t} \\ &= \frac{0.25}{0,001} \\ &= 250 \text{ A} \end{aligned}$$

11.

$$\begin{aligned} \triangle t &= \frac{Q}{I} \\ &= \frac{30}{20\ 000} \\ &= 1.5 \text{ x } 10^{-3} \text{ s} \end{aligned}$$

12. Convert mC to C: $0.003 \text{ mC} = 0.000003 \text{ C}$

$$\begin{aligned} \Delta t &= \frac{Q}{I} \\ &= \frac{0.000003}{200} \\ &= 1.5 \text{ x } 10^{-8} \text{ s} \end{aligned}$$

13. In direct current, the charges flow in one direction only. In alternating current the flow of charge reverses direction at regular intervals.

Back to Unit 1: Assessment

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Unit 2: Resistance in an electric circuit

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Describe resistance in an electric circuit.
- Describe how the following properties of a conducting material affect resistance:
  - length
  - cross-sectional area
  - type of material.
- Determine the relationship between load (total resistance} and current, and describe the general principle.

What you should know

Before you start this unit, make sure you can:

- Apply the basic principles of electric circuits.
- Apply the concepts of electrical current, as covered in Subject outcome 4.3, Unit 1.

Introduction

Electrical devices convert the electrical energy carried by the charges into other types of energy such as heat, sound, and motion. Components in the appliance resist the flow of charge and are referred to as resistors. In this unit[1] you will understand what resistance is, the factors that affect the resistance and the relationship between resistance and current.

What is resistance?

Resistance is a measure of 'how hard' it is to 'push' electricity through a circuit component or through an entire circuit (when it is referred to as the load). On a microscopic level, electrons moving through the conductor collide with the particles of which the conductor (metal) is made. The electrons then slow down. The energy that the electrons carry (referred to as electrical energy) is then transferred to the resistor. The transferred energy causes the resistor to heat up. You can feel this directly if you touch a cell phone charger when you are charging a cell phone – the charger gets warm because its circuits have some resistors in them.

The greater the resistance in a circuit the slower the charges will move, so the current will be less.

1. Parts of the text in this unit were sourced from Siyavula Physical Science Gr 10 Learner's Book, Chapter 16, released under a CC-BY licence

All conductors have some resistance. For example, a piece of copper wire has less resistance than a light bulb filament, but both have resistance.

A lightbulb contains a very thin wire surrounded by a glass housing. The high resistance of the small wire (filament) in a lightbulb causes the electrons to transfer a lot of their electrical energy in the form of heat. The heat energy is enough to cause the filament to glow white-hot which produces light.

The wires connecting the lamp to the cell or battery hardly get warm while conducting the same amount of current. This is because they are thicker (have a larger cross-section) and so have a lower resistance.

An important effect of a resistor is that it converts electrical energy into other forms of energy. All electrical devices contain resistors.

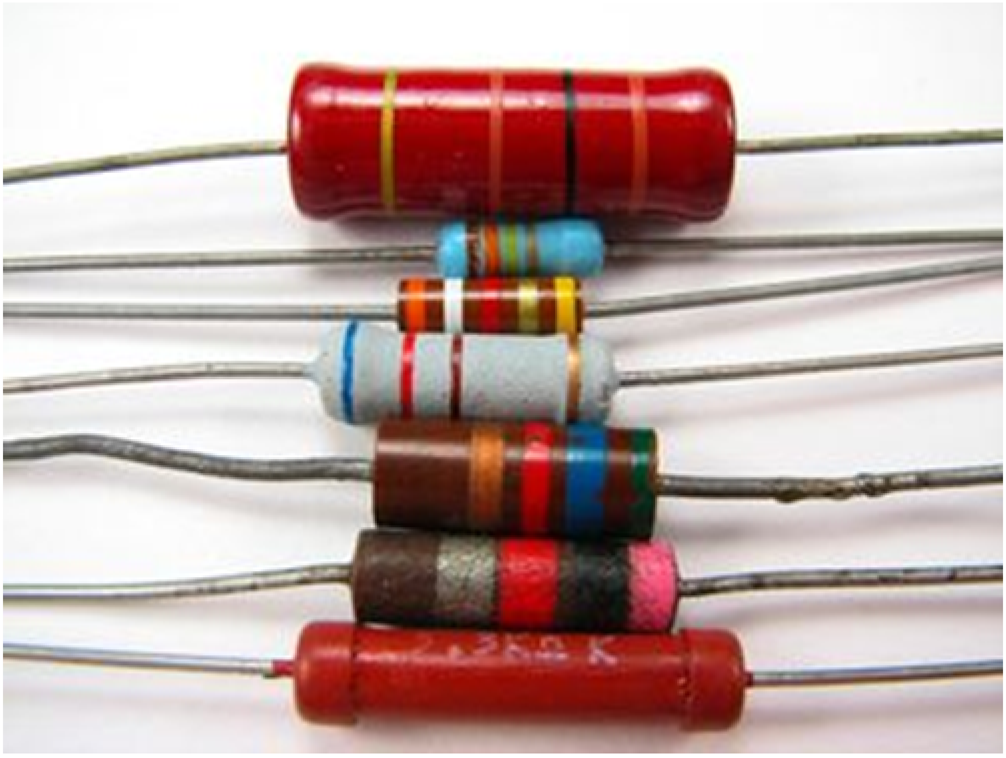


Figure 1: Various resistors

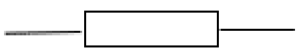


Figure 2: The symbol for a resistor in an electrical circuit

The unit in which electrical resistance is measured is the Ohm (Ω).

Factors that affect resistance

There are four factors that affect the flow of current and resistance.

Factor influencing the flow of current in a conductor	How does it influence current flow in a conductor?	Explanation
Type of material	Current flow will differ according to the type of material used.	What the object is made of will have an effect on its resistance. Not all metals are equally good at conducting electricity. Metals are given a resistivity value which indicates their relative resistance.
Length	The longer the resistance wire, the lower the current.	A longer length will make it more difficult for current to flow, as there is more material to travel through. This *increases* the resistance.
Diameter/cross-sectional area	The thicker the wire, the greater the current.	The thicker the wire, the more charge can travel simultaneously through a given length of wire. Therefore, a larger cross-sectional area *reduces* the resistance.
Temperature	The higher the temperature, the lower the current.	When the temperature rises, the metal atoms also vibrate more making it difficult for the electric charges to flow due to more frequent collisions. This increases the resistance.

Note

Watch this video about electrical resistance to consolidate the concept of resistance and the factors that affect resistance. You can scan the QR code or click on the link (Duration: 3.00).

Exercise 2.1

Use the table of resistivity values for different metals to answer the questions.

Material	Resistivity (Ωm)
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.82×10^{-8}
Iron	1.0×10^{-7}
Constantan	4.9×10^{-7}
Graphite	2.5×10^{-6}

1. Which metal in the table has the highest resistivity?
2. Which metal in the table has the lowest resistivity?
3. Suppose you had wires made from gold and iron, each with exactly the same dimensions. Which would have the highest resistance?
4. How would the resistance and resistivity change if:
   a. the diameter was increased?
   b. the length was increased?
   c. the temperature was increased?

The full solutions are at the end of the unit.

The relationship between load and current

Do this activity to explore the relationship between load and current.

Activity 2.1: Determine the relationship between load (total resistance) and current

Time required: 10 minutes

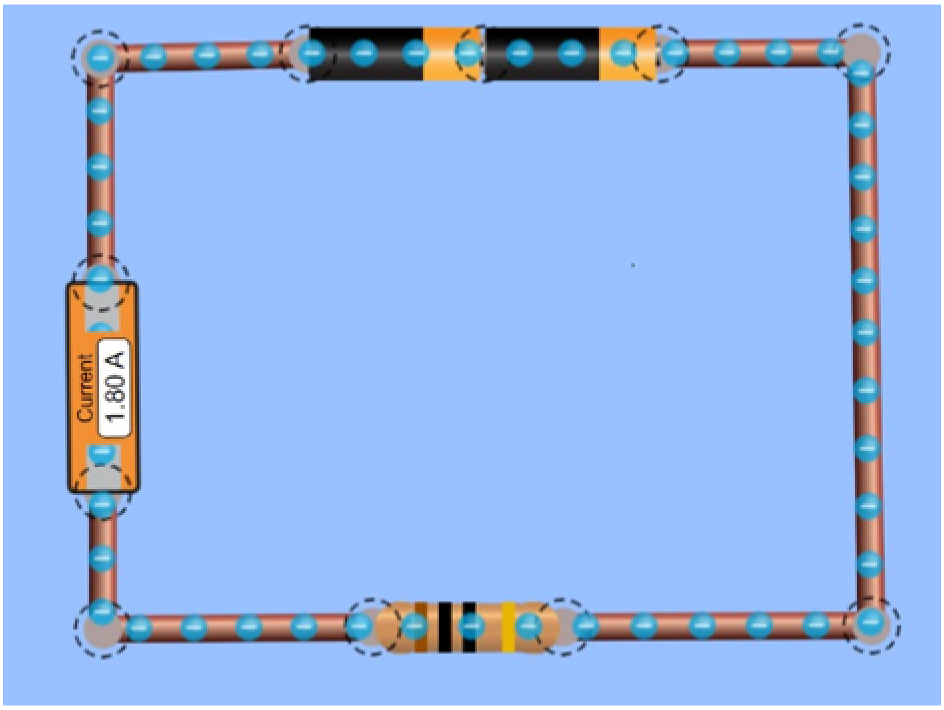
What you need:

- internet access

What to do:

1. Open this link for the PHeT virtual circuit construction lab.

2. Click on 'intro'
3. Build a circuit with the components in the side boxes by dragging them into the centre space. You can lengthen the wires by dragging the dotted circles at each end, then join them to the dotted circles on the next component.
4. Build a circuit with a battery of two cells, an ammeter, and one resistor, as illustrated in the screenshot below:



5. Double click on the resistor so that it is highlighted in a yellow box. This will open a slider for you to change the resistance of the resistor.
6. Note the resistance of the resistor (in Ohms) and the current reading on the ammeter.
7. Move the slider to increase the resistance of the resistor and note what happens to the current reading on the ammeter.
8. Observe how the rate at which the electrons move in the circuit changes as you adjust the resistance of the resistor.

What did you find?

As the resistance of the resistor increases, the current reading decreases. This can be confirmed by noting that the electrons move more slowly through the circuit when the resistance increases.

In the activity you saw that as the load (total resistance) increases in a circuit, it becomes more difficult for the charges to flow through the circuit. Because current is the rate at which charges move through a circuit, the current will consequently decrease.

Summary

In this unit you have learnt the following:

- Resistance is a measure of how hard it is for charges to flow through a conductor.
- A resistor is a component in a circuit with a higher resistance than the conducting wires so it converts electrical energy into other forms of energy.
- The resistance affects the current in a circuit; the higher the resistance the less the current.
- Resistance is measured in Ohms (Ω)
- Factors that affect the resistance of a resistor are:
    - type of material: some metals have greater resistance than others (called their resistivity)
    - length: the longer the resistor, the greater the resistance
    - diameter: the thicker the resistor, the less the resistance
    - temperature: the higher the temperature of the resistor, the greater the resistance.

Unit 2: Assessment

Suggested time to complete: 10 minutes

1. Explain the meaning of resistance in an electrical circuit.
2. 2. Give the unit in which resistance is measured in a word and a symbol.
3. Give three examples of resistors in an electrical circuit and the energy conversion that takes place in them.
4. List four factors that determine the resistance of a resistor.
5. Describe what you would do to make a resistor with a very high resistance.
6. You have a light bulb that will be damaged if the current through it is too high. You only have a battery that will produce a current that is too high for your light bulb. Suggest how this problem can be solved and include your reasoning.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. Graphite (highest resistivity value on table)
2. Silver (lowest resistivity value on the table)
3. Iron (higher resistivity than gold)
4.
    a. resistance would decrease (greater diameter, lower resistance – easier for charges to move); resistivity remains the same (resistivity is a fixed value for the type of material)
    b. resistance would increase (greater length, greater resistance – charges have further to push through); resistivity remains the same
    c. resistance would increase (higher temperature, greater resistance – more difficult for charges to

move through when metal atoms are vibrating faster); resistivity remains the same

Back to Exercise 2.1

Unit 2: Assessment

1. Resistance is a material's opposition to the flow of electric current, or how hard it is for the charges to move through the material.
2. Ohms, Ω
3. Any appropriate examples are acceptable here, e.g.

   Light bulb – electrical energy to heat and light energy
   Electric motor – electrical energy to kinetic energy
   Fan – electrical energy to kinetic energy
   Kettle – electrical energy to heat energy
   Hairdryer – electrical energy to heat and kinetic energy
4. Type of material, length, diameter (or cross-sectional area), temperature.
5. The resistor should be made of a material with high resistivity. It should be long and thin, as both these features increase resistance, and it should be kept as cool as possible.
6. The light bulb can be connected to the battery as long as another resistor is placed in the circuit as well. This will increase the load (total resistance) and consequently decrease the current.

Back to Unit 2: Assessment

Media Attributions

Unit 3: Voltage in an electric circuit

LEIGH KLEYNHANS

Unit outcomes

By the end of this unit you will be able to:

- Define electrical potential difference (voltage) and emf.
- Give examples of sources of potential difference and emf.
- Determine potential change when cells are grouped.
- Determine potential division in a series circuit.

What you should know

Before you start this unit, make sure you can:

- Apply the basic principles of electrical circuits.
- Apply the concepts of electrical current, as covered in Subject outcome 4.3, Unit 1.
- Apply the concepts of resistance in an electric circuit, as covered in Subject outcome 4.3, Unit 2.

Introduction

When a circuit is connected and complete, charge can move through the circuit. Charge will not move unless there is a reason, a force to drive it around the circuit. Think of it as though charge is at rest and something has to push it along. This means that work needs to be done to make charge move. A force acts on the charges, doing work, to make them move. The force is provided by the battery in the circuit.

Potential difference (voltage)

A battery has the potential to drive charge around a closed circuit, the battery has potential energy that can be converted into electrical energy by doing work on the charges in the circuit to make them move. The charges then carry this electrical energy around the circuit.

Potential difference is defined as the work done per unit of charge.

A voltmeter is an instrument for measuring the potential difference between two points in an electric circuit. The units of potential difference are volts (V). Potential difference can also be referred to as voltage.

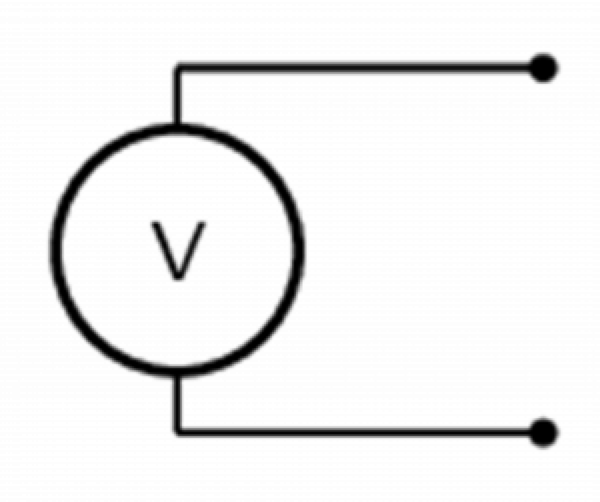


Figure 1: A voltmeter (left) and the symbol for a voltmeter in a circuit diagram (right)

One lead of the voltmeter is connected to one end of the battery and the other lead is connected to the opposite end of the battery. The voltmeter may also be used to measure the voltage across a resistor or any other component of a circuit but must be connected in parallel (Figure 2).

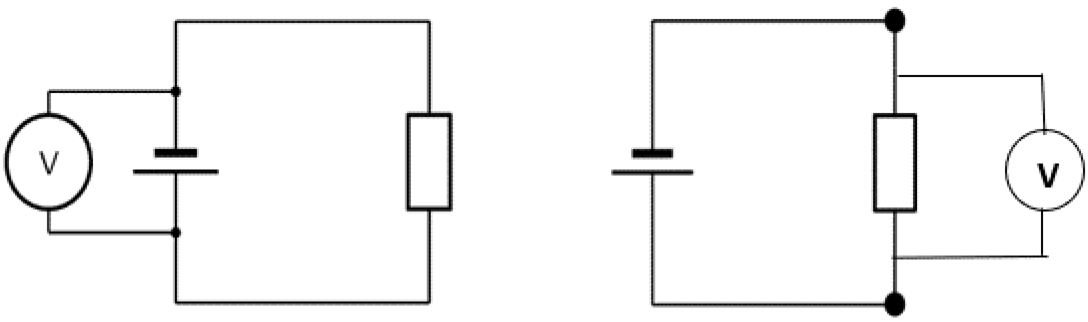


Figure 2: A voltmeter connected in parallel across a battery (left) and across a resistor (right)

Electromotive force (emf)

When you buy a battery there is a voltage label on the casing.

Figure 3: Batteries with different emf ratings

These values indicate the electromotive force (emf) of the battery. They are given in volts (V) but the values are not exactly the same as the voltage reading when a battery is connected in a circuit.

Activity 3.1: Determine the difference between potential difference (voltage) and emf

Time required: 5 minutes

What you need:

- internet access

What to do:

1. Open the link for the PHeT virtual circuit construction lab.

2. Click on Lab.
3. Build a circuit with a battery of two cells, one resistor, a switch and a voltmeter connected in parallel across the battery.
4. Note the reading on the voltmeter when the switch is open.
5. Click on Advanced and use the slider in the 'battery resistance' block to set the battery resistance at 2 Ω.
6. Close the switch and take note of what happens to the voltmeter reading.

What did you find?

The voltmeter reading is higher when the switch is open (no charges flowing in the circuit). When the switch is closed (charges are flowing), the voltmeter reading drops.

When you measure the potential difference across (or between) the terminals of a battery that is in an open circuit, you are measuring the emf of the battery. This is the maximum possible amount of work per coulomb of charge that the battery can do to drive charge from one terminal, through the circuit, to the other terminal.

When the circuit is closed and charges start to flow, some work is required to drive the charges through the battery itself. All batteries will have a certain amount of resistance to the flow of charge. The voltmeter then reads the voltage between the terminals of the battery after the charges have already done some work. This reading will always be lower than the emf. The difference between the readings is the work done per coulomb of charge to drive the charges through the battery itself.

Sources of potential difference and emf

If potential difference is the work done per coulomb of charge, sources of potential difference create a situation where charges at one point have more energy than at another point. In cells, this happens as a result of a chemical reaction. (You will cover this in further chemistry sections.) A potential difference will be created until the chemicals are depleted. The charges will flow in one direction (DC).

A potential difference can also be created in power stations using the interaction of movement and magnetic fields. (You will learn more about this in your physics modules). The source of the movement can be hot water which causes steam, or falling water, solar panels or wind turbines.

Figure 4: A variety of voltage sources (clockwise from top left): the Brazos Wind Farm in Fluvanna, Texas (credit: Leaflet, Wikimedia Commons); the Krasnoyarsk Dam in Russia (credit: Alex Polezhaev); a solar farm (credit: U.S. Department of Energy); and a group of nickel metal hydride batteries (credit: Tiaa Monto).

Voltage and grouping cells to make batteries

A number of cells connected together forms a battery. There are two ways of connecting cells together to form a battery:

Cells in series

To create cells in series, the positive terminal of one cell is connected to the negative terminal of the next cell. Charges move through all the cells, therefore the potential difference across the battery will be the sum of the potential difference in each cell.

$V_{\text{battery}} = V_{\text{cell 1}} + V_{\text{cell 2}} + V_{\text{cell 3}} \ldots$

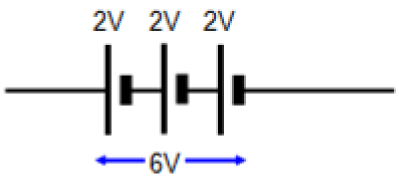


Figure 5: Three $2\ \text{V}$ *cells connected in series*

Because the voltage increases with every cell added in series, the charges will have more electrical energy. An example of where this type of connection is used would be in a torch as the higher voltage would result in increased brightness.

Cells in parallel

For cells in parallel, all the positive terminals of the cells are connected together, and all the negative terminals are connected together. Charges have alternative pathways, and each charge only passes through one cell and thus only has the amount of energy provided by one cell. The voltage of the battery will be equivalent to the voltage of one cell.

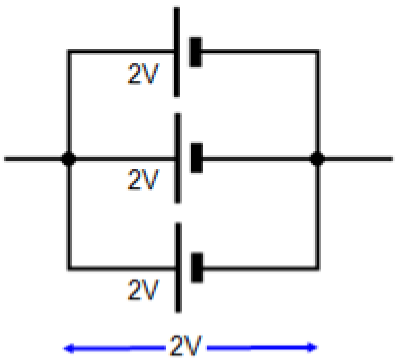
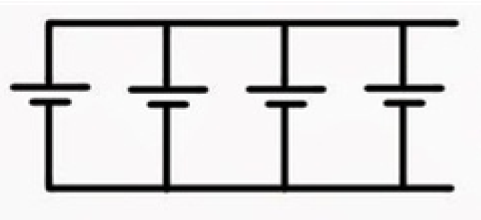


Figure 6: Three $2\ \text{V}$ *cells connected in parallel*

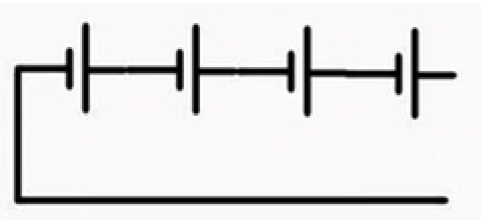
Adding cells in parallel will not increase the voltage of the battery, however, the battery will last longer. This arrangement is used in devices that do not require high voltages but are used for long periods, for example a clock.

Exercise 3.1

1. Six $1{,}5\ \text{V}$ cells are connected in series. What is the voltage of the battery?
2. Four $1{,}5\ \text{V}$ cells are connected in parallel. What is the voltage of the battery?
3. The cells in the circuit diagrams below are each $2\ \text{V}$. Determine the voltage of the battery:
   a.



   b.



The full solutions are at the end of the unit.

Potential difference across resistors in a series circuit

When we add resistors in series to a circuit, there is only one path for current to flow. All the charges have to go through all the resistors.

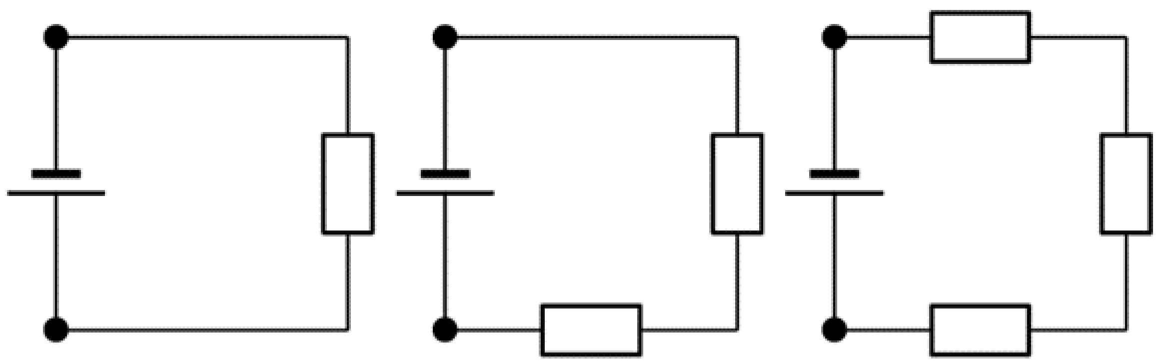


Figure 7: Adding resistors in series

When resistors are added in series the current is the same at every point in the circuit. If you remember what you learnt in Unit 2, the total resistance (load) in a circuit determines how fast the charges can flow (the current). As resistors are added in series the total resistance increases, so the current decreases.

The voltage of the battery, however, is shared across the resistors. This is because the charges will do work (transfer energy) as they move through each resistor. The voltage across the battery in the circuit is equal to the sum of voltages across the all the series resistors:

$$V_{\text{battery}} = V_{\text{resistor1}} + V_{\text{resistor 2}} + V_{\text{resistor 3}} \cdots$$

Let us look at this in a bit more detail. In the picture below you can see what the different measurements for three identical resistors in series could look like. The total voltage across all three resistors is the sum of the voltages across the individual resistors. Resistors in series are known as *voltage dividers* because the total voltage is divided amongst the individual resistors.

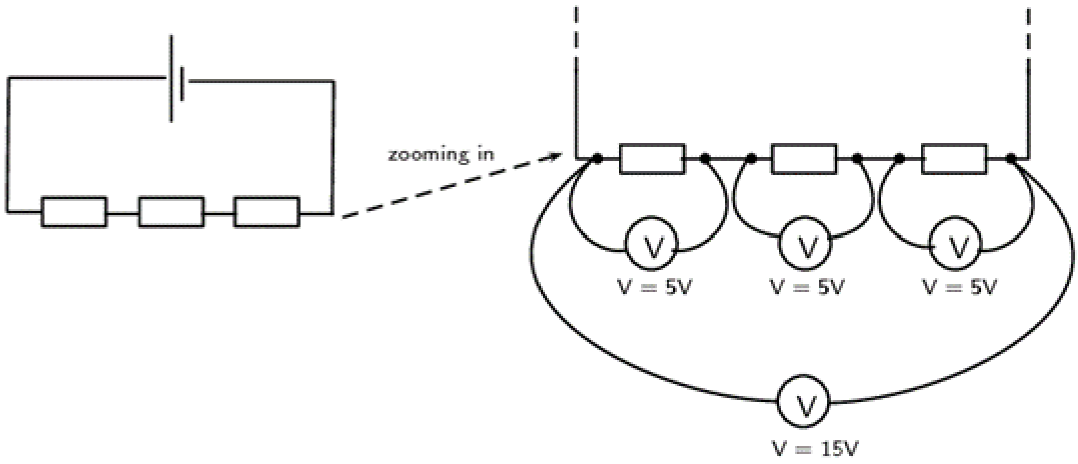


Figure 8: The total voltage is divided between resistors in series

Activity 3.2: Determine the potential division in a series circuit

Time required: 10 minutes

What you need:

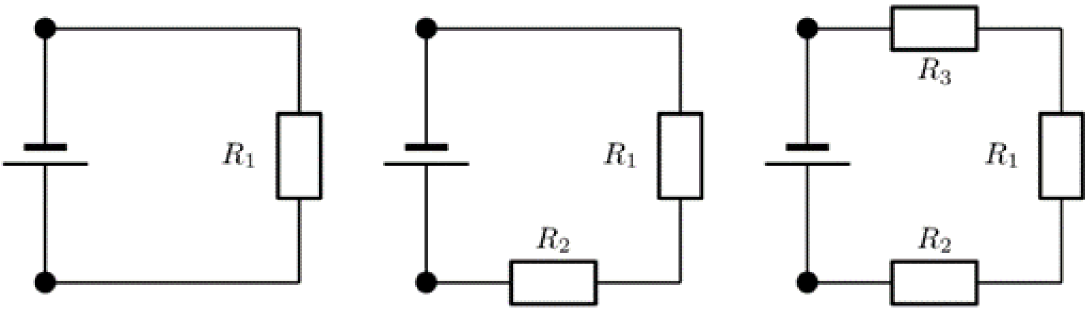
- internet access

What to do:

1. Open the link for the PHeT virtual circuit construction lab.

2. Click on Lab.

3. Construct the circuits illustrated below, and for each circuit use the voltmeter to measure the voltage of the battery and each resistor.



What did you find?

- When one resistor is connected (R1), the voltage across the resistor is equal to the voltage across the battery.
- When two resistors are connected in series (R_1 and R_2), the voltage across the battery is shared between them. Each resistor gets half the voltage.
- When three resistors are connected in series (R_1, R_2 and R_3), the voltage across the battery is shared between all three resistors. Each resistor gets one third of the voltage.

In Activity 3.2 the resistors are identical, so the voltage of the battery is divided equally. If there are resistors of different resistance in series, the voltage is divided in proportion to their resistance. The greater the resistance, the more energy is transferred per coulomb, therefore the voltage will be greater.

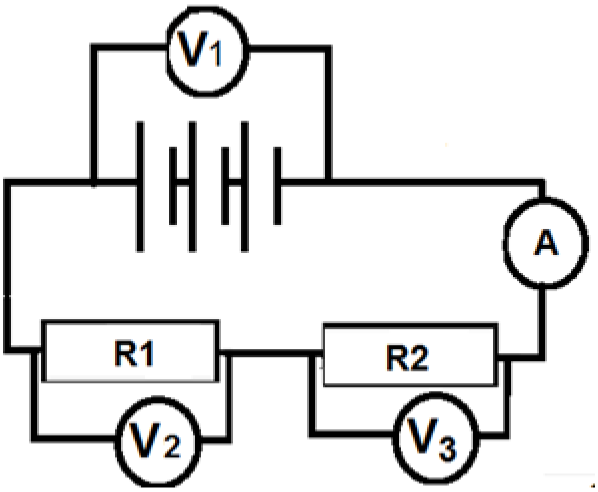


Figure 9: Circuit showing two resistors in series

In this circuit in Figure 9, the voltage across the battery $V_1 = 20\ V$.

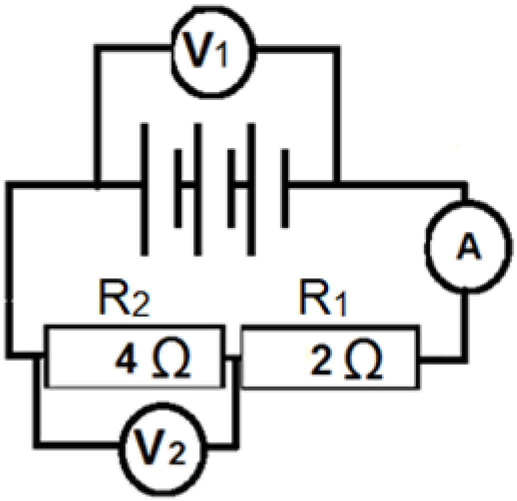
If the resistors $R1$ and $R2$ are of equal resistance, the voltmeters would read as follows: $V_2 = 10\ V$ and $V_3 = 10\ V$

However, if the resistances were different, for example, if $\mathrm{R1} = 1\ \Omega,\ \text{and}\ \ \mathrm{R2} = 3\ \Omega$ then the voltage provided by the battery is shared in proportion to the resistance.

The resistance ratio is $1 : 3$, therefore the voltage will be $\mathrm{V_2} = 5\ \mathrm{V}\ \ \text{and}\ \mathrm{V_3} = 15\ \mathrm{V}$

Exercise 3.2

Study the following circuit:



If the voltmeter $\mathrm{V_1} = 12\mathrm{V}$, determine the reading on voltmeter $\mathrm{V_2}$.

The full solutions are at the end of the unit.

Note

You can consolidate the concepts covered in this unit by watching this video called Voltage explained by The Engineering Mindset (Duration: 10.51).

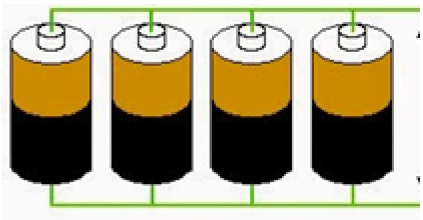
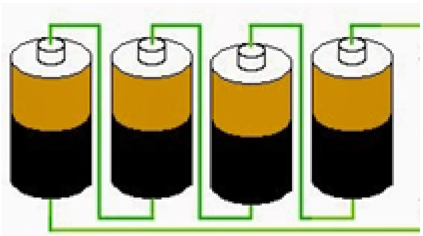
Summary

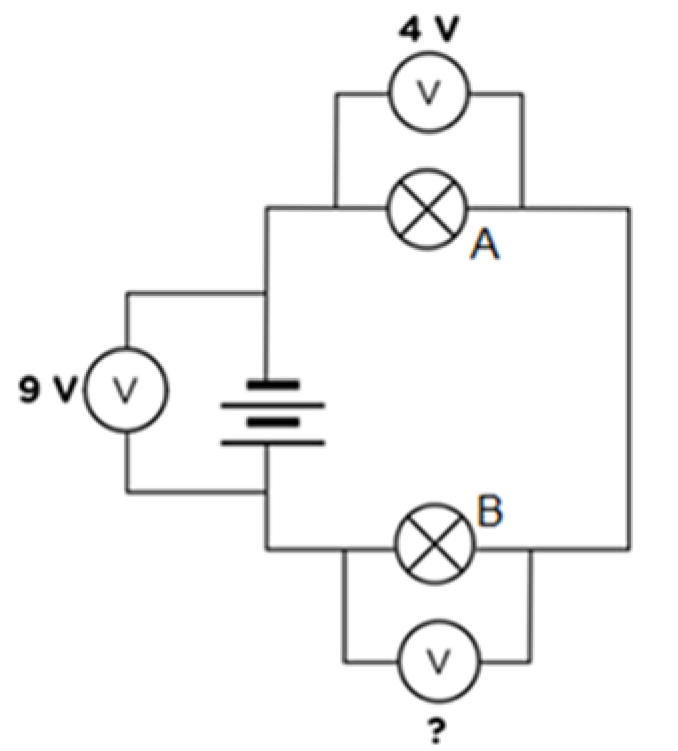
In this unit you have learnt the following:

- Electrical potential difference is what makes the charge move in an electric circuit.
- Potential difference (voltage) is defined as the work done per unit charge.
- Emf (electromotive force) is the total possible amount of work done per unit charge by the battery. It will be more than the work done by a unit of charge once it leaves the battery as energy is used to drive charge out of the battery itself.
- Batteries are portable sources of potential difference.
- Power stations create potential difference using magnetism and motion.
- Cells connected in series increase the potential difference of the battery.
- Cells connected in parallel do not increase the voltage, but the battery will last longer.
- When resistors are connected in series, the voltage of the battery is shared between them. The sum of the individual voltages across resistors will be equal to the voltage of the battery.
- When resistors in series have equal resistance, the battery voltage is shared equally between them.
- When resistors in series have different resistance, the battery voltage is shared in the same ratio as the resistance.
- When resistors are connected in series, the current is the same everywhere in the circuit.

Unit 3: Assessment

Suggested time to complete: 20 minutes

1. Define voltage.
2. Explain the difference between emf and the voltage reading across a battery in a closed circuit.
3. Identify the type of arrangement of the cells in the batteries illustrated in the diagrams below:
   a.
   
   b.
   
4. In a series circuit, one resistor has a voltage of $2\ \text{V}$, another $8\ \text{V}$ and a third of $10\ \text{V}$. What is the voltage across the battery?
5. If the voltage across a battery in a series circuit of three resistors is $24\ \text{V}$ and the voltage across one resistor is $12\ \text{V}$:
   a. What is the total voltage across the other two resistors?
   b. If the other two resistors are identical, what is the voltage across each one?
   c. What is the ratio of the resistances of the three resistors?
6. Study the circuit below which has two light bulbs as resistors, A and B.



a. What is the reading on the voltmeter across light bulb B?
b. What would happen to the reading on the voltmeter across the battery if light bulb A was removed, leaving a gap in the circuit. Explain your answer.
c. What would the reading be on the voltmeter across light B, if light bulb A was removed and the wires reconnected?

The full solutions are at the end of the unit.

Unit 3: Solutions

Exercise 3.1

1. 9 V ($V_{\text{battery}} = V_{\text{cell 1}} + V_{\text{cell 2}} + V_{\text{cell 3}} \ldots$)
2. 1.5 V (cells in parallel give a battery with a voltage equivalent to one cell)
3.
   a. 2 V (cells in parallel)
   b. 8 V (cells in series)

Back to Exercise 3.1

Exercise 3.2

The resistors are in series, therefore the voltage of the battery is shared in proportion to their resistance:

$$\begin{aligned} R_1 : R_2 &= 2 : 4 = 1 : 2 \\ \text{Voltage of 12 V will be shared in the ratio } 1 : 2 \\ V_2 &= 8 \text{ V} \end{aligned}$$

Back to Exercise 3.2

Unit 3: Assessment

1. Voltage is the work done per unit of charge.
2. The emf will be higher than the voltage reading across the battery. This is because the emf is the total possible work done per unit charge. Some work is done to drive the charges out of the battery, so by the time they leave the battery they will already have done some work and the potential difference (voltage) will be less.
3.
   a. parallel (all the positive terminals are connected together, and all the negative terminals are connected together.)
   b. series (the positive terminal of the first cell is connected to the negative terminal of the next cell, and so on)
4.
$$\begin{aligned} V_{\text{battery}} &= V_{\text{resistor1}} + V_{\text{resistor 2}} + V_{\text{resistor 3}} \\ &= 2 + 8 + 10 \\ &= 20 \text{ V} \end{aligned}$$
5.
   a.
$$\begin{aligned} V_{\text{battery}} &= V_{\text{resistor1}} + V_{\text{resistor 2}} + V_{\text{resistor 3}} \\ 24 &= 12 + V_{\text{resistor 2}} + V_{\text{resistor 3}} \\ V_{\text{resistor 2}} + V_{\text{resistor 3}} &= 12 \text{ V} \end{aligned}$$
   b.
$$\begin{aligned} &\text{12 V shared between two identical resistors} \\ &\frac{12}{2} = 6 \text{ V} \end{aligned}$$
   c.
$$\begin{aligned} &\text{Total Voltage} = 24 \text{ V} \\ &\text{Voltage ratio} = 12 : 6 : 6 = 2 : 1 : 1 \\ &\text{Therefore resistance ratio will be } 2 : 1 : 1 \end{aligned}$$
6.
   a.
$$\begin{aligned} V_{\text{battery}} &= V_A + V_B \\ 9 &= 4 + V_B \\ V_B &= 9 - 4 = 5 \text{ V} \end{aligned}$$
   b. It would have a slightly higher reading than 9 V. This is because a voltmeter across a battery in an open circuit will read the emf.
   c. 9 V. Light bulb B will be the only resistor in the circuit so it will get the total potential difference supplied by the battery as it does not have to share with any other resistor.

Back to Unit 3: Assessment

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Unit 4: Safety with electricity

LEIGH KLEYNHANS

Unit 4 outcomes

By the end of this unit you will be able to:

- Describe the reason for electrical safety and earthing.

What you should know

Before you start this unit, make sure you can:

- Apply the basic principles of electrical circuits.
- Apply the concepts of electric current, as covered in Subject outcome 4.3, Unit 1.

Introduction

Most of us use electricity every day in many different ways so it is important that we understand the dangers, or hazards, associated with electricity and we know how to use it safely.

Electrical hazards

A thermal hazard occurs when there is electrical overheating. The current becomes too high and the temperature of the wires increases. If the wires are in contact with a flammable material, the material will catch fire.

Electric energy is converted to thermal energy at a rate faster than it can be safely dissipated. This can happen in two ways: if circuits are overloaded (too many appliances are connected to the same source) or if there is a short circuit, a low-resistance path between the terminals of a voltage source. An example of a short circuit is shown in Figure 1. Insulation on wires leading to an appliance wears through, allowing the two wires to come into contact with one another. Since the resistance of the circuit is now very small, the power dissipated is very large, much greater than that used by a typical household appliance. Thermal energy delivered at this rate will very quickly raise the temperature of surrounding materials, melting, or perhaps igniting them.

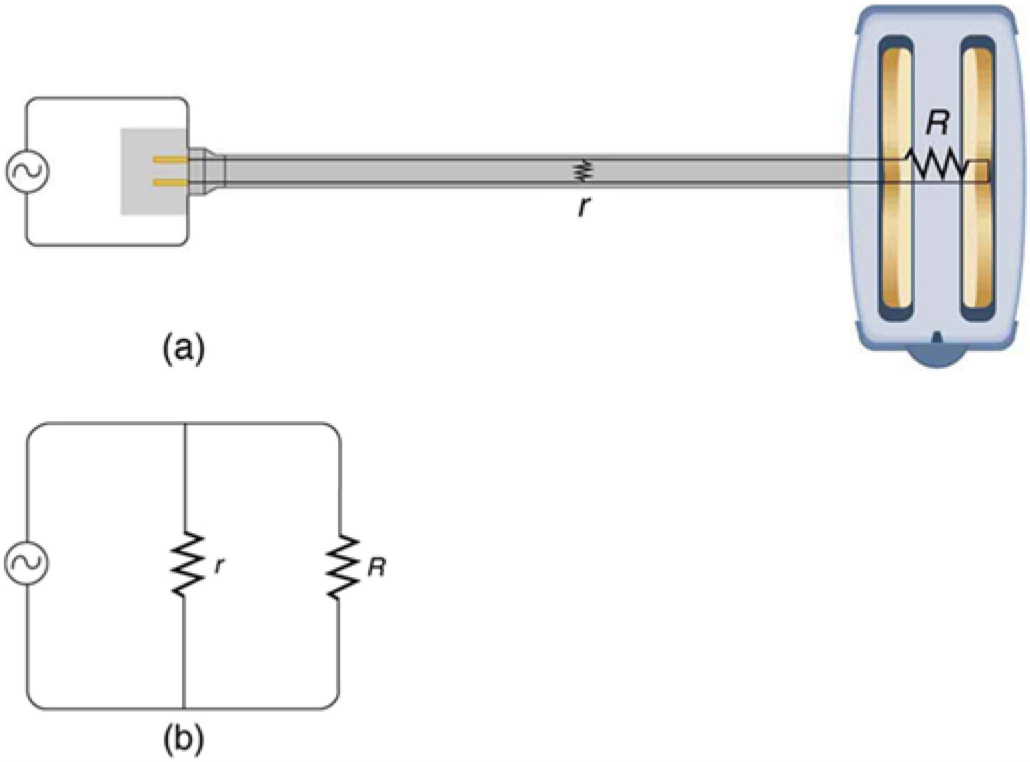

Figure 1: A short circuit is an undesired low-resistance path across a voltage source. (a) Worn insulation on the wires of a toaster allow them to come into contact making a circuit with a low resistance r, thermal power is then created so rapidly that the cord melts or burns. (b) A circuit diagram of the short circuit.

A shock hazard occurs when high electric current passes through a person. Electrical currents through people produce tremendously varied effects. An electrical current can be used to block back pain, stimulate muscle action in paralysed limbs and electrical shocks are used to bring a heart attack victim out of ventricular fibrillation (a massively irregular, often fatal, beating of the heart). A pacemaker is a device that is implanted in a human body and uses electrical shocks to stimulate the heart to beat properly. However, electric shocks can also be fatal. The major factors that determine the effects of an electrical shock depend on the amount of current and the duration.

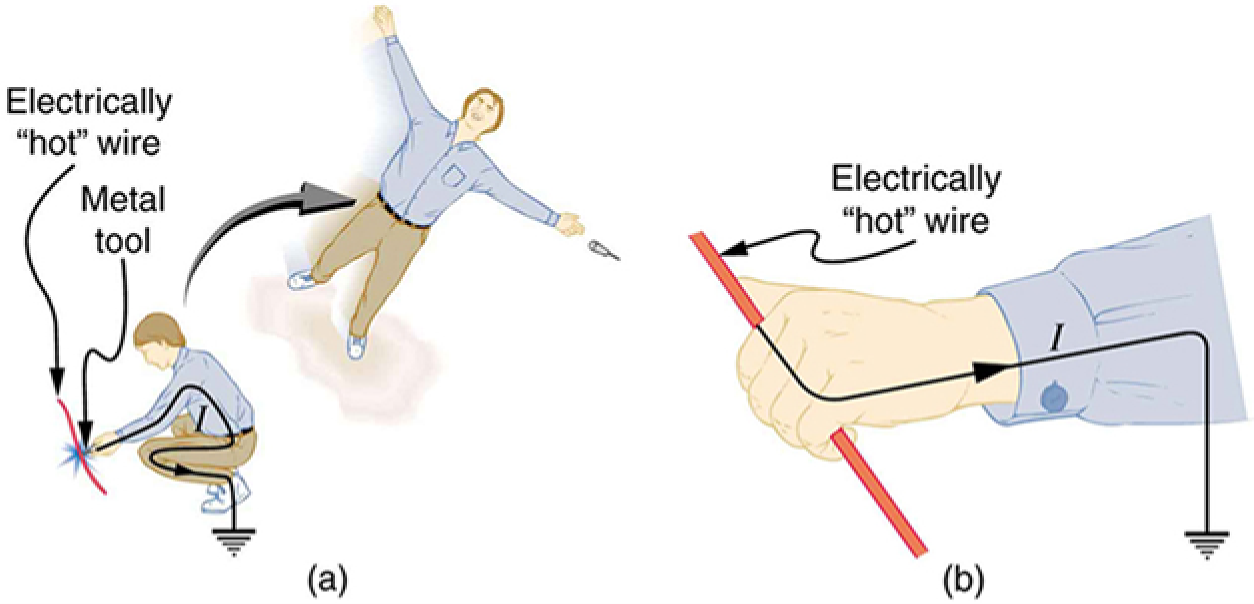

Figure 2: An electric current can cause muscular contractions with varying effects. (a) The victim is "thrown" backward by involuntary muscle contractions that extend the legs and torso. (b) The victim cannot let go of the wire that is stimulating all the muscles in the hand. The muscles that close the fingers are stronger than those that open them.

Very high currents will cause a fatal shock, referred to as electrocution. There are lots of ways in which we can be electrocuted including:

- touching frayed electrical cables
- touching damaged or incorrectly wired plugs
- allowing water or wet objects to enter plug sockets or touching frayed cables
- pushing metal objects into plug sockets.

Safety features

Modern appliances have features to prevent both thermal and shock hazards.

Fuses

A fuse breaks the circuit if a fault in an appliance causes too much current to flow. This protects both the wiring and the appliance and prevents the overheating of wires. The fuse contains a piece of wire that melts easily. If the current going through the fuse is too great, the wire heats up until it melts and breaks the circuit, preventing further overheating which could cause a fire.

Figure 3: A fuse

A fuse should be rated at a slightly higher current than the device needs, so:

- if the device works at 3 A, use a 5 A fuse
- if the device works at 10 A, use a 13 A fuse.

This will ensure that, if the current starts to increase beyond the maximum capacity of the device it will melt and break the circuit before serious overheating arises.

Circuit breakers

Circuit breakers act as resettable fuses. These are automatically operated electrical switches that protect electrical circuits from overloading or short circuiting. They detect faults and then stop the flow of electricity. Small circuit breakers protect individual household appliances, whereas larger ones can protect high voltage circuits supplying electricity to entire cities.

Figure 4: A circuit breaker

Earthing

Earthing is the connection of an electrical device or supply to the Earth for the purpose of creating a pathway for excess charge to return safely into the ground.

A mains electricity cable contains two or three inner wires. Each has a core of copper because copper is a good conductor of electricity. The outer layers are flexible plastic because plastic is a good electrical insulator. The inner wires are colour coded and have different functions:

- brown: this is the live wire that is connected to the voltage source
- blue: this is the neutral wire that completes the circuit
- green and yellow stripes: this is the earth wire that allows excess charge to travel to the Earth.

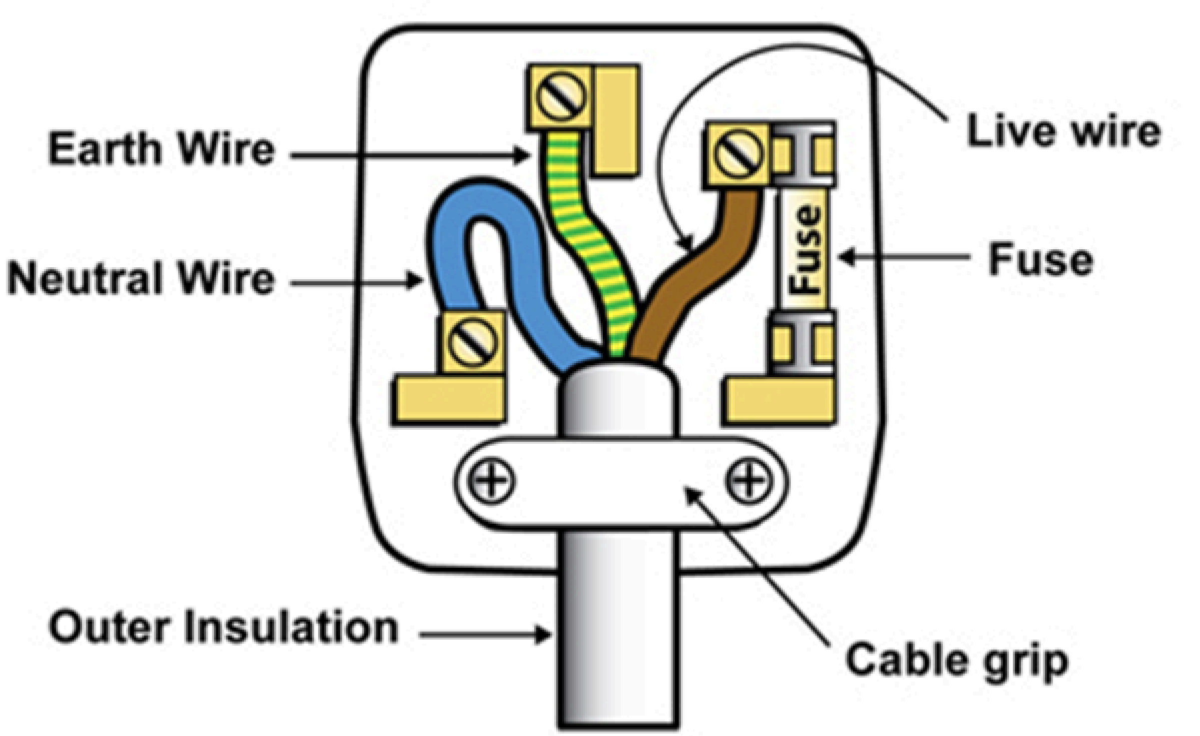

Figure 5: Wiring of a plug

Many electrical appliances, including stoves, washing machines and refrigerators, have metal cases. You would get an electric shock if the live wire inside an appliance, such as a stove, came loose and touched the metal casing. However, the earth terminal is connected to the metal casing so that the current goes through the earth wire instead of causing an electric shock.

Double insulation

Some appliances, such as hairdryers and electric drills, do not have an earth wire. This is because they have plastic casings, or they have been designed so that the live wire cannot touch the casing. As a result, the casing cannot give an electric shock, even if the wires inside become loose. These appliances have double insulation.

Note

To consolidate the concepts covered in this unit, watch this video called Wires by Fuseschools (Duration:

3.59).

Summary

In this unit you have learnt the following:

- Electrical hazards can be divided into thermal hazards and shock hazards.
- Thermal hazards, like overloading and short circuits, can result in fires.
- Shock hazards can cause severe injury or even death.
- Electrical safety features include:
  - fuses
  - circuit breakers
  - earthing
  - double insulation.

Unit 4: Assessment

Suggested time to complete: 10 minutes

1. Choose the letter of the most correct answer to the following questions:
   a. Which colour wire carries high voltage in an electric cable?
      A. Red
      B. Blue
      C. Green and yellow stripes
      D. Brown
   b. What colour is the neutral wire in an electric cable?
      A. Red
      B. Blue
      C. Green and yellow stripes
      D. Brown
   c. What colour is the earth wire in an electric cable?
      A. Red
      B. Blue
      C. Green and yellow stipes

        D. Brown

    d. What causes a fuse to blow in a circuit?
        A. Too little current
        B. Too little voltage
        C. Too much current
        D. Too much voltage
    e. The functioning of a fuse is based on the fact that:
        A. it is made of an insulator
        B. it has no resistance
        C. it does not allow current to flow through it
        D. it is made of a metal that melts easily
    f. How does an earthing wire function as a safety feature?
        A. It has a low resistance so charge can flow quickly to the Earth
        B. It has a high resistance so excess charges are prevented from flowing
        C. It connects to the casing of an appliance to disperse charge around the outside of the appliance
        D. It melts when there is excess charge in the appliance
    g. Which of these describes the relationship between the current in an electrical device and a fuse?
        A. The fuse rating and the current should be equal
        B. The current should be higher than the fuse rating
        C. The fuse rating should be much higher than the current
        D. The fuse rating should be slightly higher than the current
2. Explain why it is dangerous to use electrical appliances in a bathroom.

The full solutions are at the end of the unit.

Unit 4: Solutions

Unit 4: Assessment

1.
    a. D
    b. B
    c. C
    d. C (too much current increases the thermal energy in the wire and melts it)
    e. D (the circuit needs to be broken so melting creates a gap in the circuit)
    f. A (low resistance will mean charges can go quickly into the ground and reduce danger of a shock)
    g. D (the fuse must break the circuit when current is slightly higher than capacity of appliance so that overheating will not occur)
2. Water conducts electricity because dissolved particles (ions) are charged particles. The water can therefore conduct electricity from any electrical appliance to the person who is holding it and they could be shocked.

Back to Unit 4: Assessment

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SUBJECT OUTCOME X

MATTER AND MATERIALS: IDENTIFY, DESCRIBE, AND CLASSIFY MATTER ACCORDING TO DIFFERENT MACROSCOPIC PROPERTIES

Subject outcome

Subject outcome 5.1: Identify, describe, and classify matter according to different macroscopic properties.

Learning outcomes

- Identify and describe the phases of matter (physical property of matter).
- Distinguish between the phases of matter in terms of energy, shape and volume.
- Classify and describe materials using observation and research according to macroscopic properties.

Range: Macroscopic properties referred to are metals, semi-metals and non-metals; magnetic and non-magnetic materials; electrical conductors, semi-conductors and isolators; thermal conductors and isolators; relative density; acids, bases (and related pH).

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify and describe the phases of matter

Tell the difference between the phases of matter by their:

- Energy
- Shape
- Volume

Unit 2 outcomes

By the end of this unit you will be able to:

- Tell the difference between materials because of their macroscopic properties such as:
    - thermal conductors and insulators
    - electrical conductors and insulators
    - metals and non-metals
    - density
    - acids and bases
    - magnetic materials.

Unit 1: Phases of matter

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Identify and describe the phases of matter
- Tell the difference between the phases of matter by their:
  - Energy
  - Shape
  - Volume

Introduction

In this unit, you will explore the three phases of matter and then look at the properties and differences between them. You will explore their shape, volume, and kinetic energy. Let's get started by doing an activity.

Activity 1.1: Make a model to see how particles behave

Time required: 20 minutes

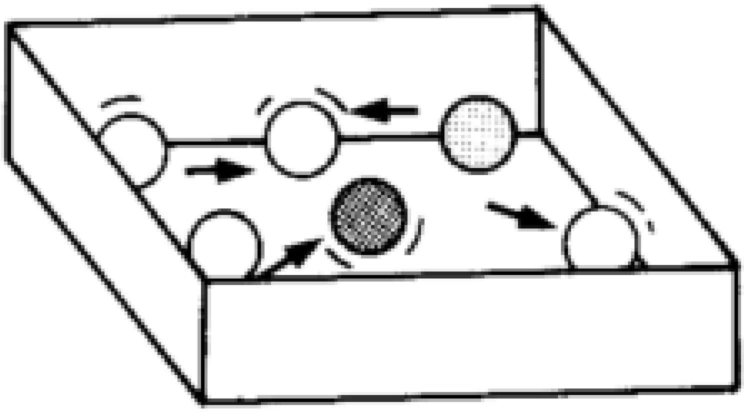
What you will need:

- a rectangular box (as big as a shoebox lid,) large enough to allow free movement for five marbles
- 5 marbles (or small hard balls of the same size) – one should be different in colour from the others
- a broad flat board that can fit into the box and can close off the end of the box (see diagram in Part A), like a small ruler
- a watch or timer, for example on a cellphone

What to do:

Task 1

Place the marbles in the box on a flat surface such as a table. (Remember that your box should be large enough to allow free movement of the marbles.) Shake the box in all directions for 30 seconds, but without lifting it off the table. Then answer the questions below:



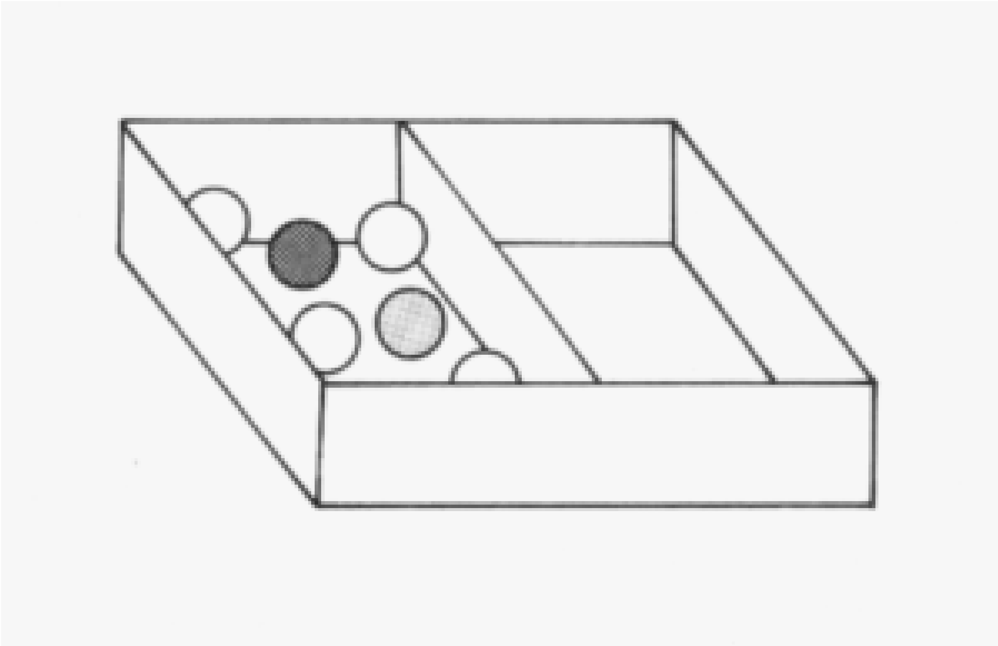
1. Describe the movement of the marbles.
2. Can you predict where a marble will move? Explain your answer.
3. Repeat this task and watch one of the marbles. List all the things it bumps against in the 30 seconds.

We call this disorganised movement shown by the marbles random motion (disorganised movement by particles).

In task 2, we will reduce the space in the box to find out how the marbles behave in a smaller space.

Task 2

Use the broad flat board (or a ruler) to make the space inside the box half as big, as shown here. Now shake the box as before. Answer the following questions:

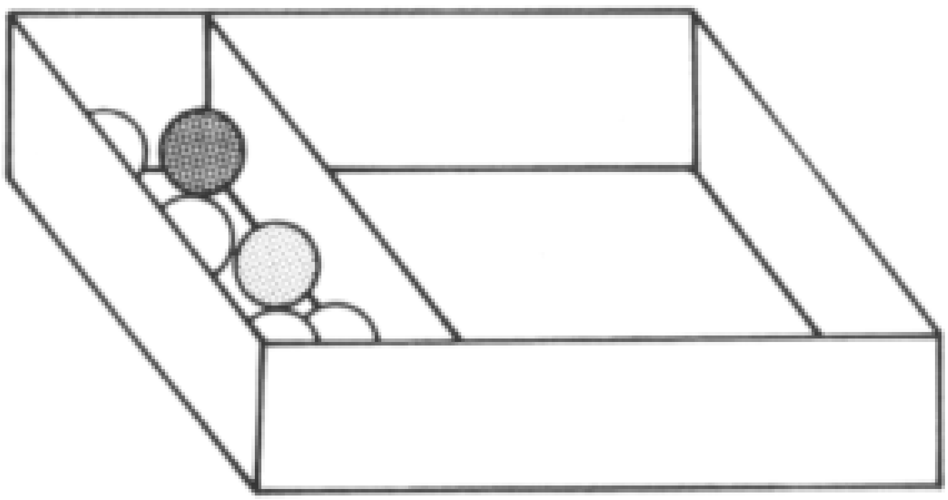


1. Compare the movement of the marbles with your observations in task 1.
2. Count the number of collisions the marble makes with its neighbouring marbles and with the sides of the box.

In task 3 we will decrease the space even further.

Task 3

Place your board such that the marbles are as tightly packed as possible, but do not squash them. Shake the box as before, and then answer the questions below:



1. How do the marbles move now?

2. Shake the box faster.
3. Can you see any difference in the motion of the marbles?
4. Count the collisions of the marbles and compare the movement of the marbles now to how they moved in tasks 1 and 2 of this activity.

What did you find?

In task 1, the marbles were far apart and moved freely in a large space. This is also true of the particles in a gas. They have large spaces between them and move about freely. You would have observed, during the activity, that the particles collide with one other and with the sides of the container. There are also large spaces between the particles, on average. By 'on average' we mean there are large spaces most of the time except when they are colliding. Clearly, when they are colliding, they are close together. But they have great freedom of movement.

In task 2, the particles were closer together but very loosely packed and there was some room for the marbles to move. This is like the arrangement of particles in a liquid, where the particles are close together, but they can still slide over one another.

In task 3, the marbles were fixed in position and could not move about. This arrangement is similar to the arrangement of particles in solids.

Phases of matter

Matter is the name given to all the things around you. All matter is made of particles. Matter can be found in one of three phases: It can be a gas, liquid, or solid. These are called the phases of matter. As you can see in Figure 1, each state of matter has particular properties which can be used to identify them.

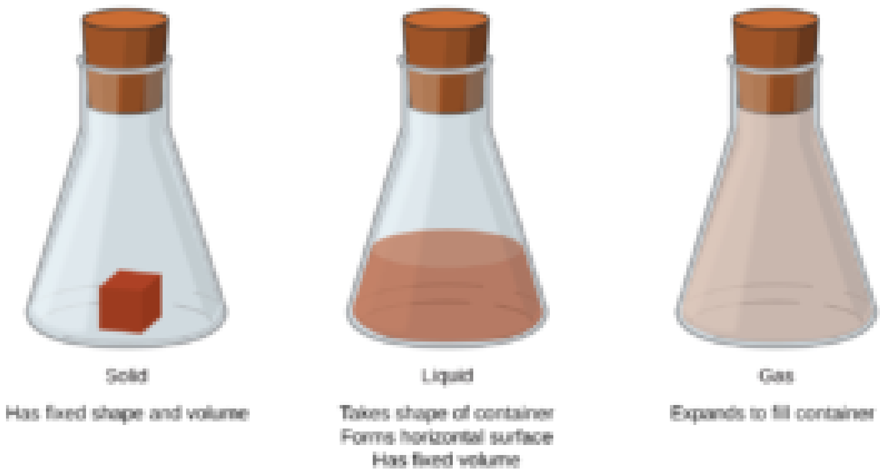


Figure 1: The three states of matter

Properties of the phases of matter

Each phase of matter has specific properties by which it can be identified, and which determine its behaviour as matter.

Solids

As shown in Figure 2, solids form dense 3-D lattice structures. It takes energy to break apart these structures because the particles in a solid have a strong force of attraction and this means that solids also have a high density. There is no space between the particles so you cannot compress or pour a solid. Examples of solids include gold, flour, sand, wood, diamonds, ice, and coal.

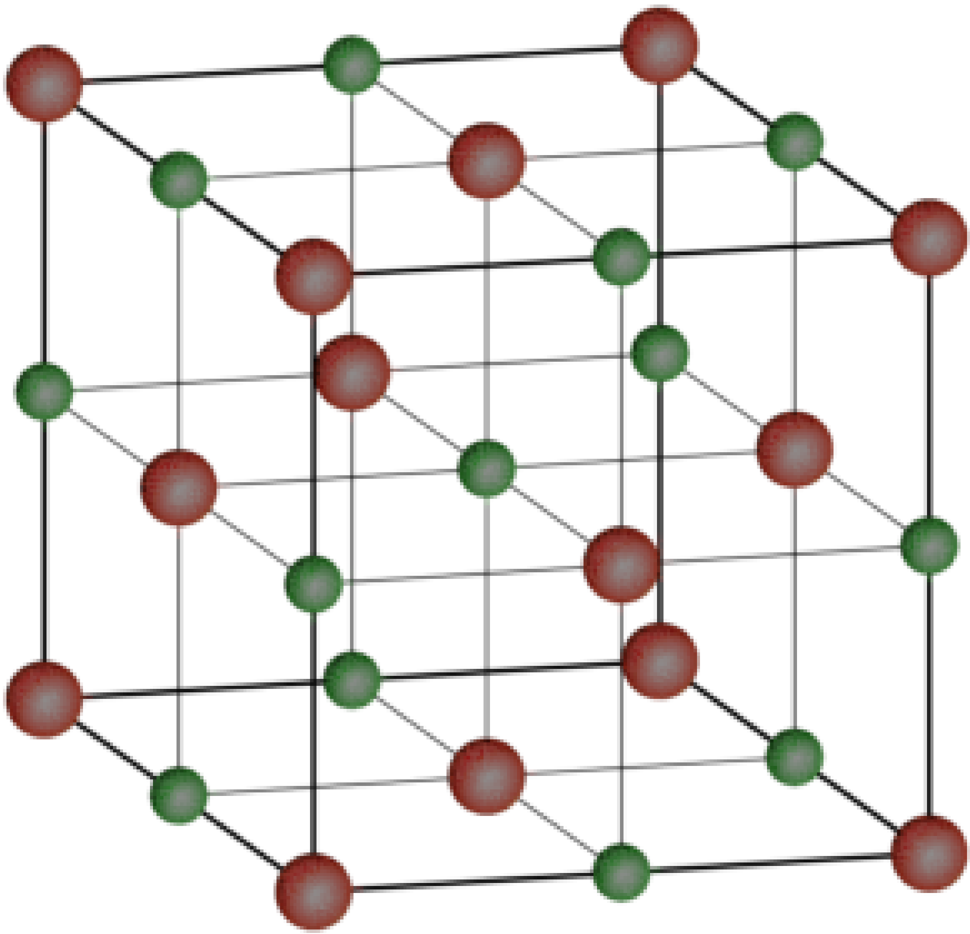


Figure 2: A lattice structure of a solid

Liquids

Liquids have spaces between the particles which means they can flow past one other. You can pour a liquid. Liquids have a fixed volume and will take the shape of the bottom of any container. Liquids have a medium density because of the spaces between them, but you cannot easily compress a liquid. Examples of liquids include milk, water, oil, petrol, and ethanol.

Gases

Gases have more energy than solids and liquids. This means that they can move around in all directions, filling the whole container in which they are stored. Gases can be poured and can be compressed because there is a lot of space between the particles. Gases have a low density and have a very weak force of attraction between the particles. Examples of gases include carbon dioxide, oxygen, methane, helium, and water vapour.

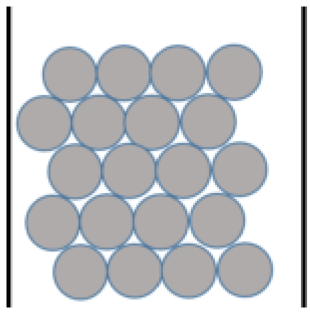
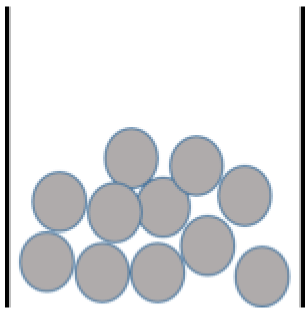
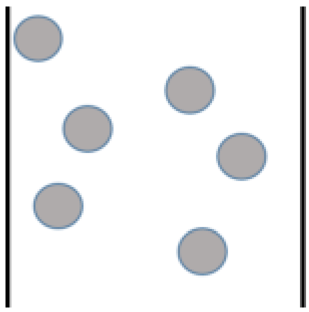
Did you know?

There is a fourth state of matter called plasma. Plasma is the most common state of matter found on earth. Simply put, plasmas are very excited gases and give out light and heat which is why they are used in television sets, and in plasma torches to cut through pieces of metal. The sun is the biggest ball of plasma that we can see from Earth. Other examples are stars, lightning, and the aurorae.

Figure 3: A plasma torch being used to cut metal

Summary of the properties of the phases of matter

Here is a summary of the properties of the three phases of matter.

Solid	**Liquid**	**Gas**
		
Particles very close together	Particles further apart	Particles very far apart
Fixed lattice shape	Takes the shape of bottom of container	Takes the shape of the whole container
Cannot flow; particles vibrate around a fixed position	Can flow; particles can move past each other	Can flow; particles move freely in all directions
Fixed volume	Fixed volume	No fixed volume
High density	Medium density	Very low density
Cannot compress	Cannot compress	Can compress
Strong forces of attraction	Weaker forces of attraction	Very weak forces of attraction

Temperature is a measure of how much kinetic energy particles have. The hotter something is, the more energy the particles have, and the colder something is, the less energy the particles have. Particles in a solid have much less energy than the particles in a gas. The particles in a bowl of ice cream are going to have much less energy than the particles in a steaming cup of tea.

Activity 1.2: Investigate the phases of matter

Time required: 15 minutes

What you will need:

- An Internet connection

What to do:

1. Open this simulation.
2. Click on States of Matter, or States.
3. Change the atoms and molecules from neon to water.
4. Change the temperature from K to °C.
5. Using the slider, slowly add heat to the solid ice to about -5 °C and observe how the molecules change shape and volume and how the molecules have more kinetic energy. Can you explain why the shape, volume, and motion changes as the temperature changes?
6. Heat the liquid water to about 60 °C using the slider. Can you explain why some of the molecules are 'breaking away' from the liquid?
7. Heat the liquid to 100 °C. What happens to the number of particles that are 'breaking away' from the liquid?

What did you find?

As the temperature increases in Step 5, the particles will gain more energy and their movement will increase.

If the particles are in a solid state and the temperature increases, then the state of matter will change, and it will become a liquid. This will change the shape and the motion of the particles, but not necessarily the volume.

If the particles are in a liquid state and the temperature increases, then the state of matter will change, and it will become a gas. This will change the shape; the particles' motion will increase, and the volume will increase.

In Step 6 molecules 'break away' from the surface of a liquid because they have gained energy and therefore their motion increases as they change from a liquid to a gas. This does not only happen at the boiling point of the liquid.

Exercise 1.1

1. What are the three phases of matter?
2. Identify the state of matter in each case:
    a. Particles which have lots of energy and a weak force of attraction between them.
    b. Particles that form 3-D lattice structures.
    c. Particles that can move past one other, take the shape of the bottom of a container, and have a medium density?

The full solutions are at the end of the unit.

The particle theory of matter

The particle theory of matter states that:

- All matter is made up of particles.
- Particles are in constant motion.
- Temperature affects the speed at which particles move.
- Particles have forces of attraction between them.

Activity 1.3: Investigate how heat affects the speed of movement of particles in a liquid

Time required: 10 minutes

What you will need:

- 2 transparent glasses or beakers
- food colouring
- hot and cold water

What to do:

1. Half fill one glass or beaker with water from the cold tap and half fill the second glass or beaker with hot water. (Be careful and do not burn yourself!)
2. Add a drop of food colouring to the water in both glasses or beakers at the same time and observe what happens for 5 minutes.

What did you find?

The particles in the hot water were moving fast and transferred some of their heat to the food colouring particles. All the particles were moving faster so the food colouring mixed faster. The particles in the cold water have less energy so the food colouring will spread out at a much slower rate.

Temperature is a measure of the average kinetic energy, and heat energy is transferred from the hotter particles to the cooler ones.

Temperature affects the speed at which particles move.

Water is made of one type of particle, and food colouring a different type of particle. When they are put together, they make a mixture.

All matter is made up of particles.

The particles in both the water and the food colouring are moving. When the food colouring is added, the particles in the food colouring move to spread out into the water. This is called diffusion.

Particles are in constant motion.

The food colouring can mix with the water because there are spaces between the water particles. The different particles are attracted to each other, therefore they mixed.

Particles have forces of attraction between them.

Exercise 1.2

1. Give a definition for:
   a. Diffusion
   b. Temperature
2. What is the particle theory of matter?

The full solutions are at the end of the unit.

Changing phase

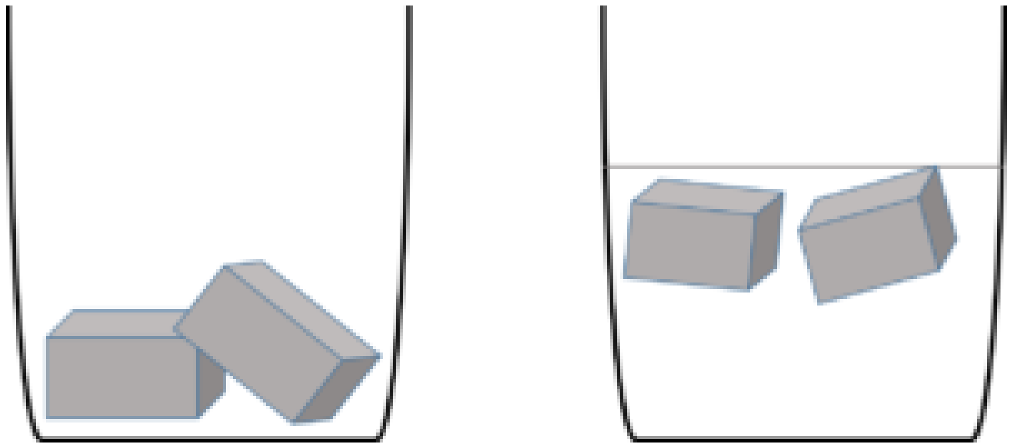
You will now do a practical investigation.

Activity 1.4: Investigate the conditions under which particles of matter can change phase

Time required: 20 minutes

What you will need:

- a few ice cubes
- 2 transparent glasses or 2 transparent bottles with the tops cut off
- a small pot with a lid



What to do:

1. Put ice cubes into each glass. Half fill one of the glasses with some tap water.
   a. Do you notice that the ice floats? Do you know why?
   b. In which glass do you think the ice will melt faster? Can you explain why?
2. Leave the glasses for about 15 minutes.
   a. Look at the glasses. What has changed?
   b. What do you notice about the state and volume of the of ice/water in each of the glasses?
3. Pour the ice and the liquid from both glasses into a small pot. Heat the pot on a stove. Observe what happens in the pot. After a few minutes, the ice should have completely melted, and you should see steam coming into the air. Carefully hold the pot lid over the steam.
   a. What happens on the lid?
   b. Can you explain why?

What did you find?

   a. Ice floats because it is less dense than the water. This is because air bubbles get trapped in the ice as it freezes.
   b. The ice will melt faster in the warmer water, because there is more kinetic energy in the warm water. This gives kinetic energy to the particles in the ice more quickly, allowing them to have the energy to break the bonds holding them to the other particles in the ice, and change from a solid to a liquid.
   a. After about 15 minutes, the ice in both glasses should have begun to melt.
   b. The ice in the warmer water should have completely melted and changed from a solid to a liquid. The volume of liquid in the glass should have increased.
2. As the liquid heats up, the motion of the particles will increase i.e. the particles will gain more kinetic energy. This allows them to break the bonds between the other liquid particles and change from a liquid to a gas. You are able to see this as the steam escapes.

You know that ice cream will melt on a hot day, and you have seen steam rising from a hot cup of tea on a cold day. This happens because substances can change phase from a solid to a liquid, a liquid to a gas, a solid to a gas, and vice versa.

All matter can change from one phase to another phase by adding or removing energy, usually in the form of heat energy. Adding heat energy increases the kinetic energy the particles of a substance have and removing heat energy reduces the kinetic energy the particles of a substance have.

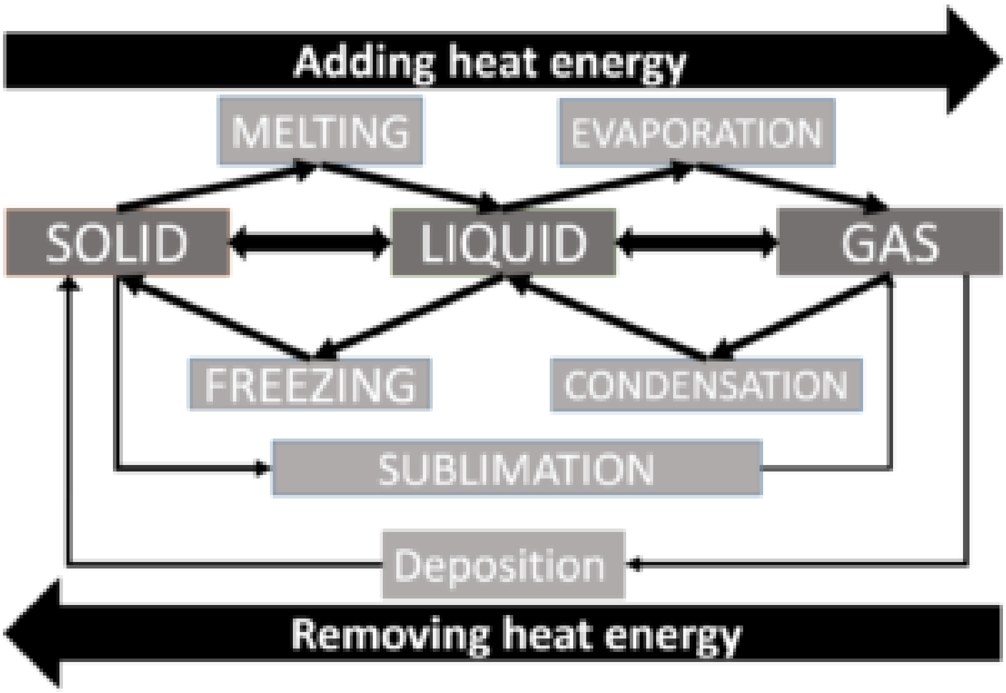


Figure 4: Flow diagram showing the changes of phase substances can go through

Adding energy

If you heat a solid, the particles stay the same, but they vibrate faster. As a result, they move slightly further apart, so the solid expands. If you carry on applying heat, the forces of attraction in the solid are weakened, and the solid melts and becomes a liquid. This also will change the *volume* and the *shape* of the substance.

This change happens at the solid's melting point.

If you carry on heating the liquid, the particles move around even more quickly. As the liquid gets hotter, the forces of attraction holding the particles together in the liquid break, and the particles are free. The liquid boils and becomes a gas. This is called evaporation and this change happens at the liquid's boiling point. This also will change the *volume* and the *shape* of the substance.

Some substances can change from their solid phase straight to their gas phase without going through the liquid phase. This is called sublimation. Dry ice, which is frozen carbon dioxide, does this at room temperature, as does a substance called naphthalene.

Take note!

Liquids do not need to be at their boiling point before they will change into a gas. Particles at the surface can change to a gas if they have absorbed enough energy. Pure substances always melt and boil at certain fixed temperatures. The melting point of pure water is 0 °C, and the boiling point is 100 °C.

Removing energy

When a substance condenses, it changes from a gas to a liquid. This requires energy to be removed. The temperature at which a liquid condenses is the same as its boiling point. The particles move less because they are losing kinetic energy. The volume and shape of the substance will also change as it becomes a liquid.

When a substance freezes, it changes from a liquid to a solid. This requires kinetic energy to be removed. A substance's freezing point is the same temperature as its melting point. The particles move less because they are losing kinetic energy and the shape and volume of the substance will change as it becomes a solid.

Deposition is when a gaseous substance changes into a solid substance without a liquid phase. This is how frost is formed. Water vapour in the air changes into solid ice because lots of kinetic energy is removed as the air temperature drops in winter.

Summary of the phase changes

The table below summarises the phase changes of substances when energy is removed or added.

Change of state	Energy added or removed	Temperature	Change of state
Solid to liquid	Added	Increases	Melting
Liquid to gas	Added	Increases	Evaporation
Solid to gas	Added	Increases	Sublimation
Gas to liquid	Removed	Decreases	Condensation
Liquid to solid	Removed	Decreases	Freezing
Gas to solid	Removed	Decreases	Deposition

Exercise 1.3

1. Ice cream will melt if it is not stored in a freezer. Explain why this happens.
2. Wet washing will dry on a washing line, and rain puddles will dry out eventually. Why does this happen? Explain your answer.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- All matter is made of tiny particles that are constantly moving. This is the particle theory of matter.
- Matter exists as a solid, liquid, gas, or plasma.
- A solid has a fixed volume, fixed shape, and little energy.
- A liquid has a fixed volume, takes the shape of the bottom of the container it is in, and its particles have some energy.
- A gas takes the shape of the whole container it is in, has no fixed volume and the particles have lots of energy.
- Solids, liquids and gases can change state if energy is either removed or added to their particles.
- All matter is made of particles that are constantly moving.
- Particles move because they have energy.

- Particles' energy increases with increasing temperature.
- Particles in the solid state have the least amount of energy compared to a liquid or gas.
- Particles in the liquid state have more energy than a solid, but less than a gas.
- Particles in the gaseous state have the most energy compared to a solid or liquid.
- The melting point of a solid is the temperature at which it will change to a liquid.
- The boiling point of a liquid is the temperature at which it will change to a gas.

Unit 1: Assessment

Suggested time to complete: 30 minutes

1. Give one word or term for each of the following descriptions.
   a. The change in phase from a solid to a gas.
   b. The change in phase from liquid to gas.
2. Water has a boiling point of 100 °C.
   a. Define the term 'boiling point'.
   b. What change in phase takes place when a liquid reaches its boiling point?
3. Describe a solid in terms of the kinetic particle theory.
4. Refer to the table below which gives the melting and boiling points of a number of elements and then answer the questions that follow. (Data sourced from: www.chemicalelements.com)

Element	**Melting point °C**	**Boiling point °C**
Copper	$1\ 083$	$2\ 567$
Magnesium	650	$1\ 107$
Oxygen	-218.4	-183
Carbon	$3\ 500$	$4\ 827$
Helium	-272	-268.6
Sulphur	112.8	444.6

   a. What state of matter (i.e. solid, liquid or gas) will each of these elements be in at an average room temperature of 25 °C?
   b. Which of these elements has the strongest forces between its atoms? Give a reason for your answer.
   c. Which of these elements has the weakest forces between its atoms? Give a reason for your answer.

5. In your notebook, draw particle diagrams to show what water will look like in the following phase:
   a. solid
   b. liquid
   c. gas

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1. Solid, liquid and gas
   a. gas
   b. solid
   c. liquid

Back to Exercise 1.1.

Exercise 1.2

a. Diffusion – the movement of particles from an area of high concentration to an area of low concentration until they are equally spread.
b. Temperature – a measure of how much kinetic energy a particle has.

2. Particle theory of matter – everything is made of matter, which is constantly moving.

Back to Exercise 1.2.

Exercise 1.3

1. The particles in the ice cream will absorb thermal energy from the air surrounding it. This will give the energy needed for the particles to start moving away from each other and become a liquid.
2. Liquid particles will evaporate when they have enough energy. The liquid particles in wet clothes and in puddles will change into gas particles when they have absorbed enough energy from their surroundings.

Back to Exercise 1.3.

Unit 1: Assessment

a. Sublimation
b. Evaporation
a. Boiling point is the temperature at which a liquid will change to a gas.
b. Evaporation

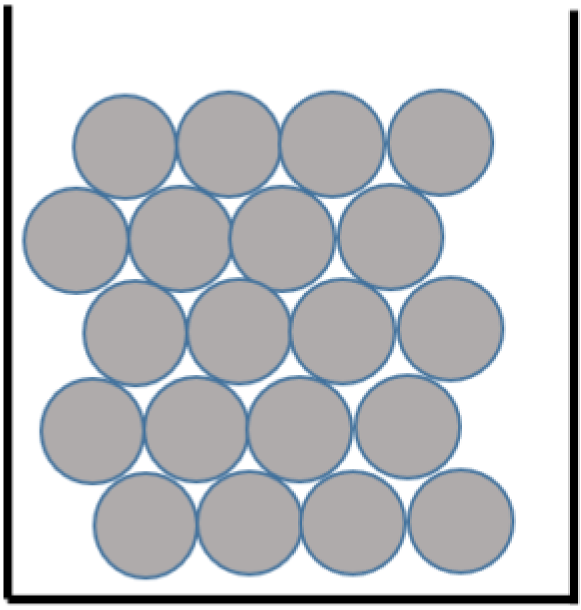
2. A solid has very little kinetic energy and its particles will only vibrate around a fixed position.
   a.

Element	**Melting point °C**	**Boiling point °C**	**State at 25 °C**
Copper	$1\ 083$	$2\ 567$	Solid
Magnesium	650	$1\ 107$	Solid
Oxygen	-218.4	-183	Gas
Carbon	$3\ 500$	$4\ 827$	Solid
Helium	-272	-268.6	Gas
Sulphur	112.8	444.6	Solid

b. Copper, because the difference between its melting point and boiling point is the highest, which means that more energy is needed to break the forces of attraction between each particle so that it can change state.

c. Helium. The difference between the melting and boiling points is the lowest so less energy is needed to break apart the forces of attraction between the particles.

a.



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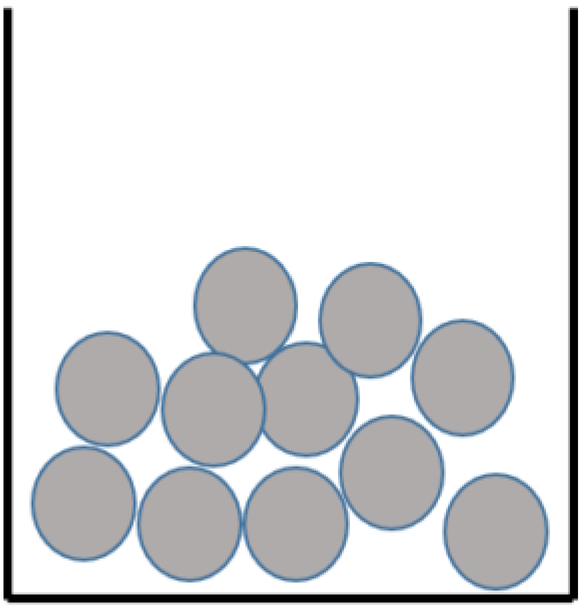
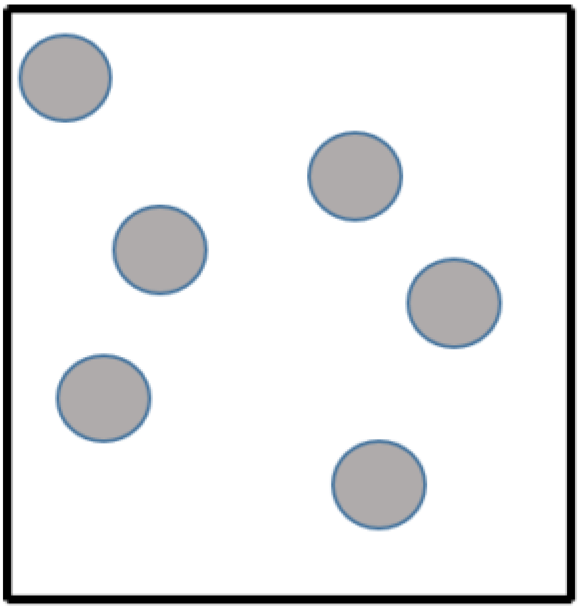


c.



Back to Unit 1: Assessment.

Media Attributions

Unit 2: Properties of Materials

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Tell the difference between materials because of their macroscopic properties such as:
    - thermal conductors and insulators
    - electrical conductors and insulators
    - metals and non-metals
    - density
    - acids and bases
    - magnetic materials.

Introduction

In this unit you will learn about different materials by investigating and observing the behaviour of their properties. This will include learning about the differences between metals and non-metals; whether they are isolators or conductors of electricity and heat, whether they are magnetic, how dense they are and whether they are acidic or basic.

Characteristics of materials

Materials can be divided into three main groups according to their macroscopic properties. These groups are metals, non-metals, and metalloids.

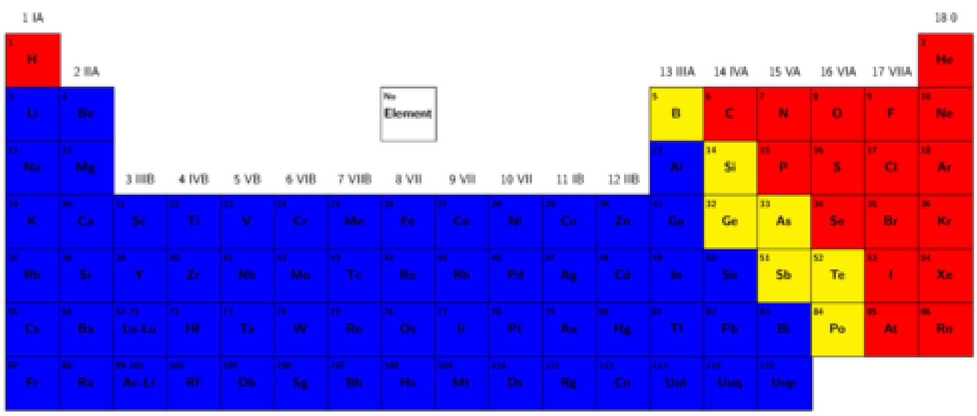


Figure 1: The periodic table divided into metals, non-metals and metalloids.

If you look at the periodic table in Figure 1, the metals can be found on the left-hand side of the table, shown in blue, and the metalloids and non-metals can be found on the right-hand side. The non-metals are indicated in red and the metalloids are shown in yellow. You should also notice that there are many more metals than non-metals.

Metals include copper, gold, silver, potassium, and lead. Non-metals include oxygen, carbon, helium and nitrogen, and metalloids include silicon and boron.

Properties of metals

These are the general macroscopic properties of metals:

- Metals are *good conductors of heat* and are therefore used to make cooking utensils such as pots and pans.
- Metals are *good conductors of electricity* and are therefore used in electrical conducting wires. Most wiring is made from copper because it is particularly good at conducting electricity.
- Metals have a characteristic shiny appearance and are often used to make jewellery.
- Metals can be *ductile and malleable*. Malleable means that they can be bent into shape without breaking and ductile means they can be stretched into thin wires.
- Metals usually have a *high melting point* and are used to make cooking pots and other equipment that needs to become extremely hot, without melting or catching fire.
- Almost all metals are solid at room temperature which means they have a *high density*. Mercury is the only metal that is a liquid at room temperature.
- Only three metals iron, cobalt and nickel are *magnetic*, the others are non-magnetic.

Properties of non-metals

Non-metals include helium, carbon, oxygen, and iodine.

These are the general macroscopic properties of non-metals:

- Non-metals are *isolators of electricity* which means they do not allow electricity to pass through them.
- Non-metals are *heat isolators* which means that they will not allow heat to travel through them easily.
- The *density* of a non-metal is dependent on its state of matter at room temperature. Most non-metals are either solid or gases at room temperature. Only bromine is a liquid.
- None of the non-metals are *magnetic*.

Properties of metalloids

Metalloids are all solid at room temperature and have mostly non-metallic properties. One of their distinguishing characteristics is that their conductivity increases as their temperature increases. This is the opposite of what happens in metals. This property is known as semi conductance and the materials are called semi-conductors. Semi-conductors are important in digital electronics, such as computers and cellphones. Metalloids include elements such as silicon and germanium.

Electrical Conductors and Isolators

An electrical conductor is a material that will allow an electrical current to pass through it and an electrical isolator is a material that will not allow an electrical current to travel through it.

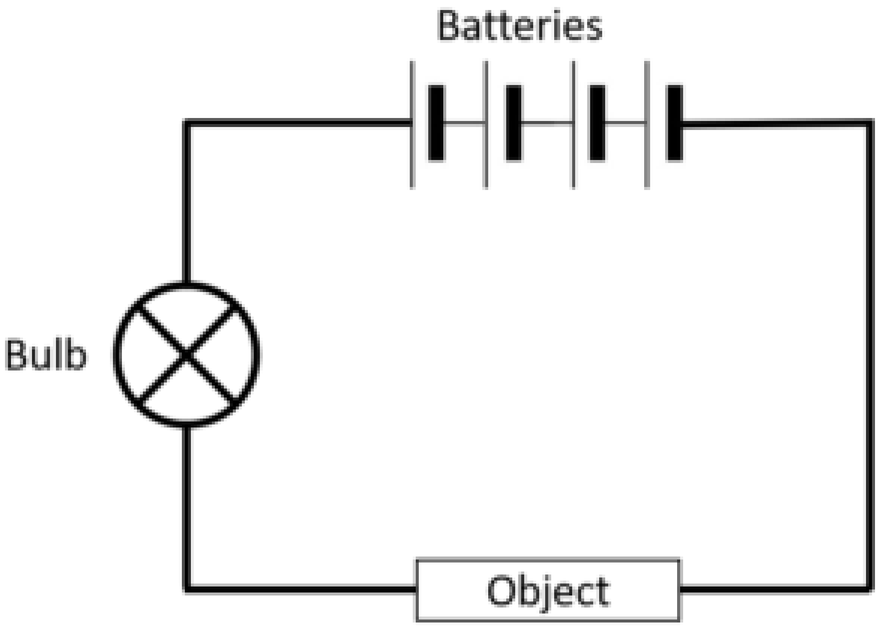
Electrical conductors are usually metals. Copper is one of the best electrical conductors, and therefore it is used to make conducting wire. Silver has an even higher electrical conductivity than copper, but silver is too expensive to use for general electrical wiring. Graphite is the only non-metal that will conduct electricity.

Activity 2.1: Investigate the electrical conductivity of different materials

Time required: 30 minutes

What you will need:

- two or three batteries
- a light bulb
- crocodile clips
- wire leads
- a selection of test substances (e.g. piece of plastic, aluminium can, metal pencil sharpener, magnet, wood, chalk, cloth, a pencil sharpened at both ends)



What to do:

1. Set up the circuit as shown in the diagram.
2. Place the test substances one by one between the crocodile clips and see what happens to the light bulb.

If the light bulb shines it means that a current is flowing and the substance you are testing is an electrical conductor.

Draw a table in your notebook to record your results, use the headings as shown in the table below:

Test substance	Metal/non-metal	Light on/off	Conductor or isolator?

Write a conclusion based on your results. *When you write your conclusion, remember to include your results and explain why you got those results.*

What did you find?

For the substances that were tested, the metals were able to conduct electricity and the non-metals, except graphite were not. Metals are good electrical conductors and non-metals are not.

Test substance	Metal/non-metal	Light on/off	Conductor or isolator?
Paper clip	Metal	On	Conductor
Piece of plastic	Non-metal	Off	Isolator
Iron nail	Metal	On	Conductor
Pencil sharpened at both ends	Non-metal	On	Conductor
Fork	Metal	On	Conductor
Mug	Non-metal	Off	Isolator

Thermal conductors and isolators

A thermal conductor is a material that allows energy in the form of heat to be transferred within the material, without any movement of the material itself.

A thermal isolator is a material that does not allow a transfer of heat energy. Materials that are poor thermal conductors can also be described as being good thermal isolators.

Take note!

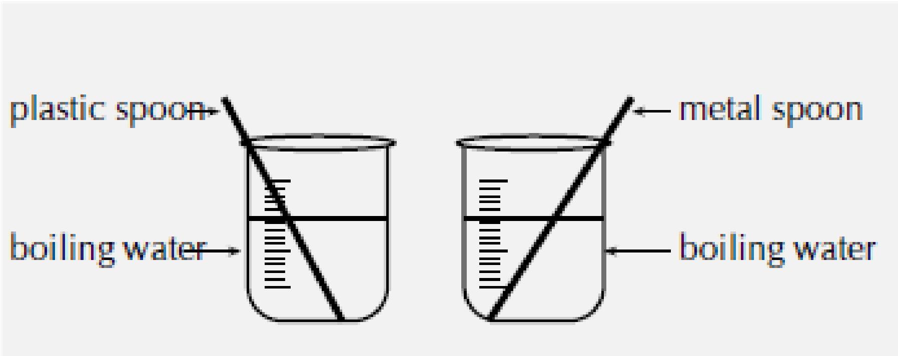
A material with a high thermal conductivity value will lose heat more quickly because it is a good conductor.

Activity 2.2: Demonstrate the ability of different materials to conduct heat materials

Time required: 15 minutes

What you will need:

- 2 glasses or beakers
- 1 plastic spoon and 1 metal spoon
- hot water
- a timer



What to do:

1. Set up the apparatus as shown in the diagram.
2. CAREFULLY pour hot water into both glasses or beakers.
3. Place a spoon in each glass and take note of which spoon is the hottest after 30 seconds.

What did you find?

The metal spoon is the hottest. This is because metals are thermal conductors. The plastic spoon is not very hot. This is because non-metals are thermal isolators.
Metals are generally good conductors of heat and non-metals are good isolators of heat. A material that is a good conductor of heat will lose heat more quickly.

Exercise 2.1

Use the information in the table to answer the following questions.

Material	**Thermal Conductivity** $(W.m^{-1}.K^{-1})$
Concrete	$0.9 - 2$
Air	0.024
Polystyrene	0.03
Wood	$0.04 - 0.12$
Glass	1.05
Red brick	0.69
Polyethylene (Plastic)	$0.42 - 0.51$
Stainless steel	16
Straw	0.052
Copper	384.1
Diamond	$895 - 1\ 300$
Water	0.61
Cast iron	52

1. Using the information in the table above, name two materials that are very good thermal conductors.
2. Using the information in the table, name any two materials that are good isolators.
3. Explain why:
   a. red brick is a better choice than concrete for building houses that need less internal heating
   b. stainless steel is good for making cooking pots
4. From the information in the table, which metal would be better than stainless steel to use for cooking pots?

The full solutions are at the end of the unit.

Magnetism

Magnetism is a force that certain kinds of objects, which are called 'magnetic', can exert on each other without physically touching. A magnetic object is surrounded by a magnetic field that gets weaker as one moves further away from the object.

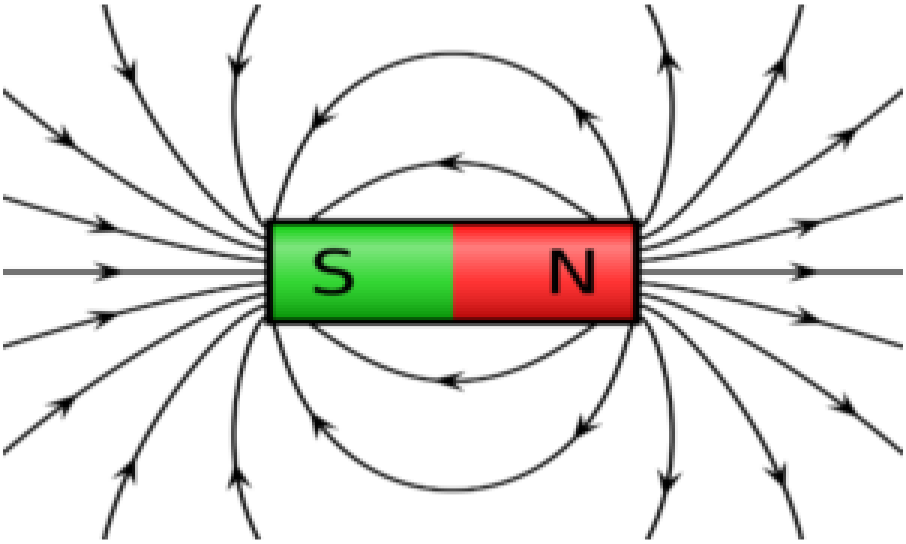


Figure 2: A magnetic field surrounds a magnet

A metal is said to be ferromagnetic if it can be magnetised, which means made into a magnet.
Some metals keep their magnetism for longer than others. For example, iron loses its magnetism quite quickly if it is taken away from the magnet. Steel on the other hand will stay magnetic for a longer time. Steel is often used to make permanent magnets that can be used for a variety of purposes.
Magnets are used to sort metals in a scrap yard, in compasses to find direction, in the magnetic strips of ATM cards where information must be stored, in computers and TVs, as well as in generators and electric motors.

Relative density

Density is a measure of how much 'stuff' a substance has in a particular volume; it is an object's mass per unit volume. An object's density is measured relative to the density of water. Water has a density of 1g/cm^3

Metals tend to be more dense than non-metals because they have more particles squashed into a given space. Gases have the lowest density.
Relative density is defined as the mass of a particular volume of a substance when compared with the mass of an equal volume of water at 4 °C.

Material	**Density (gram/cm^3)**
Water	1.0
Ethanol	0.78
Ice cube	0.92
Sunflower oil	0.923
Milk	1.03
Sodium chloride	2.17
Mercury	13.5
Aluminium	2.7
Copper	8.9
Cement	3.1
Gold	19.3

Knowing the density of an object can allow you to work out if an object will float or sink in liquids. For example, gold will sink in water because it is denser, but an ice cube will float on water because it is less dense.

Exercise 2.2

1. Using the information in the table above, list the substances in descending order of density.
2. If you fill a glass with water, which of the following objects would sink or float in it?
   a. copper
   b. sunflower oil
   c. cement

The full solutions are at the end of the unit.

Acids and bases

A substance can be classified as an acid, a base, or a neutral substance according to the pH scale. We use acids and bases all the time; vinegar and lemon juice are weak acids, soap and shampoo are weak bases.

An acid is a substance that has a sour taste, although acids used in the laboratory should never be tasted. The strength of an acid varies from a weak acid, such as lemon juice, to a strong acid, such as sulphuric acid. Strong acids like sulphuric acid are used to clean cement and make fertilisers. Nitric acid is used to make explosives, and hydrochloric acid is used to make type of plastic called PVC.

A base is the chemical opposite of an acid. Bases have a soapy feel and taste bitter. The strength of a base varies from being weak, for example sea water, to being very strong, for example drain cleaner. Sodium hydroxide is a strong base and is used to make soap and paper, and calcium hydroxide is used to clean sulphur dioxide fumes from industrial power plants.

Acids and bases will cause a particular colour change when a substance called universal indicator is added to them. The colour changes according to the strength of the substance.

As you can see in Figure 3, a strong acid turns universal indicator red, a weak acid turns the indicator yellow, a strong base turns the indicator purple and a weak base will turn the indicator blue. A neutral substance will turn universal indicator green.

Acids can have a pH of 1 – 6 and bases can have a pH of 8 – 14. A neutral substance will have a pH of 7.

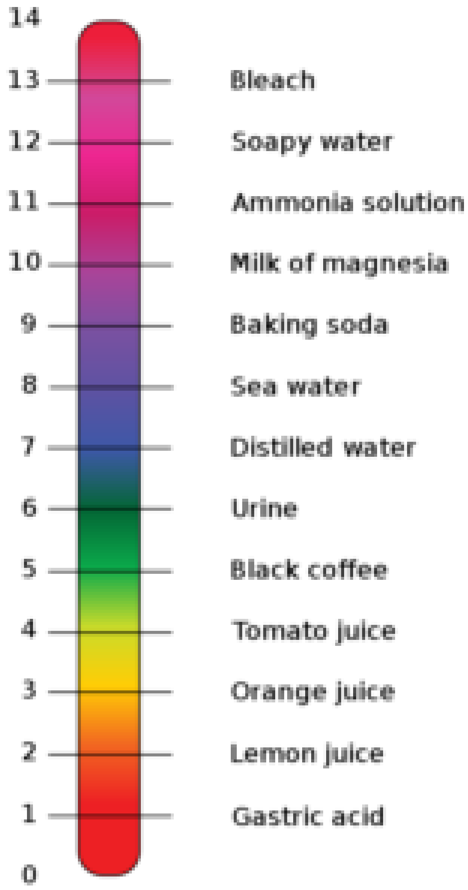


Figure 3: The pH Scale

Summary

In this unit you have learnt the following:

- Metals are good electrical and thermal conductors, they have a shiny lustre, they are malleable and ductile, and they have a high melting point.
- Metals have a high density.
- The properties of metals make them useful for making electrical wires, cooking utensils, jewellery, and for many other applications.
- Matter can be classified into electrical conductors, semi-conductors, and isolators.
  - An electrical conductor allows an electrical current to pass through it. Most metals are good electrical conductors.
  - An electrical isolator is a non-conducting material that does not carry any charge. Examples are plastic, wood, cotton material and ceramic.
- Materials may also be classified as thermal conductors or thermal isolators depending on whether or not they are able to conduct heat.
- Materials may also be magnetic or non-magnetic. Magnetism is a force that certain kinds of objects, which are called 'magnetic' objects, can exert on each other without physically touching. A magnetic object is surrounded by a magnetic 'field' that gets weaker as one moves further away from the object.
- Materials have density, relative to the density of water. Gold is denser than water and ethanol is less dense. So, gold will sink in water and ethanol will float on water.
- Liquid substances can be classified as acidic, basic or neutral depending on their ability to donate or accept protons. Acids have a pH from 1 – 6, neutral substances have a pH of 7 and bases have a pH 8 – 14.

Unit 2: Assessment

Suggested time to complete: 15 minutes

1. For each of the following materials, say which of its properties enable it to carry out its function.
   a. ceramic teacup
   b. iron burglar bars
   c. wool blanket
   d. metal jewellery
   e. red bricks for building
   f. copper wires
   g. plastic coating around wires.
2. You are given a test tube that contains a mixture of iron filings and sulphur. You are asked to weigh the amount of iron in the sample.
   a. Suggest one method that you could use to separate the iron filings from the sulphur.
   b. What property of metals allows you to do this?
3. Predict whether these objects would float or sink in water (density of water = kg/m3):
   Oil: 913 kg/m3
   Ice: 881 kg/m3
   Pumice stone: 721 kg/m3
   Sand: $1\ 602$ kg/m3
   Blood: 721 kg/m3
   Chalk: $1\ 121$ kg/m3
   Wax: 320 kg/m3
4. Pure water has a pH of 7, but rainwater has a pH of 4.5 and tap water has a pH of 6.5. Using this information, complete the table:

Substance	**pH**	**Approximate colour on the pH Scale, using universal indicator**	**Acid, base or neutral**
Pure water	7		
Rainwater	4.5		
Tap water	6.5		
Sea water	8.1		

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. copper and diamond
2. Can be any two from: concrete, air, water, polystyrene, wood, glass, red brick, polyethylene (plastic), straw.
3. a. it has a lower thermal conductivity than concrete

b. it is a good thermal conductor

4. cast iron, copper, or diamond

Back to Exercise 2.1

Exercise 2.2

1. Ethanol
   Ice cube
   Sunflower oil
   Water
   Milk
   Sodium Chloride
   Aluminium
   Cement
   Copper
   Mercury
   Gold
2. a. sink
   b. float
   c. sink

Back to Exercise 2.2

Unit 2: Assessment

1. a. ceramic is a good thermal isolator
   b. iron is strong
   c. wool is a good thermal isolator
   d. metal is shiny, malleable, and ductile
   e. good thermal isolator
   f. good electrical conductor
   g. good electrical isolator
2. a. magnetism
   b. iron is magnetic and sulphur is not
3.

Float	**Sink**
wax	sand
oil	chalk
ice	
Pumice stone	
blood	

4.

Substance	pH	Approximate colour on the pH Scale, using universal indicator	Acid, base or neutral
Pure water	7	Green	Neutral
Rainwater	4.5	Yellow	Acid
Tap water	6.5	Blue	Base
Sea water	8.1	Blue	Base

Back to Unit 2: Assessment

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SUBJECT OUTCOME XI

MATTER AND MATERIALS: IDENTIFY AND DESCRIBE ATOMS AS THE BASIC BUILDING BLOCK

Subject outcome

Subject outcome 5.2: Identify and describe atoms as the basic building block.

Learning outcomes

- Identify and sketch the orbit structure of the atom showing the position (nucleus and orbit) of the protons, neutrons, and electrons in shells.
- Differentiate between atomic number and atomic mass.
- Define and identify an isotope and refer to common examples that are used.

Unit 1 outcomes

By the end of this unit you will be able to:

- Draw atoms with the protons and neutrons in a nucleus and electrons in orbiting shells
  Identify an atom according to a diagram

Unit 2 outcomes

By the end of this unit you will be able to:

- Tell the difference between atomic number and atomic mass and explain the difference between the two.
- Understand that each element has a different atomic mass and atomic number.
- Describe and identify an isotope.
- Identify common examples of isotopes.

Unit 1: The atom

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Draw atoms with the protons and neutrons in a nucleus and electrons in orbiting shells
- Identify an atom according to a diagram

Introduction

In this unit you will learn about the atom, which is the basic building block of matter. You will learn about the structure of the atom; how atoms are made up of tiny particles called protons, electrons and neutrons and the position of electrons on shells and the protons and neutrons in the nucleus.

The structure of the atom

An atom is the basic building block of all matter. Everything you can think of is made of atoms. Atoms are so small that there are approximately 10 million million or 10^{13} of them in a pencil dot.

In work published in 1808, John Dalton proposed that all matter is composed of very small things which he called atoms. Atoms are made up of sub-atomic particles called electrons, neutrons and protons. Electrons were discovered by J.J Thompson in 1897, neutrons in 1932 by James Chadwick, and Ernest Rutherford discovered protons in 1909.

Rutherford's model of the atom described the atom as a tiny, dense, positively charged core called a nucleus surrounded by lighter, negatively charged electrons.

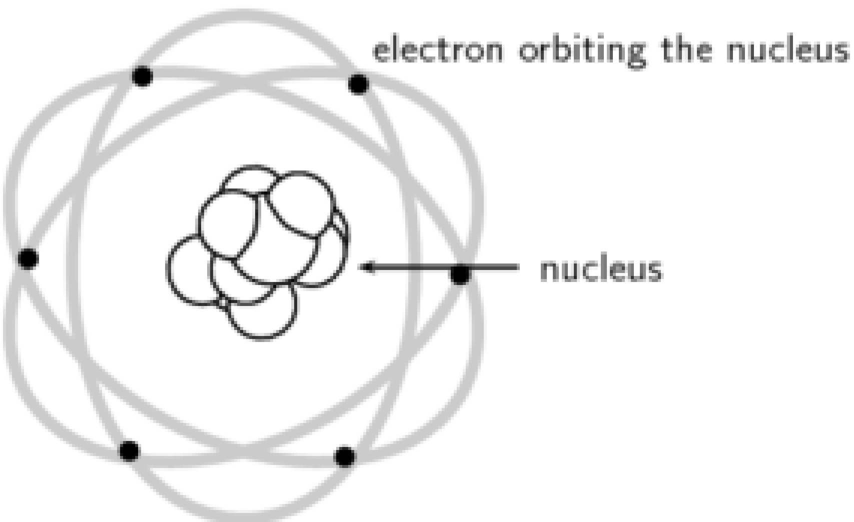

Figure 1: Rutherford's model of the atom

Niels Bohr proposed that the electrons could orbit the nucleus in certain special orbits at different energy levels around the nucleus.

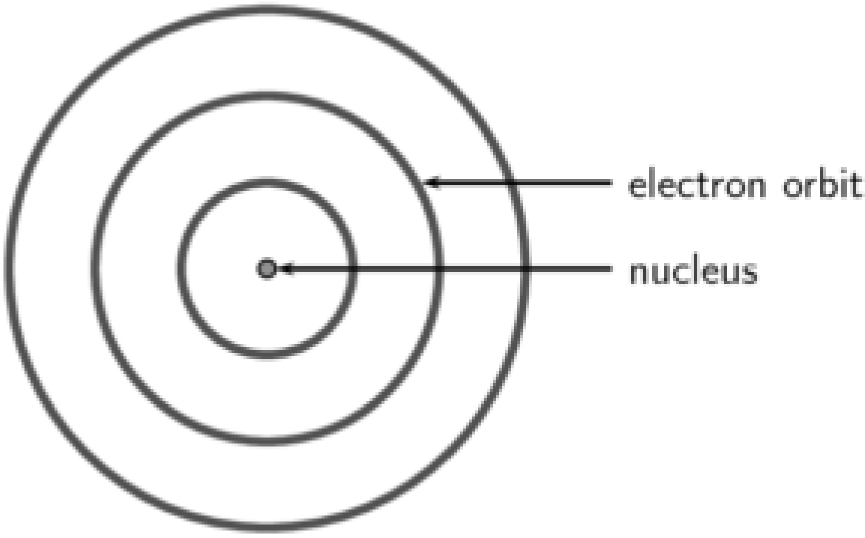

Figure 2: Bohr's model of the atom

As a result of the work done by previous scientists on atomic models, scientists now have a good idea of what an atom looks like. This knowledge is important because it helps us to understand why materials have different properties and why some materials bond with others.

Atoms consist of three different types of subatomic particles:

- negatively charged electrons
- neutrons which have no charge
- positively charged protons.

The protons and neutrons are found in the nucleus and the electrons orbit around the nucleus in shells. These are called electron shells.

The electron

The electron is a very tiny particle. It has a mass of 9.11×10^{-31} kg. The electron carries one unit of negative electric charge.

The nucleus

Unlike the electron, the nucleus can be broken up into smaller building blocks called protons and neutrons. Together, the protons and neutrons are called nucleons.

The proton

Each proton carries one unit of positive electric charge. Since we know that atoms are electrically neutral, they do not carry any extra charge, then the number of protons in an atom has to be the same as the number of electrons to balance out the positive and negative charge. The total positive charge of a nucleus is equal to the number of protons in the nucleus. A proton is much heavier than an electron (10 000 times heavier!) and has a mass of 1.6726×10^{-27} kg. When we talk about the atomic mass of an atom, we are mostly referring to the combined mass of the protons and neutrons.

The neutron

The neutron is electrically neutral, so it carries no charge at all. Like a proton, it is much heavier than an electron and its mass is 1.6749×10^{-27} kg (slightly heavier than a proton).

Exercise 1.1

1. The three basic components of an atom are:
    a. protons, neutrons, and ions
    b. protons, neutrons, and electrons
    c. protons, neutrinos, and ions
    d. protium, deuterium, and tritium
2. The charge of an atom is:
    a. positive
    b. neutral
    c. negative
    d. none of the above

The full solutions are at the end of the unit.

Activity 1.1: Building atoms

Suggested time: 15 minutes

What you need:

- internet access

What to do:

Open the Build an atom simulation. Click on ‘Build an Atom’, then select ‘Atom’.

Build atoms for different elements by adding protons, neutrons and electrons to the atom diagram.

Summary

In this unit you have learnt the following:

- An atom is made up of a central nucleus (containing protons and neutrons), surrounded by electrons. Most of the atom is empty space.
- Electrons are negatively charged particles which orbit the nucleus in shells.
- Protons are positively charged particles found in the nucleus.
- Neutrons are neutrally charged particles found in the nucleus.

Unit 1: Assessment

Suggested time to complete: 10 minutes

1. What is the centre of an atom called?
   a. The protons
   b. The nucleus
   c. The electrons
2. What is the charge on an electron?
   a. One positive charge
   b. No charge
   c. One negative charge
3. Which of the three sub-atomic particles is the lightest?
   a. The proton
   b. The neutron
   c. The electron
4. If atoms contain charged particles, why do they not have a charge?
   a. They contain the same number of protons as electrons.
   b. The charge is locked away in the nucleus.
   c. They contain equal numbers of protons and neutrons.

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1. b
2. b

Back to Exercise 1.1.

Unit 1: Assessment

1. b
2. c

3. c
4. a

Back to Unit 1: Assessment.

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Unit 2: Atomic number and atomic mass

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Tell the difference between atomic number and atomic mass and explain the difference between the two.
- Understand that each element has a different atomic mass and atomic number.
- Describe and identify an isotope.
- Identify common examples of isotopes.

What you should know

Before you start this unit, make sure you can:

- Identify the parts of an atom in Subject outcome 5.2, Unit 1: The atom.

Introduction

In this unit you will learn about atomic number, atomic mass, and isotopes. You will learn how each element has a different atomic mass and atomic number and how that relates to the charge of an atom.

You will learn that atoms of the same element can have a different number of neutrons and that these atoms are called isotopes. Isotopes are atoms that have the same number of protons, but they have a different number of neutrons.

Atomic number and mass

The chemical properties of an element are determined by the charge of its nucleus, so by the number of protons it has. This number is called the atomic number and is denoted by the letter Z.

The mass of an atom depends on how many nucleons its nucleus contains. The number of nucleons, which is the total number of protons plus neutrons, is called the atomic mass number and is denoted by the letter A.

Standard notation shows the chemical symbol, the atomic mass number and the atomic number of an element as follows:

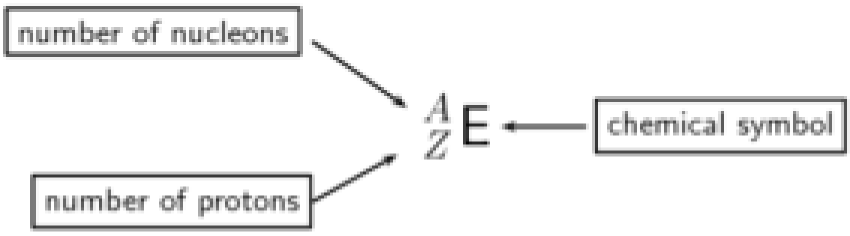


Figure 1: Standard notation of a chemical symbol. The atomic number (Z) and the mass number (A) are indicated using a standard notation.

The nucleus of the element iron has 26 protons and 30 neutrons, so is denoted as: $^{56}_{26}Fe$ where the atomic number is $Z = 26$ and the mass number $A = 56$. The number of neutrons is simply the difference $N = A - Z = 30$.

Example 1

Use standard notation to represent sodium and give the number of protons, neutrons, and electrons in the element.

1. Give the element symbol.
2. Find the number of protons.
3. Find the number of electrons.
4. Find A.
5. Work out the number of neutrons.

Solutions

1. The element symbol for sodium is Na.
2. Sodium has 11 protons, so we have: $_{11}Na$
3. Sodium is neutral, so it has the same number of electrons as protons. The number of electrons is 11.
4. From the periodic table we see that $A = 23$.
5. We know A and Z so we can find $N : N = A - Z = 23 - 11 = 12$. In standard notation sodium is given by: $^{23}_{11}Na$.

The number of protons is 11, the number of neutrons is 12 and the number of electrons is 11.

Exercise 2.1

You will need a copy of the Periodic Table to complete these questions

1. Copy the following table into your notebook and then complete the table:

Element	Atomic Mass	Atomic number	Protons	Electrons	Neutrons
Cu	12				
Ni				28	
	40		20		

2. Use standard notation to represent the following elements:
   a. potassium
   b. copper
   c. chlorine
3. For the element Cl, give the number of the following particles in the atom:
   a. protons
   b. neutrons
   c. electrons
4. In each of the following cases, give the number or the element symbol represented by X.
   a. ${}^{40}_{18}X$
   b. ${}^{x}_{20}Ca$
   c. ${}^{31}_{x}P$
5. Which of the following atoms has 7 electrons?
   a. ${}^{5}_{2}He$
   b. ${}^{13}_{6}C$
   c. ${}^{7}_{3}Li$
   d. ${}^{15}_{7}N$

The full solutions are at the end of the unit.

Isotopes

The chemical properties of an element depend on the number of protons and electrons inside the atom. So, if a neutron or two is added or removed from the nucleus, then the chemical properties will not change. This means that such an atom would remain in the same place in the periodic table. For example, no matter how many neutrons we add or subtract from a nucleus with 6 protons, that element will always be called carbon and have the element symbol C (see the periodic table). Atoms that have the same number of protons (the same atomic number Z), but a different number of neutrons (a different N value and therefore a different mass number A), are called isotopes.

The chemical properties of the different isotopes of an element are the same, but they might vary in how stable their nucleus is. We can also write elements as $E\!-A$, where the E is the element symbol, and the A is the atomic mass of that element. For example, Cl-35 has an atomic mass of 35 u (17 protons and 18 neutrons), while Cl-37 has an atomic mass of 37 u (17 protons and 20 neutrons).

In nature, the different isotopes occur in different percentages. For example, Cl-35 might make up 75% of all chlorine atoms on Earth, and Cl-37 makes up the remaining 25%.

Activity 2.1: Building isotopes

Suggested time: 15 Minutes

What you need:

- internet access

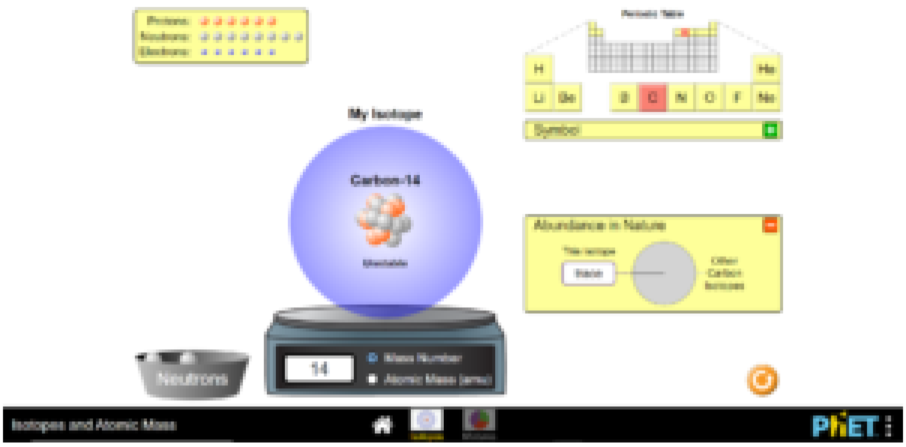
What to do:

Go to this link.

1. Click on 'Isotopes and Atomic Mass' and then select 'Isotopes'. Change the number of neutrons in the hydrogen atom to make an isotope.
2. Change the element to a different one and again change the number of neutrons to make a different isotope. Whilst you are adding neutrons, keep an eye on the pie chart as this will show you how abundant this isotope is in nature. Also note the stability of the isotope as you add neutrons.
3. Go back to the main page and click on mixtures.
4. Change the elements, select 'Nature's Mix', and see the percentage of each type of isotope naturally found for that element.

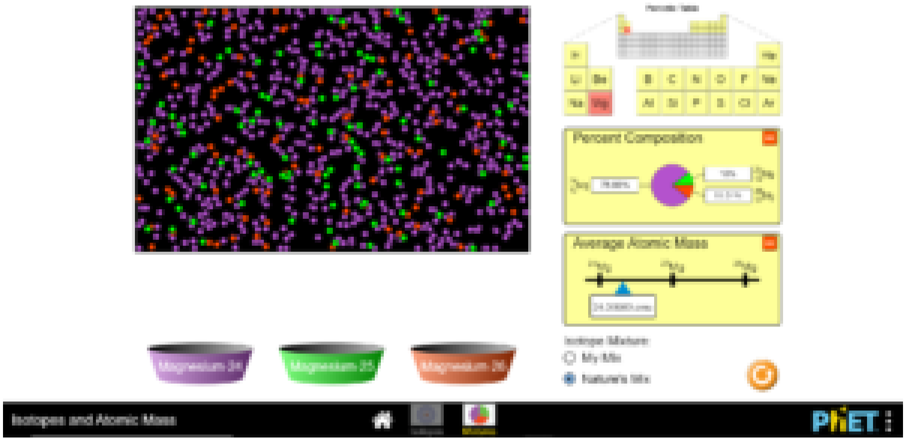
What did you find?

Isotopes: You will have noted that as you added neutrons to the nucleus, the stability of the isotope changes as does its abundance in nature.



For example, Carbon-13 is a stable isotope, but as you add another neutron to make Carbon-14, the isotope becomes unstable.

Natures Mix: As you look at the different elements, you will see the isotopes which occur naturally in different colours, and on the right of the screen you will see the naturally occurring percentages of these isotopes.



For example, Magnesium has two isotopes which make up approximately 21% of the composition of magnesium.

Exercise 2.2

1. Atom A has 5 protons and 4 neutrons, and Atom B has 6 protons and 5 neutrons. These atoms are:
   a. allotropes
   b. isotopes
   c. isomers
   d. atoms of different elements
2. For the sulphur isotopes $^{32}_{16}S$ and $^{34}_{16}S$, given the number of:
   a. protons
   b. nucleons
   c. electrons
   d. neutrons

The full solutions are at the end of the unit.

Note

If you need further explanations about isotopes watch this video: Fuse Schools: What are isotopes? (2.50).

Summary

In this unit you have learnt the following:

- The atomic number (Z) is the number of protons in an atom.
- The atomic mass number (A) is the number of protons and neutrons in the nucleus of an atom.
- The standard notation that is used to write an element, is: $^{A}_{Z}E$, where E is the element symbol, A is the

atomic mass number and Z is the atomic number.
- The isotope of a particular element is made up of atoms which have the same number of protons as the atoms in the original element, but a different number of neutrons. This means that not all atoms of an element will have the same atomic mass.

Unit 2: Assessment

Suggested time to complete: 20 minutes

1. Give the standard notation for the following elements:
   a. beryllium
   b. Carbon-12
   c. fluorine
2. For each of the following elements give the number of protons, neutrons, and electrons in the element:
   a. $^{195}_{78}Pt$
   b. $^{127}_{53}I$
3. Write down only the word/term for each of the following descriptions:
   a. The sum of the number of protons and neutrons in an atom.
   b. The defined space around an atom's nucleus, where an electron is most likely to be found.
4. The charge of an atom is:
   a. positive
   b. neutral
   c. negative
   d. none of the above.
5. Using your periodic table, copy and complete the table below:

Isotope	Z	A	Protons	Electrons	Neutrons
Carbon-14					
Carbon-12					
Iron-54					
Iron-56					
Iron-57					

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1.

Element	Atomic Mass	Atomic number	Protons	Electrons	Neutrons
Cu	63.55	29	29	29	34
Ni	58.69	28	28	28	30
Ca	40	20	20	20	20

2.
   a. ${}^{39}_{19}K$
   b. ${}^{64}_{29}Cu$
   c. ${}^{35}_{17}Cl$
3.
   a. 17
   b. 18
   c. 17
4.
   a. X = Ar
   b. x = 40
   c. x = 15
5. d. Nitrogen

Back to Exercise 2.1.

Exercise 2.2

1. b. isotopes
2.
   a. 16
   b. 1
   c. 16
   d. 16 and 18

Back to Exercise 2.2.

Unit 2: Assessment

1.
   a. ${}^{9}_{4}B$
   b. ${}^{12}_{6}C$
   c. ${}^{19}_{9}F$
2.
   a. Pt: 78 electrons and protons = 78; 117 neutrons
   b. I: 53 electrons and protons; 74 neutrons
3.
   a. Mass number
   b. Electron shell

4. b. Neutral
5.

Isotope	Z	A	Protons	Electrons	Neutrons
Carbon-14	6	14	6	6	8
Carbon-12	6	12	6	6	6
Iron-54	26	54	26	26	28
Iron-56	26	56	26	26	20
Iron-57	26	57	26	26	31

Back to Unit 2: Assessment.

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SUBJECT OUTCOME XII

MATTER AND MATERIALS: IDENTIFY, DESCRIBE AND APPLY PROPERTIES OF THE PERIODIC TABLE

Subject outcome

Subject outcome 5.3: Identify, describe and apply properties of the periodic table

Learning outcomes

- Recognise the arrangement of atoms in the periodic table according to atomic number.
- Identify and describe group, period and periodicity.
- Arrange electrons into core and valence electrons and write electron configuration of first 20 elements down.
- State the names of groups (1, 2, 7, 0) and identify the transition metal group.
- Describe and interpret the meaning of groups (similar chemical activity or activity trends).
- Recognise the distribution of metals and non-metals.

Unit 1 outcomes

By the end of this unit you will be able to:

- Describe the arrangement of the periodic table according to an element's atomic number.
- Identify that elements are in vertical groups according to similar chemical properties.
- Identify that elements are arranged in horizontal periods according to increasing atomic number.
- Recall that periodicity means the arrangement on the periodic table of elements because of their:
    - atomic radius
    - electronegativity
    - ionisation energy.

Unit 2 outcomes

By the end of this unit you will be able to:

- Arrange electrons into core and valence electrons and write electron configuration of first 20 elements.
- Write the electron configuration for the first 20 elements.

Unit 3 outcomes

By the end of this unit you will be able to:

- Give the names of groups 1, 2, 7 and 0 and identify the transition metal group.
- Predict the activity of elements in their groups.
- Recognise where the metals and non-metals are on the periodic table.

Unit 1: The periodic table

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Describe the arrangement of the periodic table according to an element's atomic number.
- Identify that elements are in vertical groups according to similar chemical properties.
- Identify that elements are arranged in horizontal periods according to increasing atomic number.
- Recall that periodicity means the arrangement on the periodic table of elements because of their:
  - atomic radius
  - electronegativity
  - ionisation energy.

What you should know:

Before you start this unit, make sure you can:

Confidently complete all the work in Subject outcome 5.2, Unit 1: The atom.

Confidently complete all the work in Subject outcome 5.2, Unit 2: Atomic number and atomic mass.

Introduction

In this unit you will learn to recognise the arrangement of atoms on the periodic table according to atomic number, groups, periods, and periodicity.

Elements are laid out vertically across the periodic table according to their atomic number (the number of protons they have). They are grouped horizontally according to their similar properties and periods because they have the same number of electron shells.

Introduction to the periodic table

The periodic table of the elements is a method of showing the chemical elements in a table with the elements arranged in order of increasing atomic number. The layout of the periodic table that we know today can mostly be attributed to a Russian chemist named Dimitri Mendeleev. Mendeleev designed the table in 1869 in such a way that recurring ("periodic") trends or patterns in the properties of the elements are apparent. Using the trends he observed, he left gaps for those elements that he thought were "missing". He also predicted the properties that he thought the missing elements would have when they were discovered. Many of these elements were indeed discovered and Mendeleev's predictions were proved to be correct.

To show the recurring properties that he had observed, Mendeleev used a series of new rows in his table so that elements with similar properties were in the same vertical columns, called groups. Each row was referred to as a period.

Note

You can download an interactive periodic table app from The Royal Society of Chemistry for either Android or Apple iOS.

Android **Apple iOS**

Or use this interactive link online.

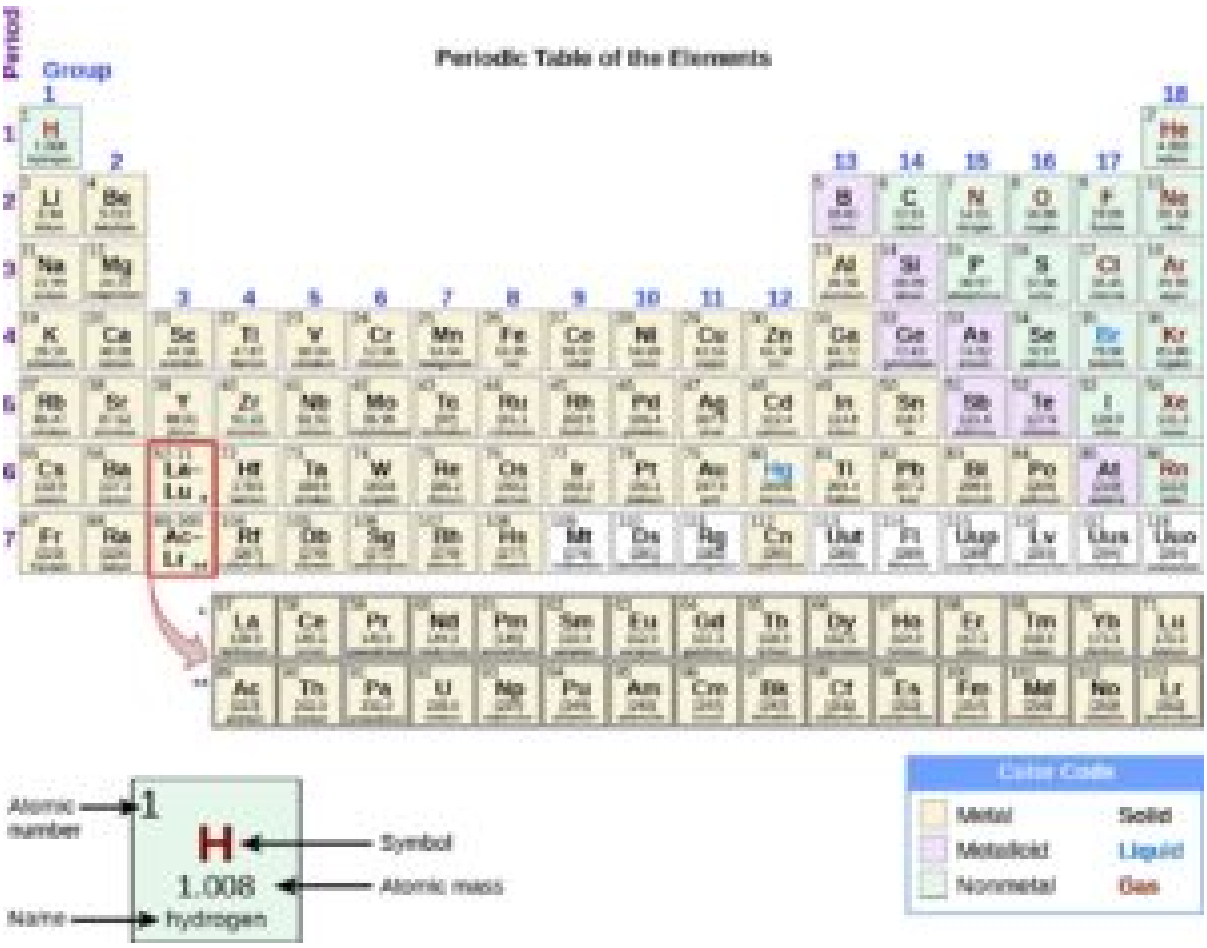


Figure 1: The periodic table of elements showing all of the known elements laid out as described by Mendeleev

Each element has an abbreviated form of its name. Most of the elements' abbreviations are either the first letter of their name and may include the second letter, which is always written in lower case, for example:

oxygen	O
carbon	C
lithium	Li
calcium	Ca
silicon	Si
sulfur	S
helium	He

Some of the abbreviations are not abbreviations of the English element name, but of the Latin or Greek element name, because they were discovered a long time ago, for example:

Latin Name	**English Name**	**Chemical Symbol**
Plumbum	Lead	Pb
Aurum	Gold	Au
Ferrum	Iron	Fe
Argentum	Silver	Ag
Natrium	Silver	Na

Did you know?

Water pipes used to be made of lead until it was discovered that lead is soluble in water and causes poor cognitive development. Plumbers are called plumbers because of lead's Latin name plumbum.

Note

For a further introduction to the periodic table you can watch this video:
Socratia: Introduction to the Periodic Table (Duration: 9.05)

or this video from Fuse Schools: How does the periodic table work (Duration: 4.30). It is part of an excellent playlist.

Layout of the periodic table

A group is a vertical column in the periodic table and is the most important way of classifying the elements. If you look at a periodic table, you will see that at the top of each column, or group, there is a number. The groups are numbered from left to right starting with 1 and ending with 18.

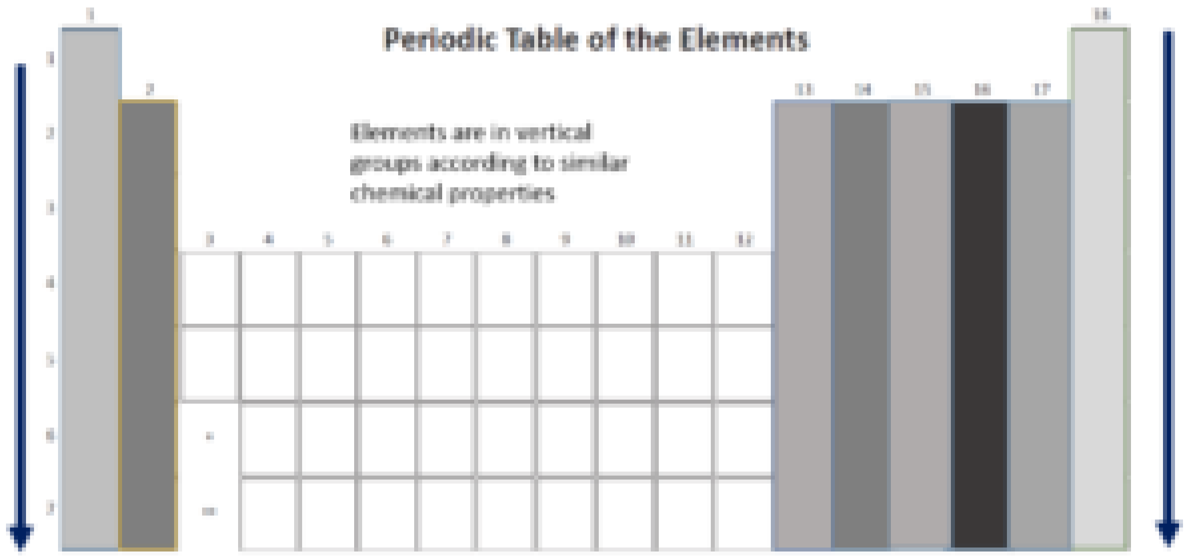


Figure 2: Vertical columns on the periodic table are called groups

Elements were placed in groups (columns) according to an increasing atomic number and in periods (rows) because they have similar chemical properties. The characteristics of each group are mostly determined by the electron configuration of the atoms of the elements in the group. A period is a horizontal row in the periodic table of the elements. The periods are labelled from top to bottom, starting with 1 and ending with 7.

Atomic radius, electronegativity, and ionisation energy

Ionisation energy is the energy needed to remove one electron from an atom in the gas phase. The ionisation energy is different for each element. The first ionisation energy is the energy needed to remove the first electron from an atom.

Electronegativity is the tendency of atoms to attract electrons. The electronegativity of the elements starts from about 0.7 (francium (Fr)) and goes up to 4 (fluorine (F)).

The atomic radius is a measure of the size of an atom.

Periods

Let's take a closer look at the periods in the periodic table.

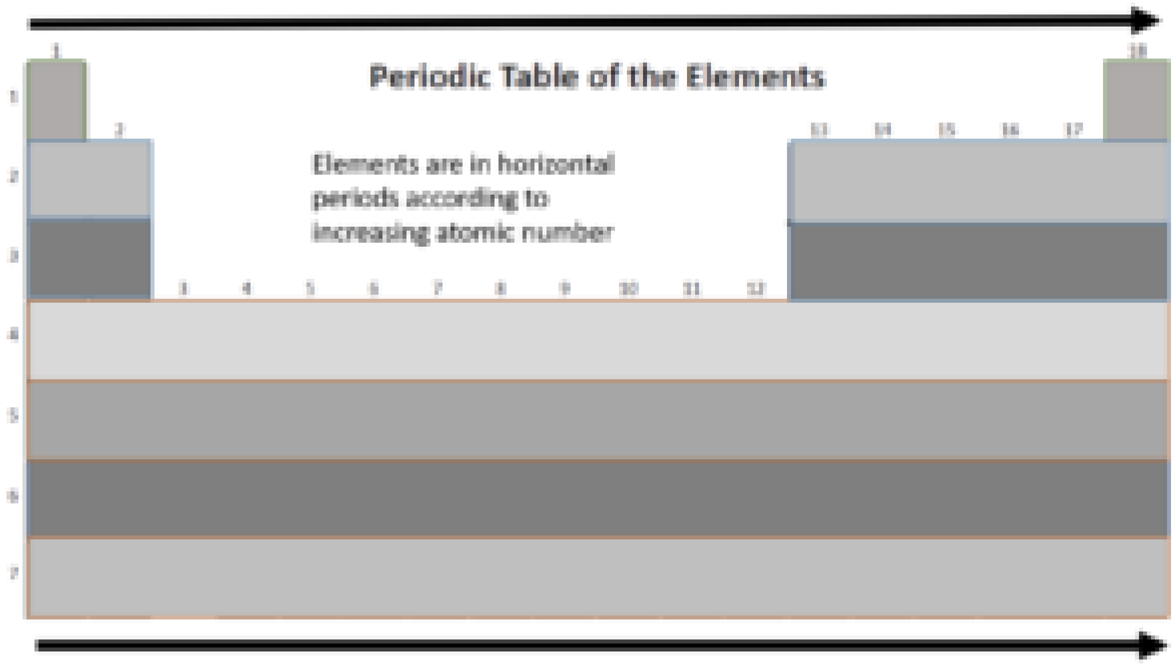


Figure 3: Horizontal rows on the periodic table are called periods

As you travel from left to right across a period, electronegativity and ionisation energy increase, and the atomic radius of an element decreases.

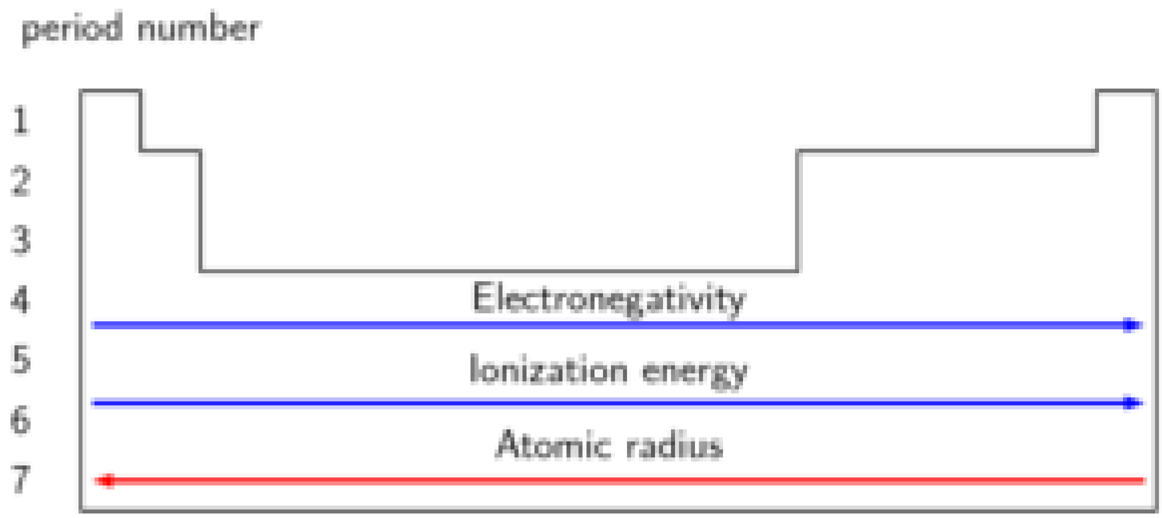


Figure 4: Electronegativity and ionisation energy increase from left to right, and the atomic radius of an element decreases.

Let's look at period 3 of the periodic table:

Group	1	2	13	14	15	16	17
Element	Sodium	Magnesium	Aluminium	Silicon	Phosphorus	Sulfur	Chlorine
Atomic radius	Decreases across a period.						
First ionisation energy	The general trend is an increase across the period.						
Electronegativity	Increases across the period.						
Melting and boiling point	Increases to silicon and then decreases to argon.						
Electrical conductivity	Increases from sodium to aluminium. Silicon is a semi-conductor. The rest are insulators.						

Groups

Let's take a closer look at the groups in the periodic table.

As you move down a group, the atomic radius and density of the element increase but the electronegativity and ionisation energy decrease.

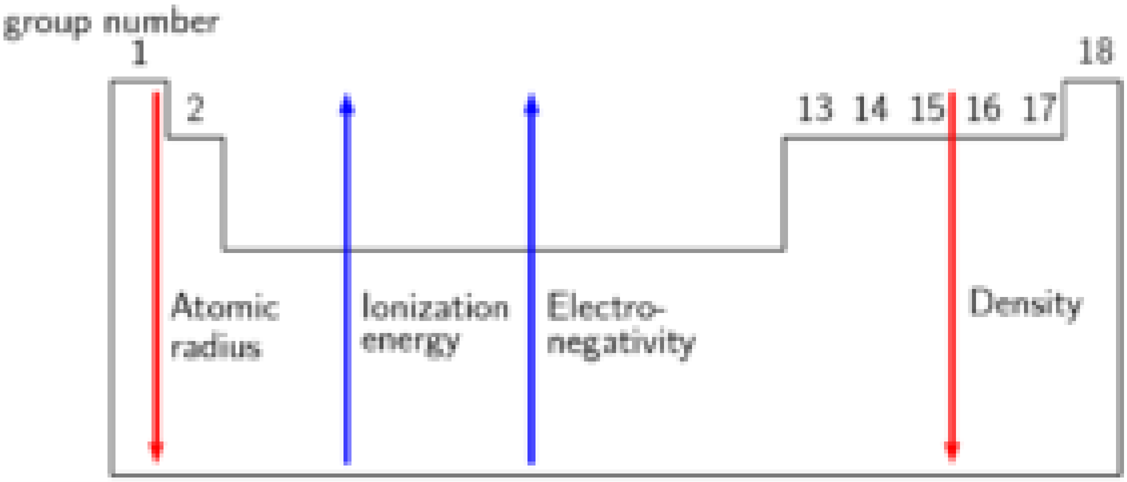


Figure 5: The atomic radius and density of the element increases from top to bottom, but the electronegativity and ionisation energy decreases.

Let's look at Group 1 of the periodic table:

Period	2	3	4	5	6
Element	Lithium	Sodium	Potassium	Rubidium	Caesium
Atomic radius	Increases as you move down the group.				
First ionisation energy	Decreases as you move down the group.				
Electronegativity	Decreases as you move down the group.				
Melting and boiling points	Decrease as you move down the group.				
Density	Increases as you move down the group.				

Please note that hydrogen is not included in the above table because it is a non-metal gas and not an actual member of Group 1. Francium has not been included because it is an extremely rare element.

Note

For further explanation on periods and groups you can watch this video:
Fuse Schools: Periods and groups in the periodic table (Duration: 2.53).

Exercise 1.1

1. Give one word or term for each of the following:
   a. The energy that is needed to remove one electron from an atom
   b. A row on the periodic table
   c. A column on the periodic table
2. Which of the following are denser:
   a. lithium or potassium?
   b. boron or tin?
3. Atomic radius and density have a trend in common. What is it?
4. The following data table gives the ionisation energy and atomic number (Z) for a number of elements in the periodic table:

Z	Name of element	Ionisation energy (kJ mol^{-1})	Z	Name of element	Ionisation energy (kJ mol^{-1})
1		1310	10		2072
2		2360	11		494
3		517	12		734
4		895	13		575
5		797	14		783
6		1087	15		1051
7		1397	16		994
8		1307	17		1250
9		1673	18		1540

   Copy the table into your notebook and complete the following:
   a. Fill in the names of the elements.
   b. Draw a line graph, with atomic number on the x-axis and ionisation energy on the -y axis.
   c. Describe any trends you can see.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- Elements are arranged in periods and groups in the periodic table. The elements are arranged from

left to right according to increasing atomic number.
- A group is a column on the periodic table containing elements with similar properties.
- A period is a row on the periodic table.
- The atomic radius is a measure of the size of the atom.
- The first ionisation energy is the energy needed to remove one electron from an atom in the gas phase.
- Electronegativity is the tendency of atoms to attract electrons.
- Across a period, the ionisation energy and electronegativity increase. The atomic radius decreases across a period.
- The atomic radius and the density both increase down a group. The ionisation energy, electronegativity, and melting and boiling points all decrease down a group.

Unit 1: Assessment

Suggested time to complete: 45 minutes

1. Magnesium and calcium are both found in Group 2 of the periodic table. Compare these elements in terms of the following properties and explain the differences in each case.
   a. Size of the atom (atomic radius)
   b. Electronegativity
   c. First ionisation energy
   d. Boiling point
2. Compare bromine and chlorine in terms of the following properties. Explain the differences in each case.
   a. Atomic radius
   b. Electronegativity
   c. First ionisation energy
   d. Boiling point
3. State the difference between a period and a group.
4. Give one word or term for each of the following:
   a. The energy that is needed to remove one electron from an atom.
   b. A horizontal row on the periodic table.
   c. A very reactive group of elements that is missing just one electron from their outer shells.
5. Look at the following table:

Element	NA	Mg	Al	Si	P	S	Cl	Ar
Atomic number	11	12	13	14	15	16	17	18
Density (g·cm−3)	0.97	1.74	2.70	2.30	1.82	2.08	3.17	1.78
Melting point (℃)	370.9	923	933.5	1687	3173	388.4	171.6	83.8
Boiling point (℃)	1156	1363	2792	3538	550	717.8	239.1	87.3
Electronegativity	0.93	1.31	1.61	1.90	2.19	2.58	3.16	–

Draw line graphs to show the patterns in the following physical properties:

a. Density
b. Boiling point
c. Melting point
d. Electronegativity

The full solutions are at the end of the unit.

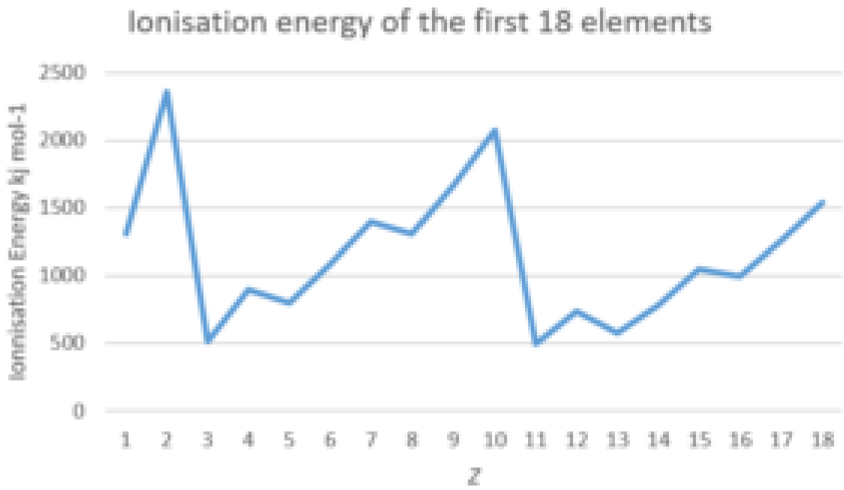
Unit 1: Solutions

Exercise 1.1

1.
    a. First ionisation energy
    b. Period
    c. Group
2.
    a. Potassium
    b. Tin
3. They both decrease as you go down a group.
4.
    a.

Z	Name of element	Ionisation energy (kJ mol^{-1})	Z	Name of element	Ionisation energy (kJ mol^{-1})
1	Hydrogen	1310	10	Neon	2072
2	Helium	2360	11	Sodium	494
3	Lithium	517	12	Magnesium	734
4	Beryllium	895	13	Aluminium	575
5	Boron	797	14	Silicon	783
6	Carbon	1087	15	Phosphorus	1051
7	Nitrogen	1397	16	Sulfur	994
8	Oxygen	1307	17	Chlorine	1250
9	Fluorine	1673	18	Argon	1540

    b.

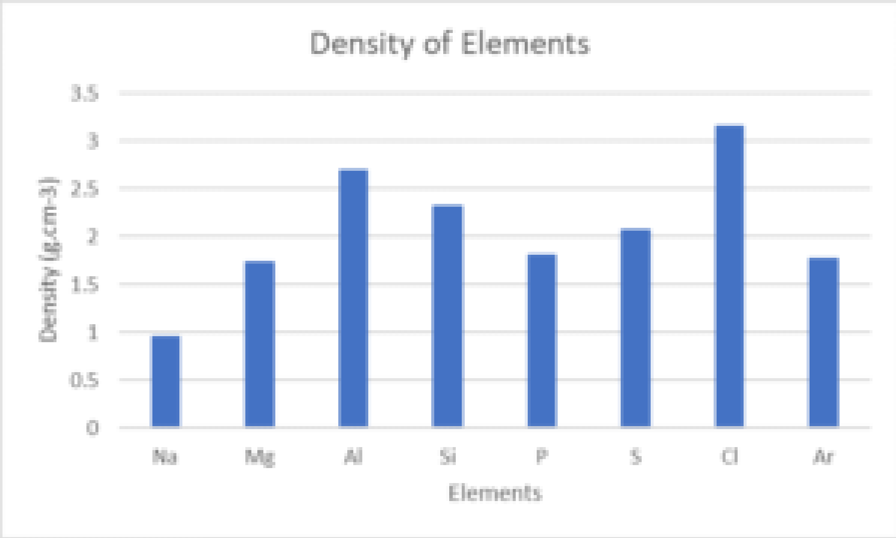


c. Ionisation energy is higher for non-metals than metals. It increases as you move across a period, then decreases at the start of a new period.

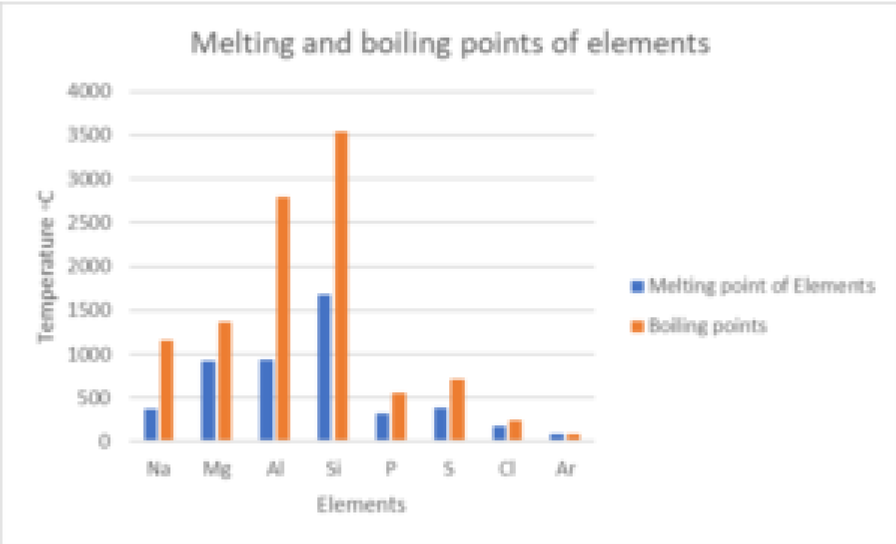
Back to Exercise 1.1

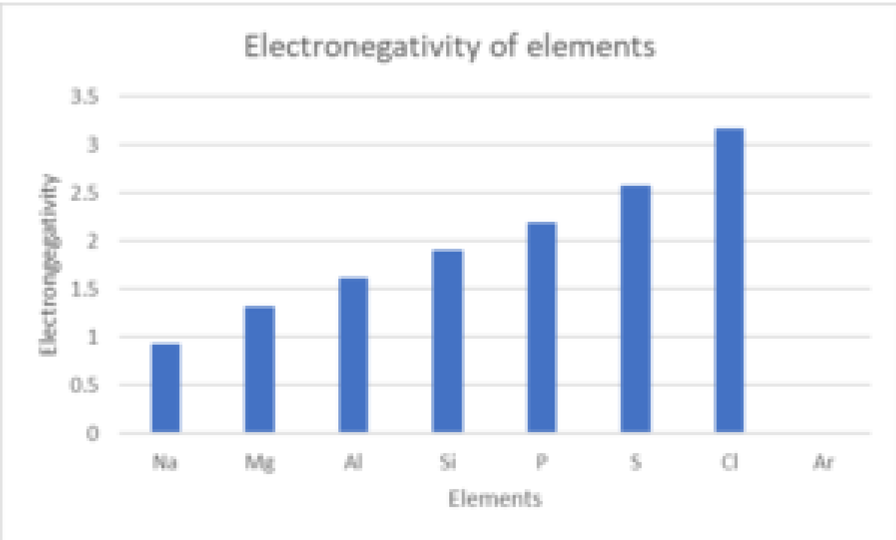
Unit 1: Assessment

1. Calcium has a bigger atomic radius
   a. Calcium's is lower
   b. Calcium's is lower
   c. Calcium's is lower
2.
   a. Chlorine's is larger
   b. Chlorine's is higher
   c. Chlorine's is higher
   d. Chlorine's is higher
3. A period is a row and a group is a column.
4.
   a. First ionisation energy
   b. Period
   c. Group 17 The Halogens
5.
   a.



b. and c.





[Back to Unit 1: Assessment](#)

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Unit 2: Electron configuration

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Arrange electrons into core and valence electrons and write electron configuration of first 20 elements.
- Write the electron configuration for the first 20 elements.

What you should know:

Before you start this unit, make sure you can:

- Confidently complete all the work in Subject outcome 5.2, Unit 2: Atomic number and atomic mass.
- Confidently complete all the work in Subject outcome 5.3, Unit 1: The periodic table.

Introduction

In this unit you will learn to arrange the first 20 elements into groups of core and valence electrons and write their electron configurations. The first 20 elements start at hydrogen (H) and continue vertically across the table until you reach calcium (Ca). They are called the first 20 elements because of their atomic number.

Electron configuration

As we learnt in SO 5.2 Unit 2: Atomic number and atomic mass, each element is made up of atoms which differ from each other because they have a different number of electrons, protons, and neutrons. The number of protons in a neutral atom of an element is called the atomic number.

If you look at the periodic table in Figure 1, you will see that there is a number above each element. Remember this is the atomic number. The number at hydrogen is 1, which means that it has 1 electron and 1 proton. If you look at copper (Cu), its atomic number is 29, which means that it has 29 electrons and 29 protons.

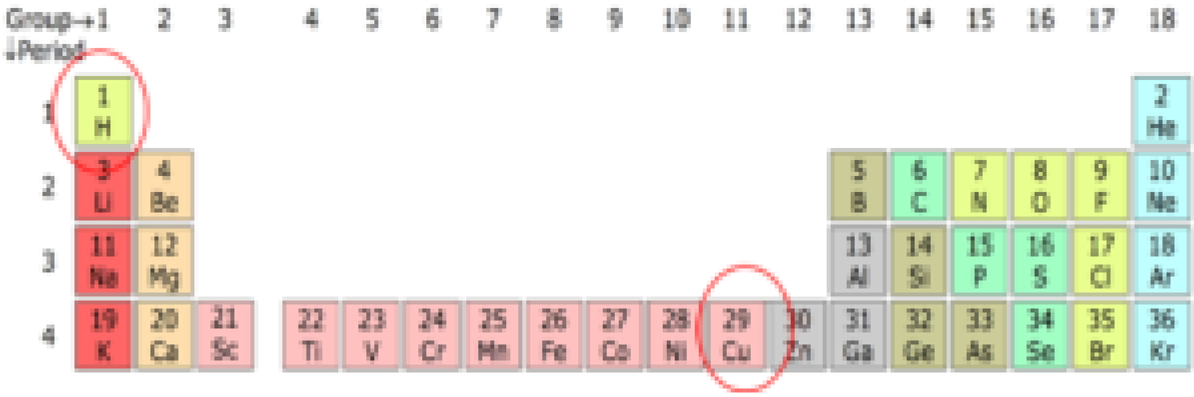


Figure 1: The periodic table showing the atomic number above each element.

Electron configuration is the way electrons are arranged around the nucleus.

We start with a simple view of the arrangement or configuration of electrons around an atom. This view simply states that electrons are arranged in energy levels (or shells) around the nucleus of an atom. The period number of an electron tells us how many electron shells it has:

- hydrogen is in period so it will only have 1 electron shell.
- potassium is in period 4 so it will have 4 electron shells.

These energy levels are numbered 1, 2, 3, 4, etc.

The number of electrons an element has on its outer most shell is given by the group number for Groups 1 and 2,and is 10 minus the group number for Groups 13 to 17. For example, calcium has 2 electrons because it is in Group 2 and oxygen, which is in Group 16, has $16 – 10 = 6$. This means it has 6 electrons on its outermost shell.

Core and valence electrons

Electrons in the outermost energy level of an atom are called valence electrons. The electrons that are in the energy shells closer to the nucleus are called core electrons. Core electrons are all the electrons in an atom, excluding the valence electrons. An element that has its valence energy level full is more stable and less likely to react than other elements with a valence energy level that is not full.

Core electrons closest to the nucleus have the lowest energy. Electrons further away from the nucleus have a higher energy.

The Importance of electron configuration

During chemical reactions, when atoms come into contact with one another, it is the electrons of these atoms that will interact first. More specifically, it is the valence electrons of the atoms that will determine how they react with one another.

An atom is at its most stable and therefore unreactive when all its orbitals are full. An atom is least stable (and therefore most reactive) when its valence electron orbitals are not full.
The valence electrons are largely responsible for an element's chemical behaviour and elements that have the same number of valence electrons often have similar chemical properties.

The most stable elements are the ones that have full energy levels. These configurations occur in Group 18 elements, otherwise known as the noble gases. The noble gases are very stable elements that do not react easily with any other elements. This is due to their full energy levels. All elements would like to reach the most stable electron configuration, in other words, all elements want to be noble gases.

This principle of stability is sometimes referred to as the octet rule. An octet is a set of 8, and the number of electrons in a full energy level is 8.

Elements are placed in groups because of their electron configuration. Group 1 metals have 1 electron on their outer shell, Group 2 elements have 2 electrons on their outer shell which they will lose easily when bonding to become ions. Group 17 elements need one electron, Group 16 needs 2 electrons to have a full outer shell. The noble gases, Group 18, are very unreactive and stable because their shells are full.

Note

Here are some key points to remember:

Electron configuration diagrams are drawn as concentric circles around the nucleus and only show the electrons in each level. Electrons are usually drawn in pairs.

The first energy level can hold 2 electrons, the second energy level can hold 8 electrons, the third level can hold 8 and the fourth can hold 2. So, it goes $2, 8, 8, 2$.

Elements want to have a stable electron configuration. They will either gain or lose valence electrons, so they can have either 2 or 8 electrons in their outer most energy shell.

Example 1

Lithium (Li) has an atomic number of 3, meaning that in a neutral atom, the number of electrons will also be 3. Lithium has two energy levels; it is found in Group 2. The first two electrons are found in the first energy level, while the third electron is found in the second energy level so, its electron configuration is $2, 1$.

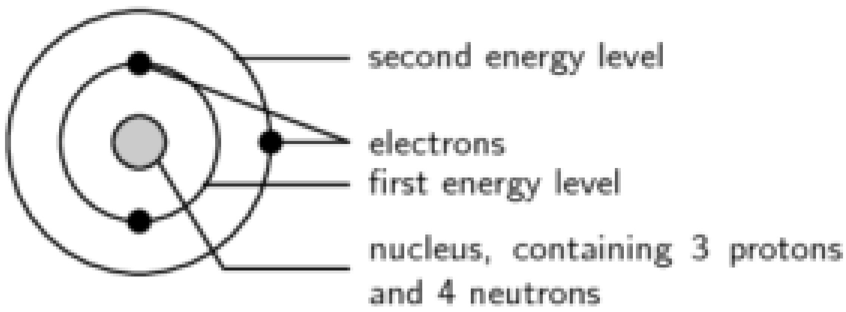


Figure 2: A shell diagram showing the energy levels and the electrons which are in each shell for lithium.

Fluorine is in period 2 so it will have two energy levels and in Group 17. The first 2 electrons are found in the first energy level, while the other 7 are found in the second energy level.
This can be written as $2, 7$.

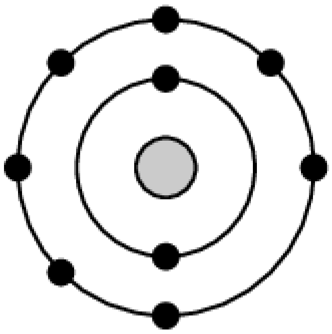


Figure 3: Fluorine (F) has an atomic number of 9, meaning that a neutral atom also has 9 electrons.

Neon is in period 2 which means that it has 2 energy levels, and 8 electrons on its outermost energy level. The first 2 electrons are found in the first energy level and the last 8 are found in the second energy level. This can be written as $2, 8$.

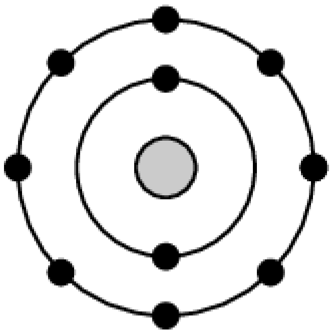


Figure 4: Neon (Ne) has an atomic number of 10, meaning that a neutral atom also has 10 electrons.

Calcium is in period 4 so it will have 4 energy levels and its electron configuration is $2, 8, 8, 2$.

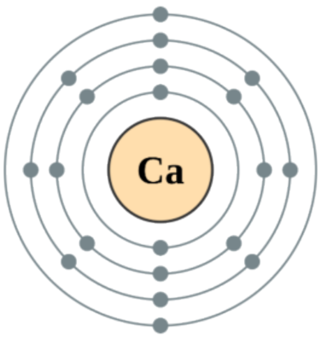


Figure 5: Calcium has the atomic number 20.

Exercise 2.1

1. Copy and complete the following table by writing the electron configuration for each element:

Element	Symbol	Atomic Number	Electron Configuration
Beryllium			
			$2, 6$
	C	6	
		19	
	Ne		
Phosphorus			

2. Draw shell diagrams showing the electron arrangement of the following elements:
   a. Nitrogen (N)
   b. Oxygen (O)
   c. Potassium (K)

The full solutions are at the end of the unit.

Summary

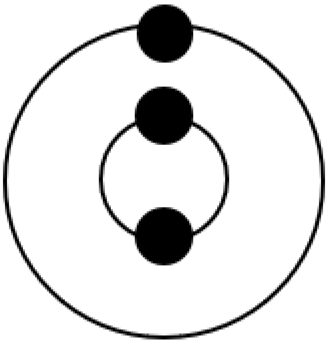
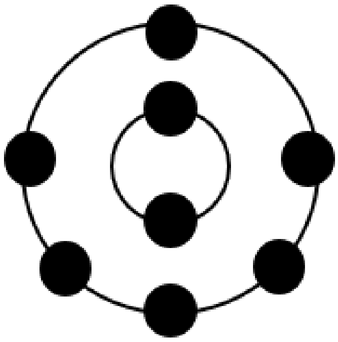
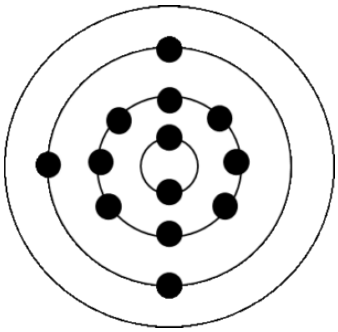
In this unit you have learnt the following:

- Electron configuration is the arrangement of electrons in energy shells.
- The electrons in the outermost energy level are called valence electrons.
- The electrons in an atom that are not valence electrons are called core electrons.
- Atoms with an outermost energy level that is full are less chemically reactive, and therefore more stable, than those atoms with an outermost energy level that is not full.

Unit 2: Assessment

Suggested time to complete: 30 minutes

1. Copy the table below into your notebook and complete it:

		Element	Group	Period	Electron configuration	Stable/ unstable
a.						
b.						
c.						

2. Copy the table below into your notebook and complete it:

Element	Number of energy levels	Number of electrons	Number of core electrons	Number of valence electrons
Mg				
N				
S				
C				

3. Draw diagrams to show the valence electrons on the outer most energy level for the elements in Question 2.

The full solutions are at the end of the unit.

Unit 2: Solutions

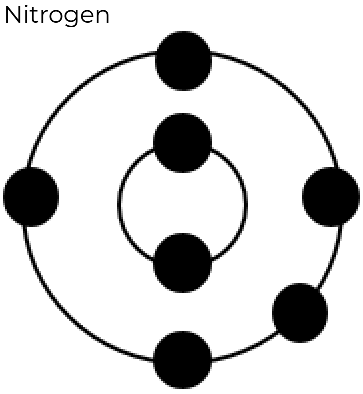
Exercise 2.1

1.

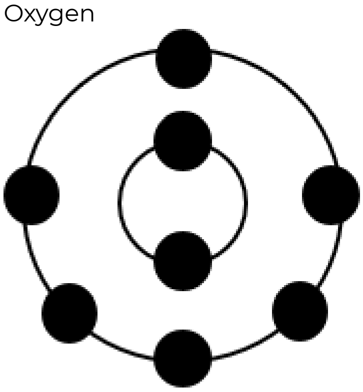
Element	Symbol	Atomic Number	Electron Configuration
Beryllium	Be	4	$2, 2$
Oxygen	O	8	$2, 6$
Carbon	C	6	$2, 4$
Potassium	K	19	$2, 8, 8, 1$
Neon	Ne	10	$2, 8$
Phosphorus	P	15	$2, 8, 5$

2.

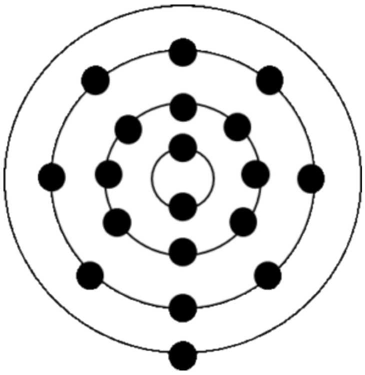
a. Nitrogen



b. Oxygen



c. Potassium



[Back to Exercise 2.1]

Unit 2: Assessment

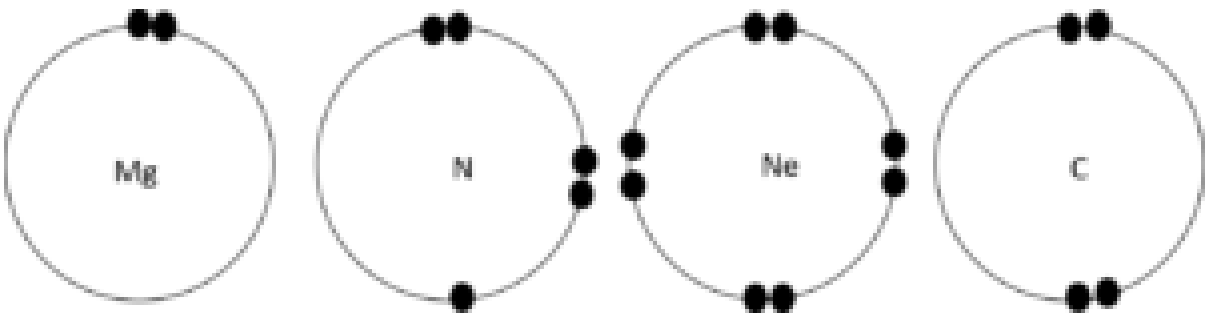
1.

Element	Group	Period	Electron configuration	Stable/unstable
Lithium	1	2	$2, 1$	unstable
Oxygen	16	2	$2, 6$	unstable
Aluminium	13	3	$2, 8, 3$	unstable

2.

Element	Number of energy levels	Number of electrons	Number of core electrons	Number of valence electrons
Mg	3	12	10	2
N	2	7	2	5
S	3	16	10	6
C	2	6	2	4

3.



Back to Unit 2: Assessment

Unit 3: The behaviour of elements in specific groups

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Give the names of groups 1, 2, 7 and 0 and identify the transition metal group.
- Predict the activity of elements in their groups.
- Recognise where the metals and non-metals are on the periodic table.

What you should know:

Before you start this unit, make sure you can:

- Recognise the arrangement of atoms in the periodic table according to atomic number and Identify and describe group, period, and periodicity in Subject outcome 5.3, Unit 1: The periodic table.

Introduction

In this unit you will learn about groups 1, 2, 17 and 18 on the periodic table and the transition metals. Groups 1 and 2 are metals and their reactivity increases as you go down the group. For example, lithium is less reactive in water than potassium. The transition metals are all very stable and include relatively well-known elements like iron, gold, and silver. Group 17 and Group 18 are non-metals, and their reactivity decreases as you go down the group, so iodine is less reactive than chlorine.

Note

On some periodic tables, the groups are labelled from Group 1 to Group 8. This numbering does not include the transition metals. Numbering of the groups which includes the transition metals from Group 1 to Group 18 is used in these books.

As we learnt in SO 5.3 Unit 1, the arrangement of the periodic table and the properties of each element in it is based on the atomic number and the arrangement of the electrons orbiting the nucleus.

Specific groups on the periodic table

Many of the groups have been given names, for example Group 1 is called the alkali metals, Group 2 the alkali earth metals, Group 18 is called the noble gases and Group 17 is called the halogens. Elements are placed in a group because they share similar behaviours and bond with other elements in a similar configuration. Elements in the same group share similar properties. The properties of elements can be predicted based on their location in the group.

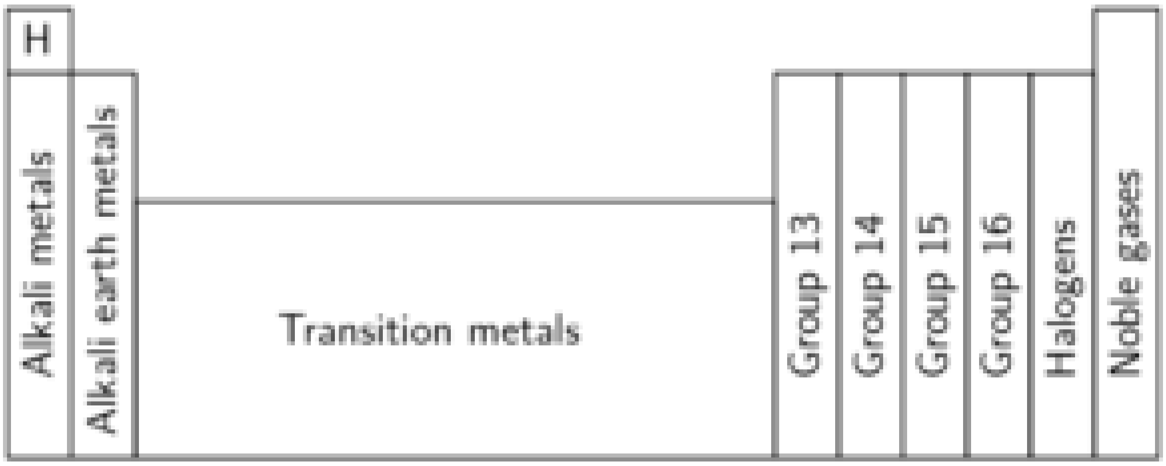


Figure 1: The group names on the periodic table; metals are on the left-hand side of the table and non-metals are on the right-hand side.

The alkali metals

If we look at Group 1, the alkali metals, the first three elements are lithium, sodium, and potassium. All three are soft, shiny metals and react with oxygen in the air. Lithium burns with a red flame, sodium with a yellow flame and potassium with a purple flame. These elements are stored in oil or paraffin to stop them from reacting with air. All three of these elements react vigorously with water.

Figure 2: Lithium metal stored in paraffin.

Note

To see the reactions of alkali metals with water you can watch this video:
Scott Milmam: Alkali metals reacting with water. (Duration: 3.16)

The alkali earth metals

Group 2 elements, the alkali earth metals, include beryllium, magnesium, and calcium. All three will react with oxygen, but only calcium reacts readily with water. Magnesium reacts with steam but not water.

Figure 3: Calcium metal

Note

The reactivity of elements in Group 1 and Group 2 increases as you go down the group. Caesium is the most reactive of all the metals and beryllium is the least reactive of the metals in Groups 1 or 2.

Note

For further explanation and to further understand some reactions of Group 2 you can watch this video: [Fuse Schools: What is Group 2?](#) (Duration: 5.30)

The transition metals

The transition metals are found in the middle of the periodic table. Transition metals have several general properties. They are harder and less reactive than the alkali earth metals. They make colourful chemical compounds with other elements. Like other metals, they are electrical conductors. Some of the transition metals are necessary in trace amounts for good health, such as iron and zinc. Gold and silver are commonly used as jewellery because they are hard, malleable, and shiny.

Figure 4: Over a R24 billion worth of gold was mined in South Africa in 2019

Mercury is the only metal element that is a liquid at room temperature. It is heavy and dense, and it is highly toxic in large amounts. Mercury is most commonly used in fluorescent lamps and used to be used in thermometers and tooth fillings.

Figure 5: Mercury is a silver liquid

The halogens

The most reactive group of non-metals are the halogens in Group 17. Fluorine is the most reactive. It is a highly toxic, yellow gas at room temperature. It is the most electronegative element, so it is highly reactive.

Figure 6: Fluorine

Figure 7: Chlorine

Chlorine is a dense, toxic green gas at room temperature. Chlorine will bleach anything it comes into contact with. Compounds of chlorine are used in cleaning products and chemicals for swimming pools. Table salt, NaCl, consists of sodium and chlorine.

Bromine is a red-brown liquid at room temperature and is the only non-metal found in a liquid state at room temperature. It is highly reactive and toxic in large amounts.

Note

For further explanation and to further understand some reactions of Group 7, you can watch this video: [Fuse Schools: Group 7 – The halogens] (Duration: 5.30).

The noble gases

Group 18 contains the noble gases. These are inert, stable elements because they have full outer shells. Helium is probably the most well-known noble gas because it is used in balloons. Helium is less dense than air, so this enables helium-filled balloons to float. If the gas is inhaled, then it changes your voice as you speak! Neon is used in electric signage and lighting.

Figure 8: Neon street signs

Note

For further explanation on the different groups in the periodic table you can watch this video: [Fuse Schools: Periods and Groups in the periodic table] (Duration: 2.53).

The activity of elements

To understand the activity of the various elements, we need to revise ionisation energy, atomic radius, and electronegativity.

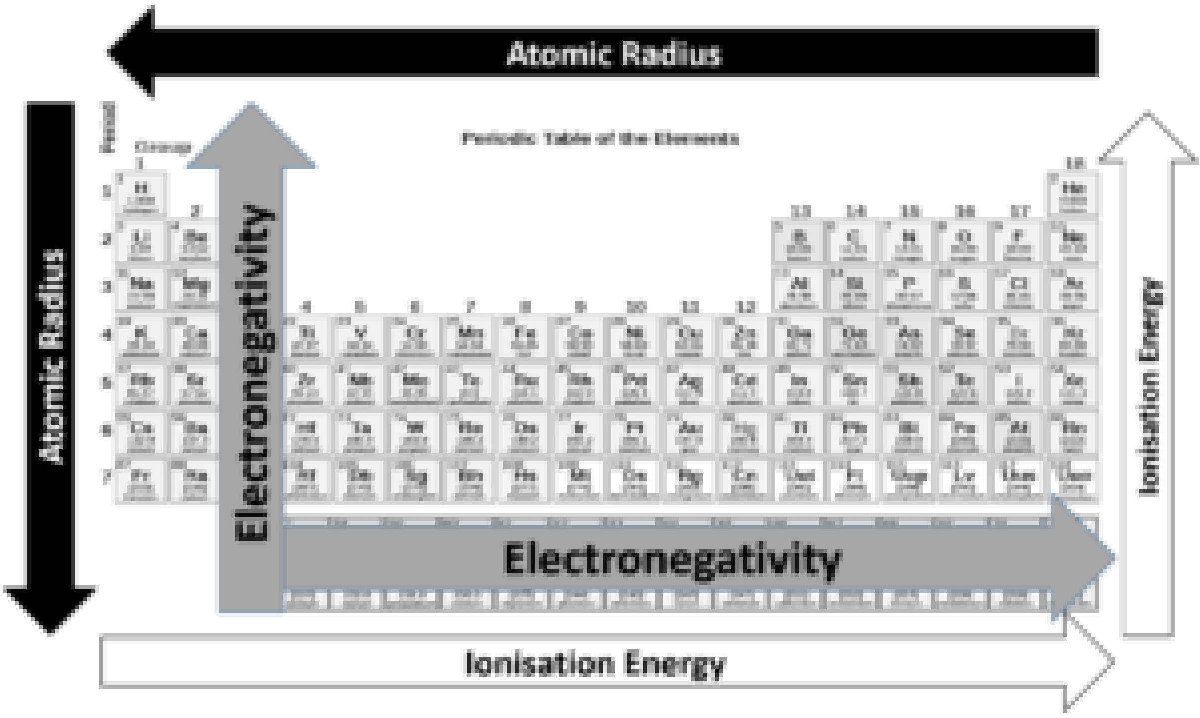


Figure 9: The periodic table showing the directions of ionisation energy, atomic radius, and electronegativity.

Going down the groups, the atomic radius increases, and the amount of energy needed to remove an outer electron decreases because the electrons are further from the nucleus and not held as tightly. This is important because how elements interact and react with each other depends on their ability to lose and gain electrons to make new compounds.

Moving from the left side of the periodic table to the right, the atomic radius decreases because each element has one additional proton and one additional electron. More protons means that electrons are pulled in more tightly towards the nucleus. This is the reason electronegativity increases from left to right.

The ionisation energy also increases from the left-hand side of the periodic table to the right. Metals tend to have a lower first ionisation energy level than non-metals, which means they will lose their valence electrons more readily.

Electronegativity decreases from the top of the column to the bottom. The melting point of the elements within a group also decreases from the top to the bottom of a group.

Reactivity refers to how likely or vigorously an element is to react with other substances, and this is usually determined by the element's ionisation energy and its electronegativity. Elements with high electronegativity will be very reactive, as will elements with low ionisation energy.

The reactivity of metals

As previously stated, the reactivity of metals in Group 1 and Group 2 increases down the group. The alkali metals are very reactive and there is a difference in the reactivity between sodium and caesium. Caesium has a lower ionisation energy and a lower electronegativity, so it is very reactive. Sodium has a greater ionisation energy than caesium, so it is not as reactive as caesium, but it is still very reactive.

If you consider the information in Table 1, you can see that the energy needed for caesium to lose its valence electron is lower than that of sodium. Therefore, caesium is more reactive than sodium. Its electronegativity is also lower because elements with a low ionisation energy will also have a lower electronegativity.

Element	**Group number**	**Period**	**Valence electrons**	**First ionisation energy KJ. Mol^{-1}**	**Electronegativity**
Caesium	1	6	1	375.7	0.78
Sodium	1	3	1	495.8	0.93
Lithium	1	2	1	520.2	0.98
Beryllium	2	2	2	899.5	1.57

Table 1: The ionisation energy of certain metals

The reactivity of the more common metals are shown in Figure 10:

Figure 10: The reactivity series

The reactivity of non-metals

Non-metals are more reactive as you travel up the group; oxygen is more reactive than sulfur and chlorine is more reactive than iodine. Non-metals generally have a higher electronegativity and first ionisation energy than metals.

Element	Group number	Period	First ionisation energy KJ. Mol^{-1}	Electronegativity
Hydrogen	–	1	1312	2.20
Fluorine	17	2	1681	3.98
Chlorine	17	3	1251.2	3.16
Bromine	17	4	1139.9	2.96
Helium	18	1	2372.3	–
Neon	18	2	2080.7	–
Argon	18	3	1520.6	–

Table 2: The electronegativity of certain non-metals

You will see in Table 2 that there is no electronegativity listed for the three noble gases. This is because they are chemically inert.

Summary

In this unit you have learnt the following:

- The groups on the periodic table are labelled from 1 to 18. Group 1 is known as the alkali metals, Group 2 is known as the alkali earth metals, Group 17 is known as the halogens and Group 18 is known as the noble gases.
- The elements in a group have similar properties.
- Metal groups are more reactive as you move down the group, so potassium is more reactive than lithium, and calcium is more reactive than beryllium.
- Non-metals are less reactive as you go down the group. For the metals (Groups 1 to 13) the melting and boiling points increase as you go up the group. For the non-metals, the melting and boiling points decrease as you go up the group.

Unit 3: Assessment

Suggested time to complete: 20 minutes.

1. Refer to the following list of elements:
   Lithium (Li), Chlorine (Cl), Magnesium (Mg), Neon (Ne), Oxygen (O), Calcium (Ca), Carbon (C)
   Which of the elements listed:
   a. belongs to Group 1?
   b. is a halogen?
   c. is a noble gas?
   d. is an alkali metal?
   e. has an atomic number of 12?
   f. has all its energy orbitals full?
   g. will have chemical properties that are most similar?
2. Are the following statements true or false? If they are false, correct the statement.
   a. The Group 1 elements are sometimes known as the alkali earth metals.

b. The Group 18 elements are known as the noble gases.
c. Group 7 elements are very unreactive.
d. The transition elements are found between Groups 3 and 4.

3. Lithium, sodium and potassium are the first three elements in Group 1. Explain why these three elements are in the same group.
4. Using the information in the following table, list the elements in order of most reactive to least reactive:

Element	Group number	Period	First ionisation energy KJ. Mol^{-1}	Electronegativity
Oxygen	16	2	1313.9	3.44
Sulfur	16	3	999.6	2.58
Fluorine	17	2	1681	3.98
Chlorine	17	3	1251.2	3.16
Bromine	17	4	1139.9	2.96

The full solutions are at the end of the unit.

Unit 3: Solutions

Unit 3: Assessment

1.
   a. Lithium
   b. Chlorine
   c. Neon
   d. Lithium
   e. Magnesium
   f. Neon
   g. Calcium and magnesium
2.
   a. False. Group 1 are called the alkali metals.
   b. True
   c. False. Group 7 are very reactive elements.
   d. False. The transition elements are found between Groups 2 and 13.
3. They have similar chemical properties and react in similar ways with water and oxygen.
4.
   Fluorine
   Chlorine
   Oxygen
   Bromine
   Iodine
   Sulfur

Back to Unit 3: Assessment

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SUBJECT OUTCOME XIII

MATTER AND MATERIALS: IDENTIFY AND DESCRIBE PARTICLES

Subject outcome

Subject outcome 5.3: Identify, describe and apply properties of the periodic table

Learning outcomes

- Identify and define atoms, ions and molecules (simple and giant).
- Identify, define and give examples (in all three phases) of pure substances: elements and compounds.
- Identify, define and give examples (using all three phases) of mixtures: heterogeneous and homogeneous (refer also to alloys).
- Identify and describe intermolecular bonding referring to covalent, ionic and metallic bonding.
- Explain macroscopic properties in terms of chemical bonding (microscopic properties).
- Name and write chemical formulae of generally used substances.

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify and define:
  - an atom
  - an ion
  - a molecule.

Unit 2 outcomes

By the end of this unit you will be able to:

- Identify, define, and give examples of:
  - a pure substance

- an element
- a compound
- a mixture
- a homogenous mixture
- a heterogenous mixture
- an alloy.

Unit 3 outcomes

By the end of this unit you will be able to:

- Identify, define and give examples of:
  - a covalent bond
  - an ionic bond
  - a metallic bond.
- Explain the macroscopic and microscopic properties of bonding.
- Name and write chemical formulae for common substances like:
  - water
  - sodium chloride
  - carbon dioxide
  - sulphuric acid.

Unit 1: Particles

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Identify and define:
  - an atom
  - an ion
  - a molecule.

What you should know:

Before you start this unit, make sure you can:

- Confidently complete all the work in Subject outcome 5.2.
- Confidently complete all the work in Subject outcome 5.3.

Introduction

In this unit you will learn to identify and define an atom, an ion, and a molecule. An atom is the simplest form of matter and an ion forms when an atom loses or gains an electron. A molecule is made up of two or more atoms joined together and can either become a compound or remain an element.

Atoms

In Unit 1 of SO 5.2, we learnt about atoms. An atom is the smallest form of matter and is made up of electrons, protons and neutrons. The negatively charged electrons orbit the nucleus of the atom. Protons are positively charged particles and neutrons are neutral particles, and they are found in the nucleus of an atom.

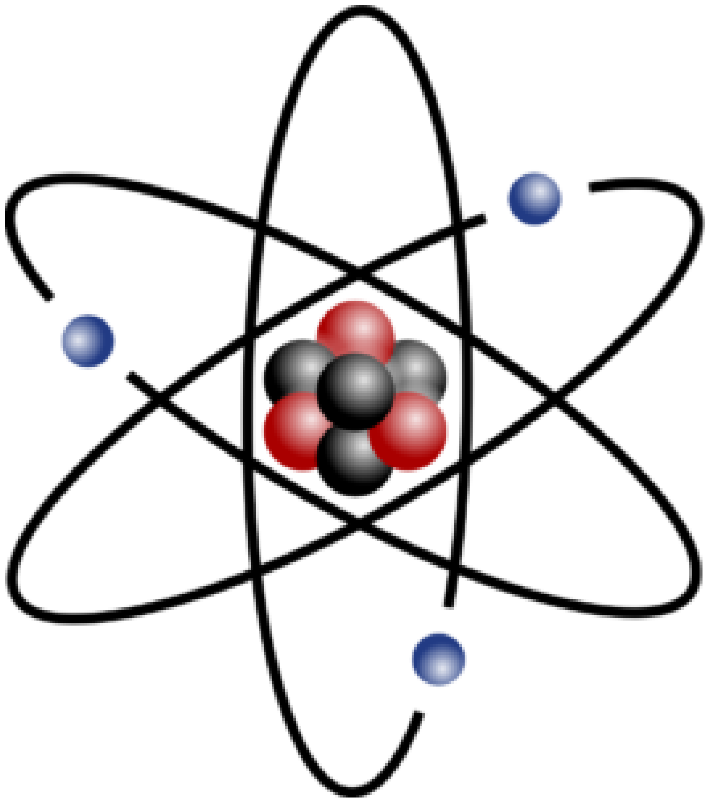


Figure 1: An atom of lithium with 3 electrons shown in blue, 3 protons shown in red and 4 neutrons shown in black.

Each atom of an element has the same number of protons and electrons. The number of protons is the atomic number. For a neutral atom, the number of electrons is the same as the number of protons, as the charge on the atom must balance. For example, each atom of the element carbon has 6 protons, 6 electrons and 6 neutrons. Lithium has 3 protons, 3 electrons and 4 neutrons.

Ions

During chemical bonding, atoms will lose or gain valence electrons. This does not change the type of atom it is, but it changes the charge of the atom. If electrons are added, then the atom will become more negative. If electrons are taken away, then the atom will become more positive. The atom that is formed in either of these two cases is called an ion. An ion is a charged atom.

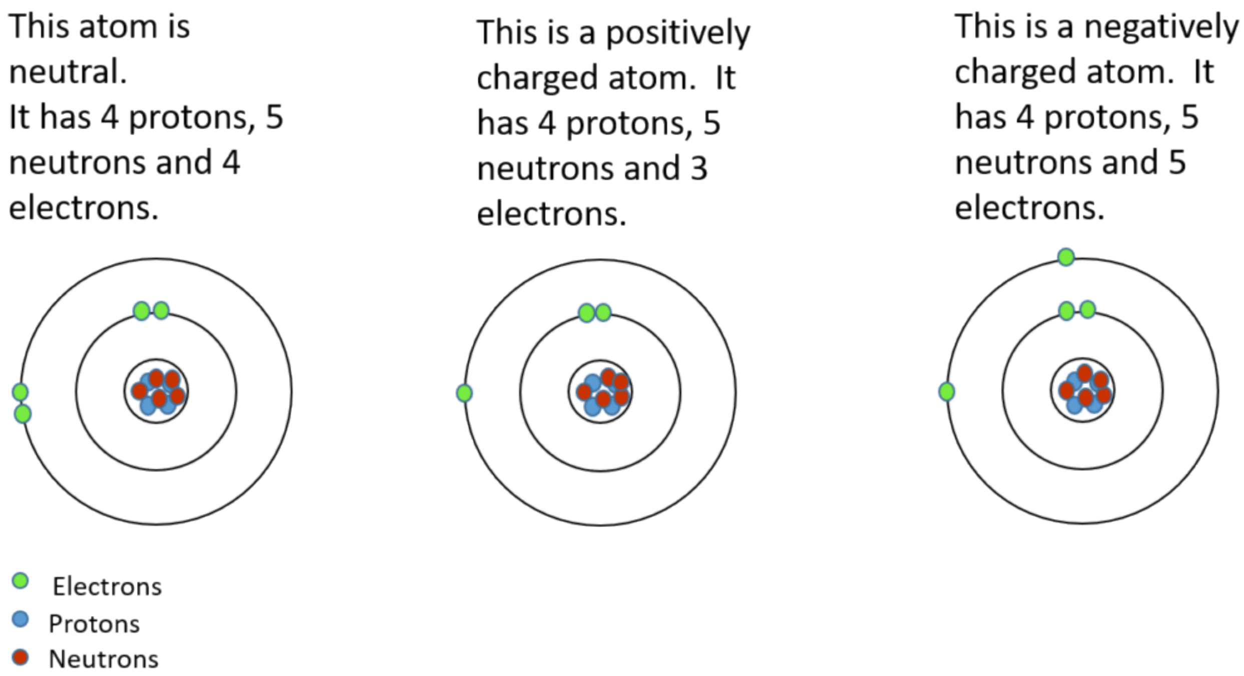


Figure 2: A positively charged ion has lost an electron and a negatively charged ion has gained an electron.

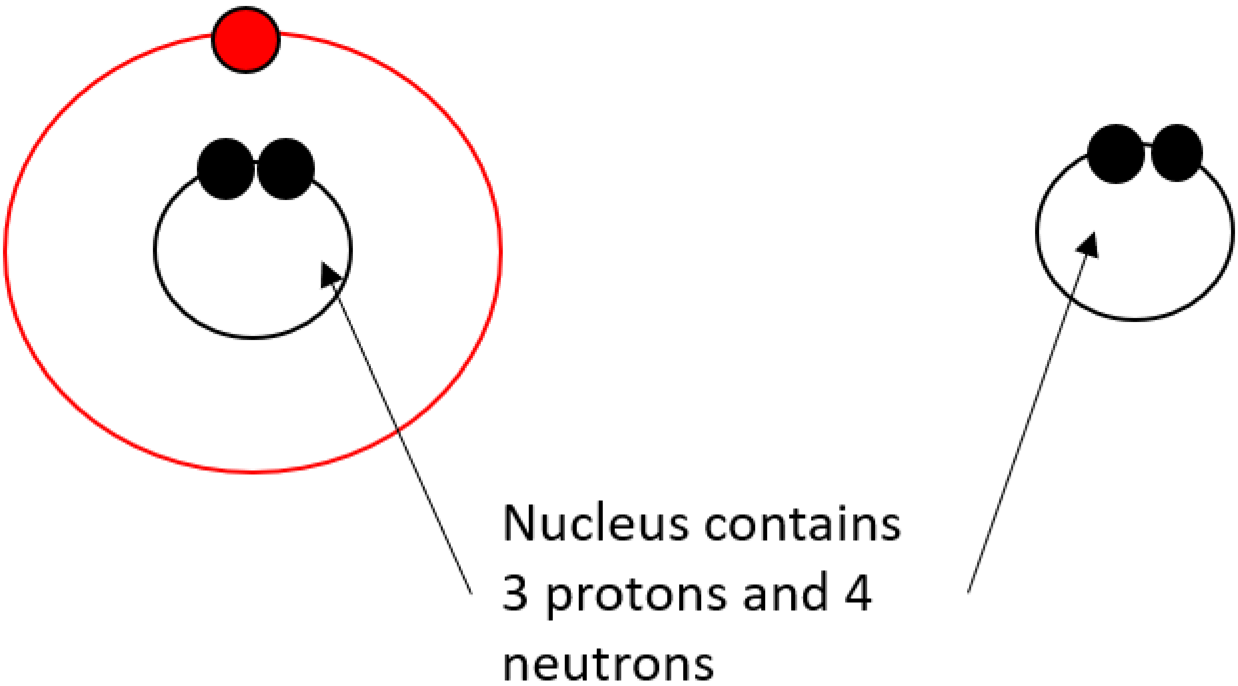


Figure 3: A neutral lithium atom loses one electron to become a positively charged lithium ion, Li+

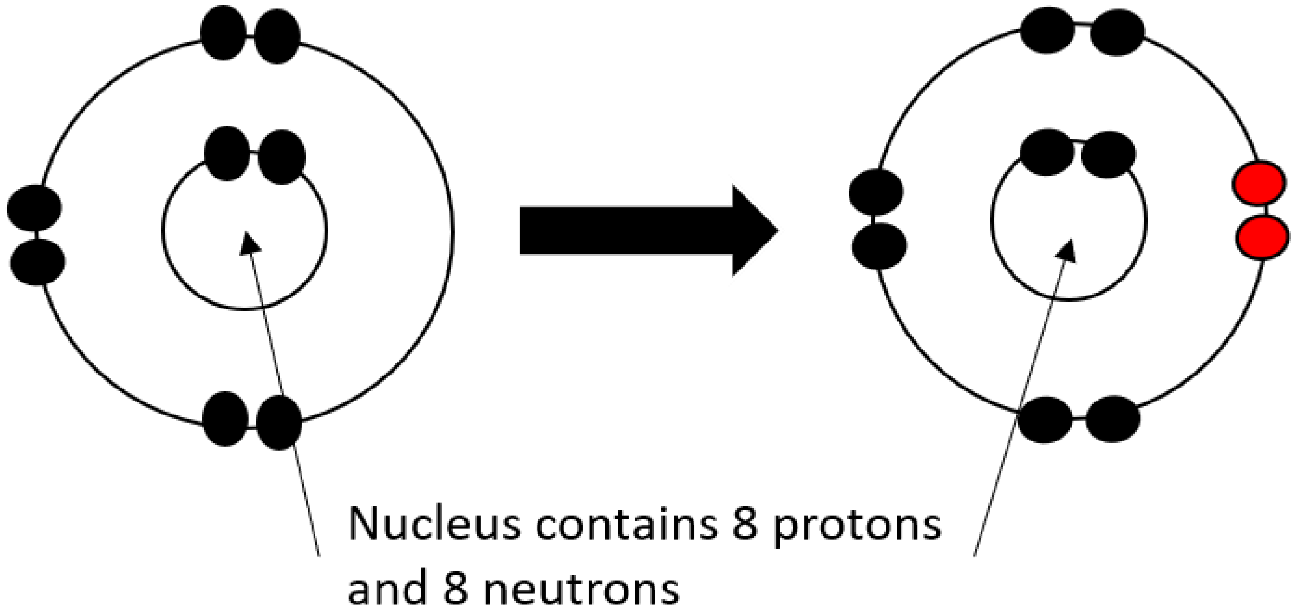


Figure 4: A neutral oxygen atom gains two electrons to become a negatively charged oxygen ion, O2-

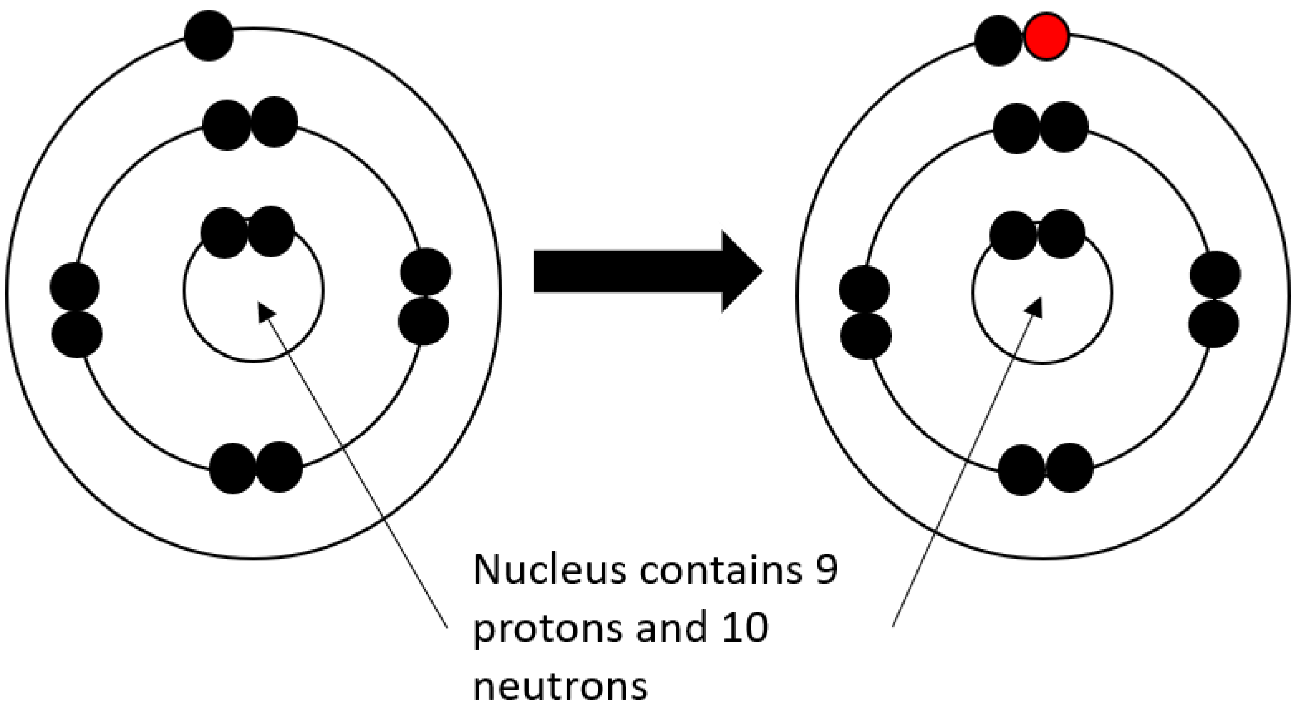


Figure 5: This Florine ion, F–, has gained one electron and now has 10 electrons instead of 9

Activity 1.1: Build an ion

Time required: 15 minutes

What you need:

- an internet connection

What to do:

You will build ions online using a program.

1. Go to this Build an Atom simulation and click on the 'Build an atom' game.
2. Click on Atom on the home screen.
3. Add 3 electrons, 3 protons, and 4 neutrons to the shells to create a lithium atom.
4. Remove an electron to create a lithium ion with a positive charge, Li+.
5. Add 8 neutrons, 8 protons and 8 electrons to the shells to create an oxygen atom.
6. Remove 2 electrons to create an O2- ion.
7. Repeat this process for the following elements:
   a. Na
   b. F
   c. Mg
   d. B

Exercise 1.1

1. Which of the following elements are ions?
   a. Be
   b. Mg^{2+}
   c. O^{2-}
2. Write a definition for an ion.
3. Describe the difference between an atom and an ion.

The full solutions are at the end of the unit.

Molecules

A molecule can be defined as two or more atoms bonded together. A molecule does not have a charge. A molecule can be made up of the same element or different elements.

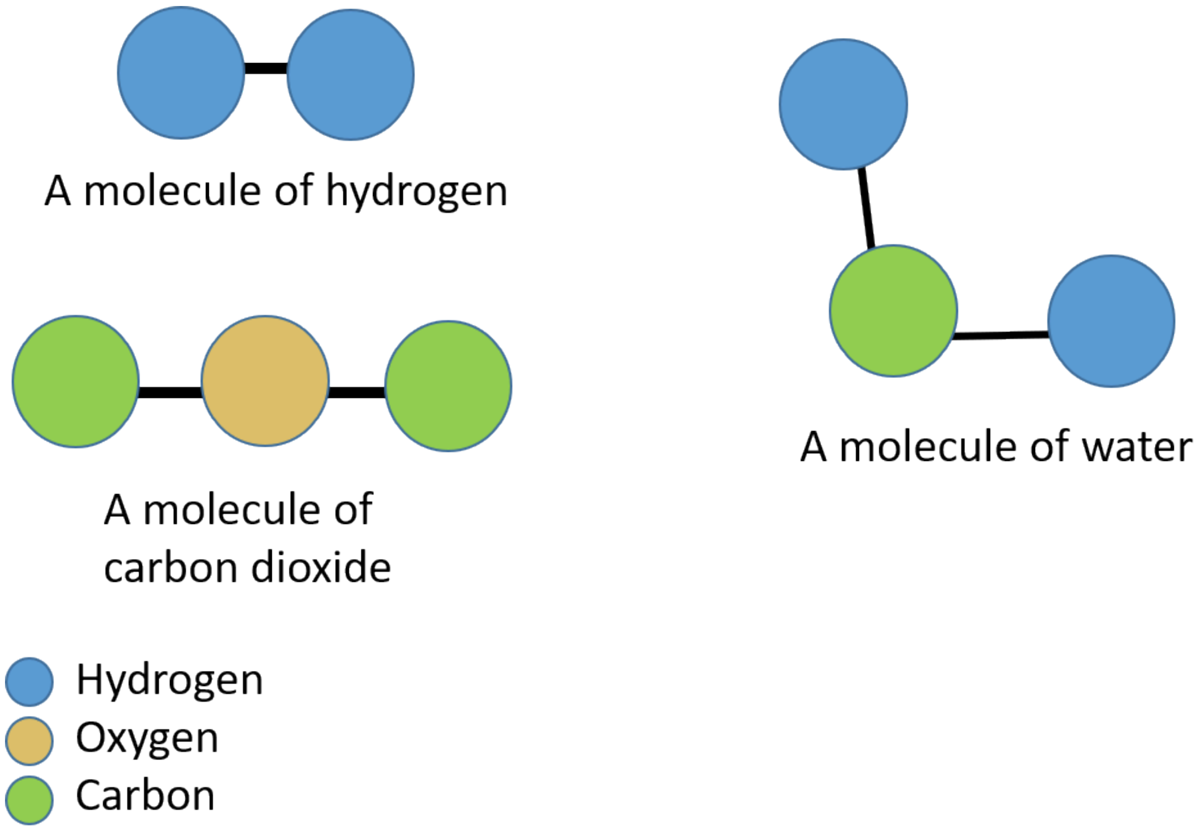


Figure 6: Examples of different molecules

In Figure 6 you can see molecules of hydrogen, water and carbon dioxide. The hydrogen molecule is made up of two hydrogen atoms. The carbon dioxide molecule is made up of one carbon atom and two oxygen atoms. The water molecule is made up of one oxygen atom and two hydrogen atoms.

There are seven elements which naturally form molecules and are called diatomic elements. They are all non-metals and most of them are halogens. These are shown in Figure 7.

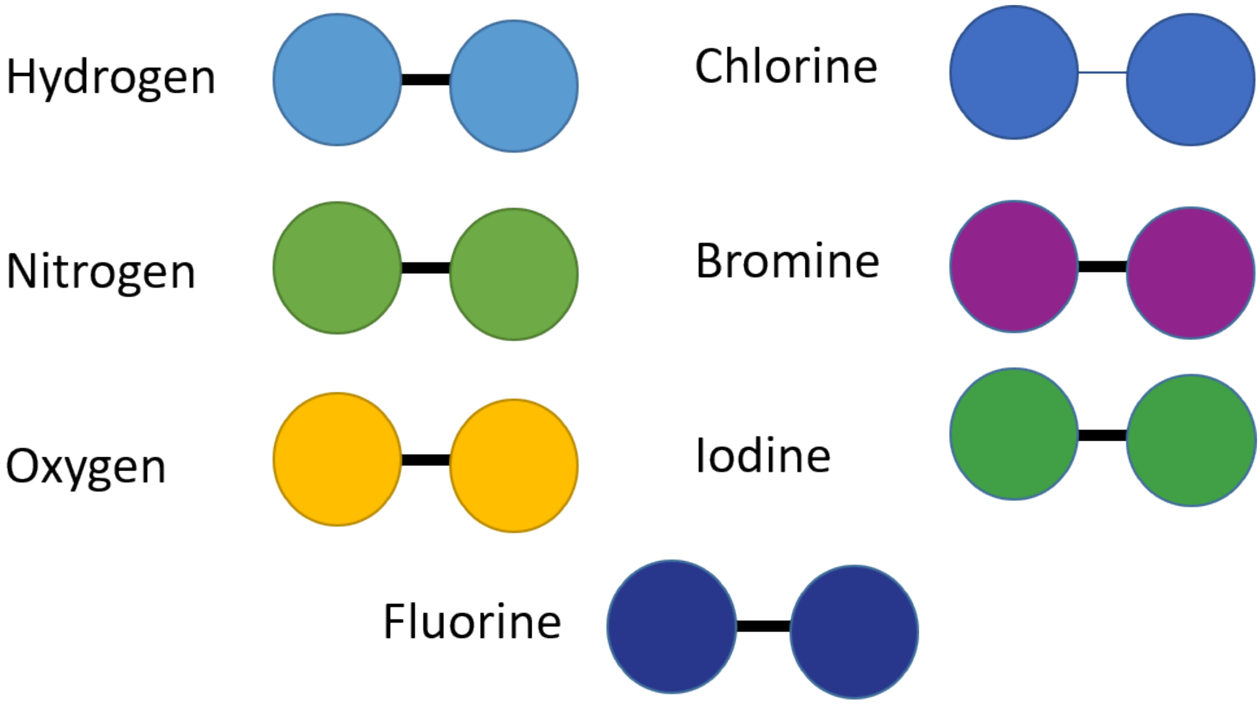


Figure 7: The seven naturally occurring diatomic elements

Activity 1.2: Building molecules

Time required: 15 Minutes

What you need:

- an internet connection

What to do:

1. Go to this Build a Molecule simulation and click on the 'Build a molecule' game.
2. Open the 'Make Molecules' tab.
3. With kit 1, build a hydrogen molecule using the atoms provided and drag it into the hydrogen window on the right.
4. Select kit 2 by pressing the yellow arrow on the bottom and make a molecule of water and drag it into the correct window.
5. Select kit 3 and make molecules of carbon dioxide and nitrogen.
6. Click on 'collect multiple' on the top row and complete the molecules.

Summary

In this unit you have learnt the following:

- Atoms are the most basic form of matter and are made up of electrons, protons and neutrons.
- If an atom loses or gains electrons to gain a stable electron configuration, it is called an ion.
- If an atom gains electrons it will have an overall negative charge.
- If an atom loses electrons it will have an overall positive charge.
- A molecule is made up of two or more atoms joined together. These atoms can be atoms of the same element or atoms of different elements. If they are made of the same elements, they are called diatomic elements.

Unit 1: Assessment

Suggested time to complete: 10 minutes

1. Ions are:
   a. atoms with a positive or negative charge
   b. atoms with no charge
   c. atoms with ONLY a positive charge
   d. atoms with ONLY a negative charge
2. If an element has 3 valence electrons, what charge will likely form on its ion? Hint: It will lose those electrons. What happens to the charge when it loses 3 electrons?
   a. +3
   b. +5
   c. -3
   d. -5
3. Molecules are made up of more than one ________.
   a. electron
   b. proton
   c. atom
   d. element
4. What is the name given to a molecule made up of two atoms of the same element?

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 1.1

1. b and c – because they have a positive charge or a negative charge.
2. An ion is an atom which has either gained or lost electrons. It will have a positive charge if it has lost electrons or a negative change if it has gained electrons.

3. An atom has a neutral charge because it has the same number of electrons and protons. An ion has the same number of protons and neutrons as when it was a neutral atom, but has either gained or lost electrons giving it a charge.

Back to Exercise 1.1

Unit 2: Assessment

1. a – ions are atoms with a positive or negative charge
2. a – the charge becomes +3 when it loses 3 electrons.
3. c – atom
4. diatomic elements

Back to Unit 1: Assessment

Media Attributions

Unit 2: Elements, mixtures, and compounds

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Identify, define, and give examples of:
  - a pure substance
  - an element
  - a compound
  - a mixture
  - a homogenous mixture
  - a heterogenous mixture
  - an alloy.

What you should know:

Before you start this unit, make sure you can:

- Identify an atom, ion and a molecule in Subject outcome 5.4, Unit 1: Particles.

Introduction

You will learn to identify, define, and give examples of pure substances that are either elements or compounds, and other substances called mixtures. Mixtures can either be homogenous or heterogenous, in other words, they are either uniform in appearance or not. Alloys are mixtures made up of particular metals and form homogenous mixtures. Brass and steel are examples of alloys.

Elements, compounds, and mixtures

All the objects that we see in the world around us are made of matter. Matter makes up the air we breathe, the ground we walk on, the food we eat and the animals and plants that live around us. Even our bodies are made of matter. Matter can be separated into two different groups, mixtures, and pure substances.

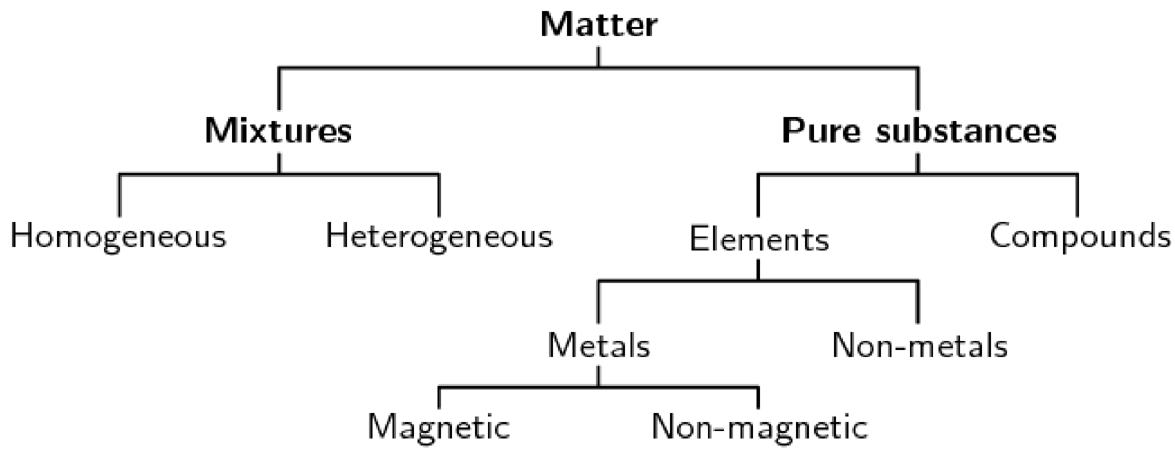


Figure 1: Matter can be separated into two main groups: mixtures and pure substances

Elements and compounds are pure substances, which means that they are not mixtures. Pure substances are substances that are made up of only one kind of particle and have a fixed composition.

- Elements are the most basic form of matter. They are made up of one type of atom and cannot be broken down into anything simpler.
- Compounds are made from two or more elements which are chemically joined together. Although compounds can be separated, it is very difficult to do so.
- Mixtures are made up of elements and/or compounds that are not chemically joined together and are easily separated. A mixture can either be homogenous or heterogenous.

Common elements, mixtures and compounds are listed in Table 1.

Elements	**Mixtures**	**Compounds**
Gold	Sea water	Water
Oxygen	Crude oil	Carbon dioxide
Lead	Canned soft drinks	Acetic acid (vinegar)
Silver	Air	Sodium chloride (table salt)
Mercury	Steel	Iron oxide (rust)
Iron	Wine	Hydrochloric acid

Table 1: Examples of common elements, mixtures, and compounds

Elements

Elements are chemical substances that cannot be divided or changed into other chemical substances by any ordinary chemical means. The smallest unit of an element is the atom. Figure 2 shows a particle diagram of an element.

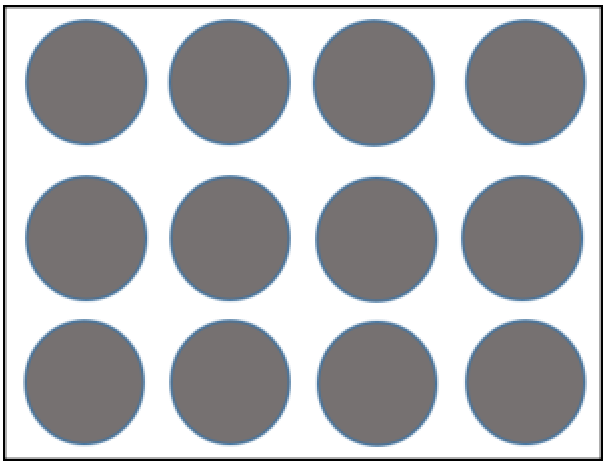


Figure 2: Particle diagram of an element

There are 118 known elements. Most of these are natural, but some are man-made.

As we have previously learnt in SO 5.3 Unit 1, elements are found on the periodic table and have a chemical symbol, for example Oxygen (O) and Calcium (Ca).

Compounds

A compound is a chemical substance that forms when two or more different elements combine in a fixed ratio. An important characteristic of a compound is that it has a chemical formula, which describes the ratio in which the atoms of each element in the compound occur.

Carbon dioxide has the formula CO_2 and is made up of one carbon atom and two oxygen atoms.

Ethanoic acid, which is more commonly known as vinegar, is made up of two carbon atoms, four hydrogen atoms and two oxygen atoms.

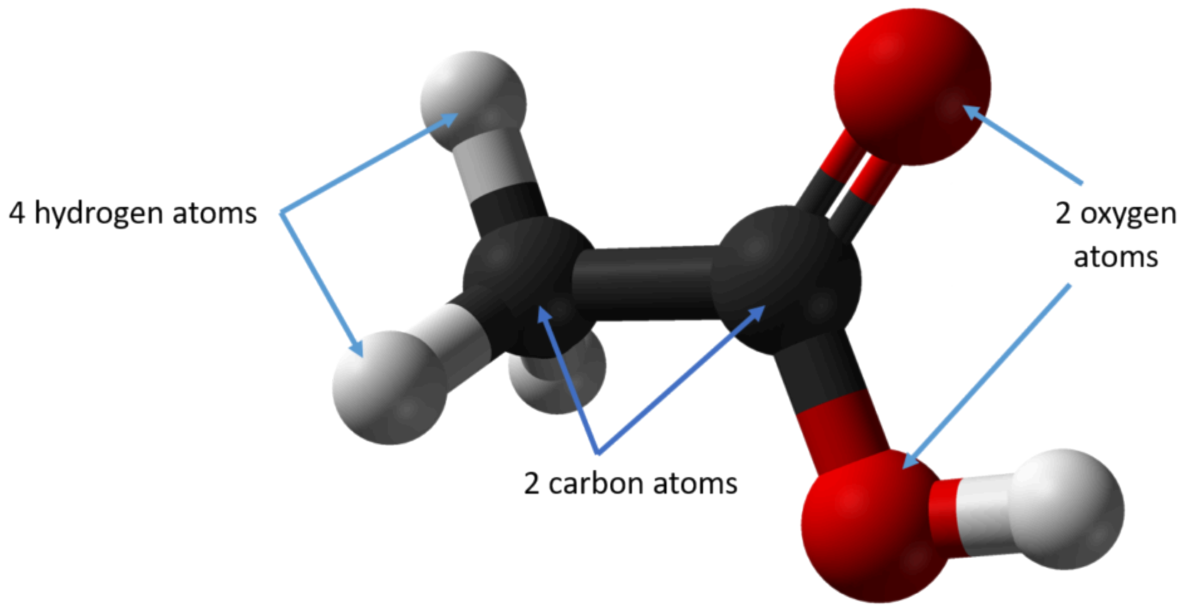


Figure 3: Ethanoic acid is made up of 2 carbon atoms, 4 hydrogen atoms and 2 oxygen atoms.

Water is a compound and is made up of two hydrogen atoms for every one oxygen atom.

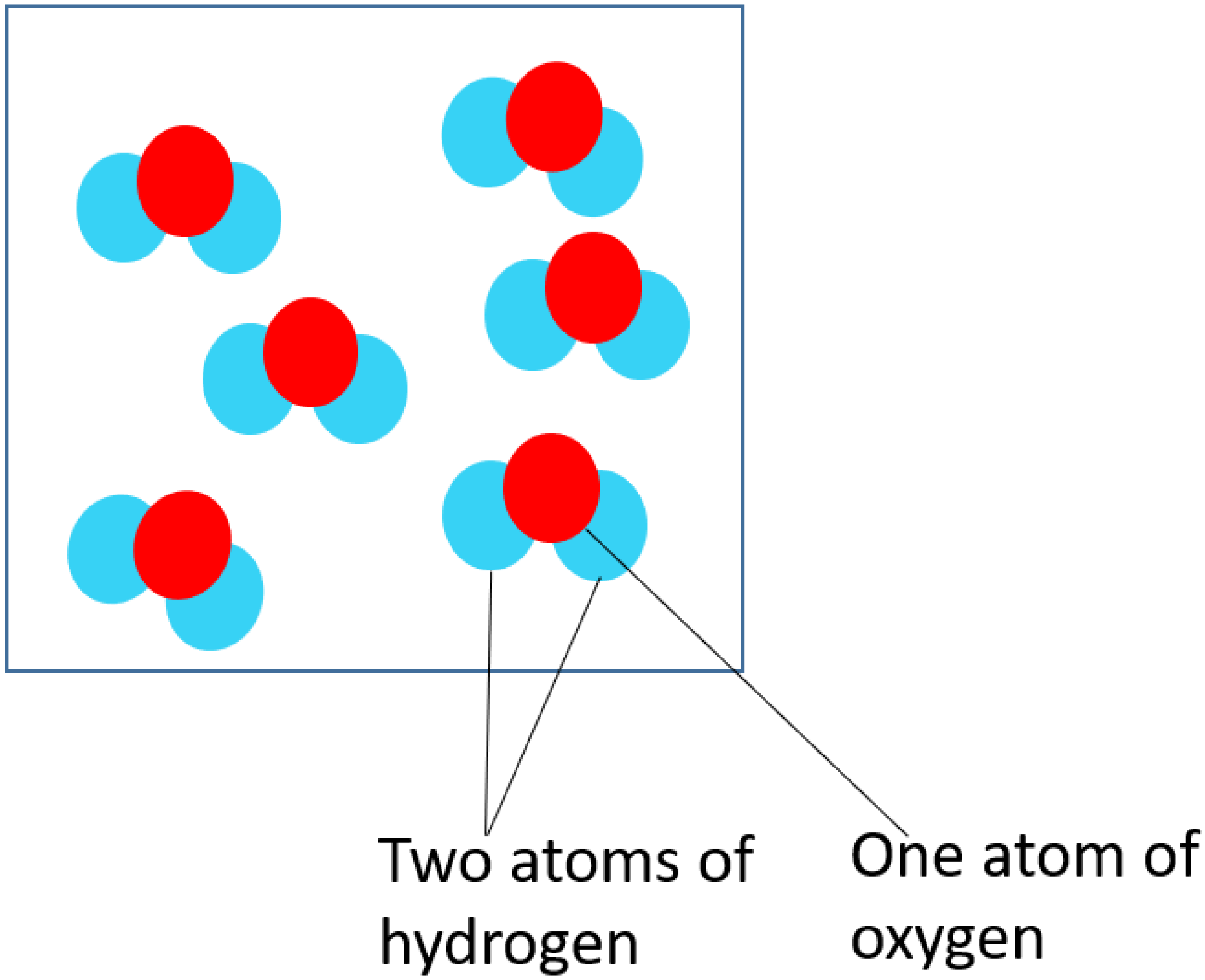


Figure 4: Water has the chemical formula H20

Sodium chloride is a compound made up of one sodium atom for every chlorine atom.

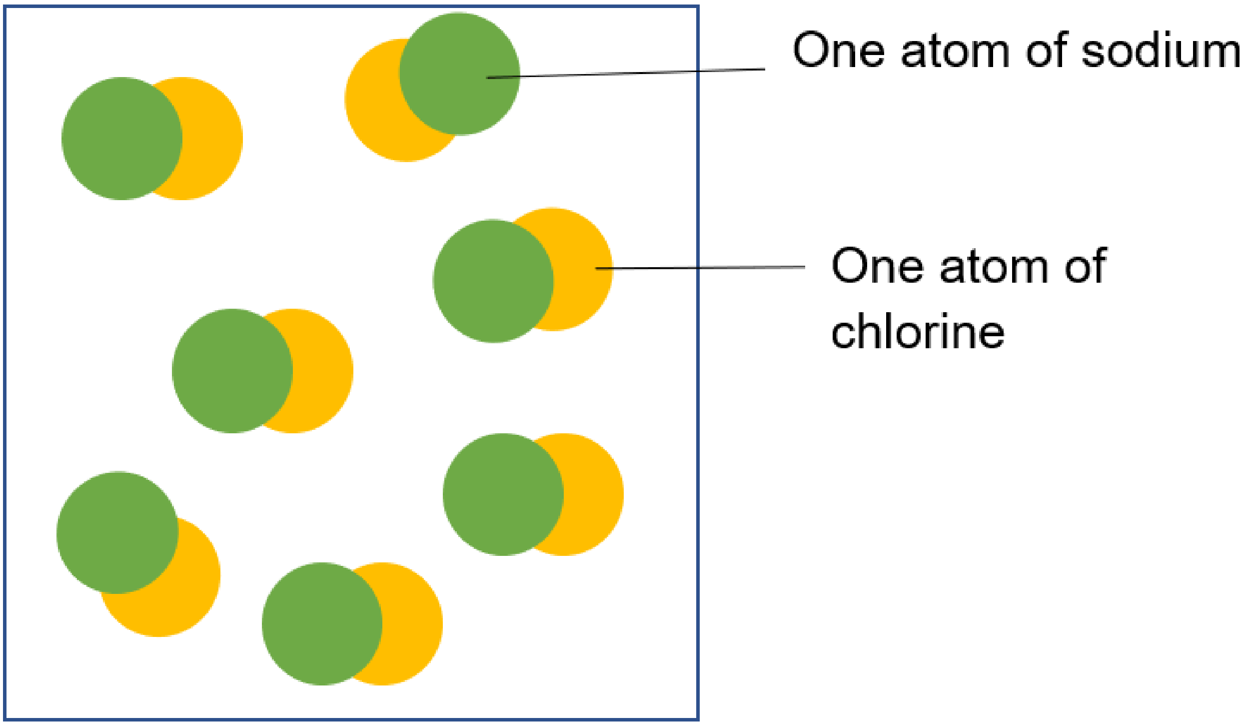


Figure 5: Sodium chloride has the chemical formula NaCl

Mixtures

A mixture is a substance which is made up of elements and/or compounds, which are not chemically joined together.

In a mixture, the substances that make up the mixture:

- are not in a fixed ratio – imagine, for example, that you have 250 ml of water and you add sand to the water. It does not matter whether you add 20 g, 40 g, 100 g, or any other mass of sand to the water, it will still be called a mixture of sand and water.
- keep their physical properties – in the example we used of sand and water, neither of these substances has changed in any way when they are mixed together. The sand is still sand and the water is still water.
- can be separated by physical means – to separate something by 'physical means' means that there is no chemical process involved. In our sand and water example, it is possible to separate the mixture by simply pouring the water through a filter. Something physical is done to the mixture, rather than something chemical.

Note

If you would like to learn about methods used to separate mixtures, you can watch this video: Fuse Schools: How to separate mixtures (Duration: 4.07).

Exercise 2.1

State whether the following statements are true of an element, mixture or compound:

1. Made up of two or more elements chemically joined together
2. Made up of one type of atom and can be found on the periodic table
3. Can be separated by mechanical means
4. Substance has a chemical formula
5. Cannot be broken down into anything simpler
6. Made up of elements and/or compounds which are not chemically joined together

The full solutions are at the end of the unit.

Different types of mixtures

We can group mixtures further by dividing them into those that are heterogeneous and those that are homogeneous.

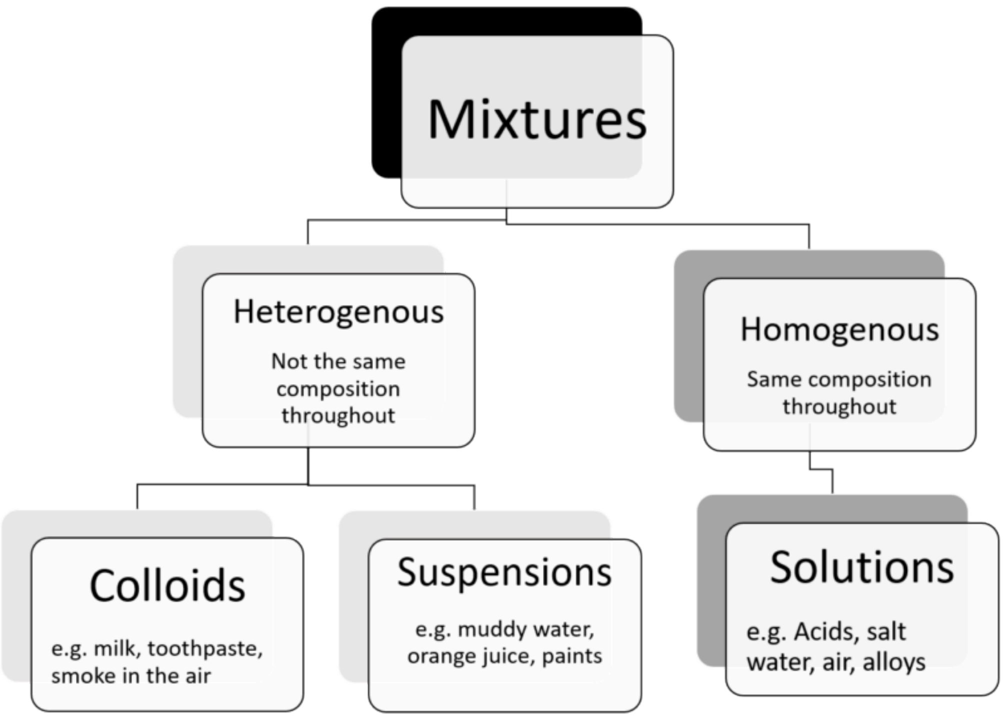


Figure 6: The different types of mixtures

Homogenous mixtures

A homogeneous mixture has a definite composition and specific properties. In a homogeneous mixture, the different parts cannot be seen. Homogenous mixtures are mixtures where all the substances which make up the mixture are in the same state. A homogenous mixture of a soluble solid and a suitable solvent will form a solution, as will a mixture of gases like the air.

Salt water is a solution of salt dissolved in water and is an example of a homogeneous mixture. Figure 7 shows that when the salt (sodium chloride) dissolves, its particles spread evenly through the water so that all parts of the solution are the same, and you can no longer see the salt as being separate from the water.

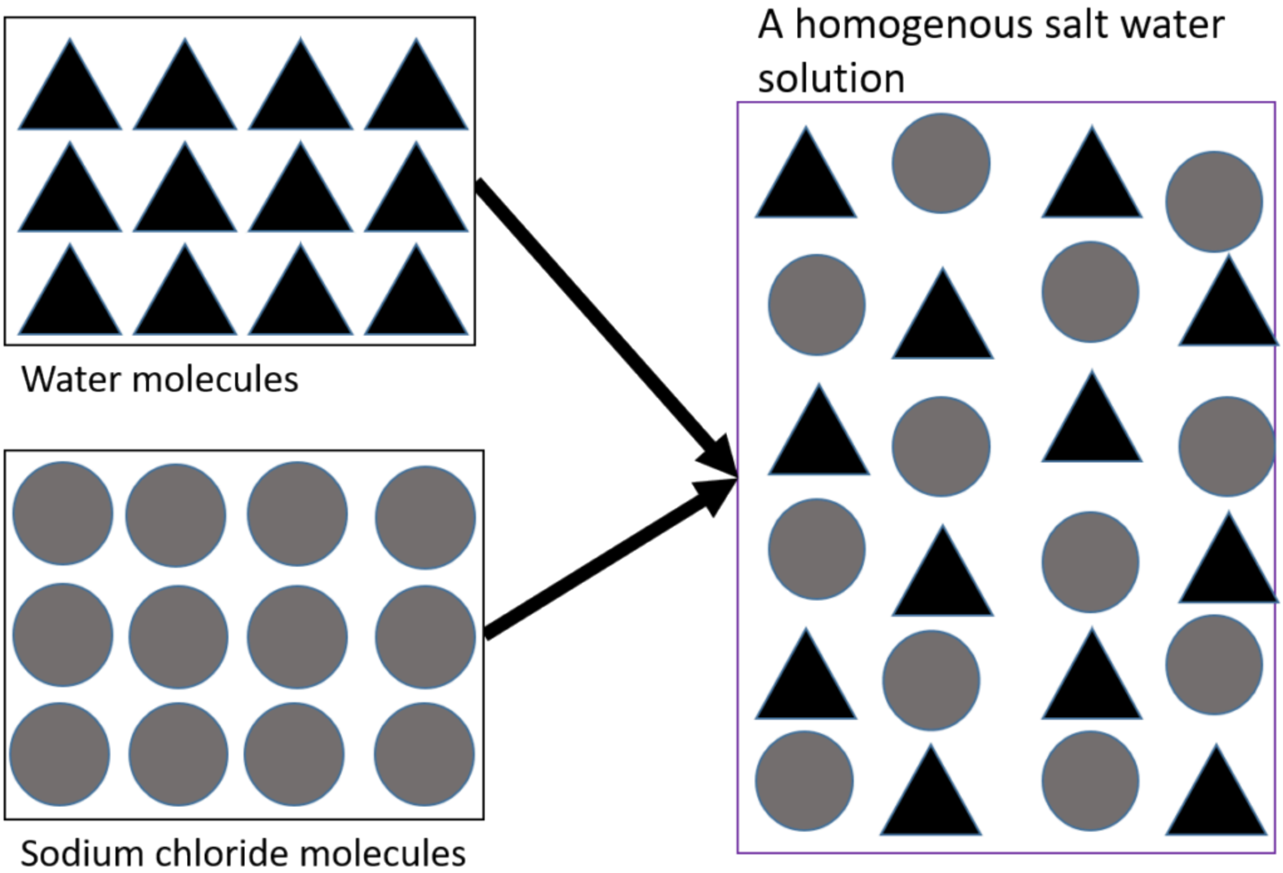


Figure 7: A particle diagram showing how salt particles spread evenly through the water particles to form a homogenous mixture.

The air we breathe is another example of a homogeneous mixture as it is made up of different gases which are in a constant ratio, and which cannot be visually distinguished from each other. In other words, you cannot see the different components. Homogenous mixtures tend to be transparent, and can be either solids, liquids or gases.

Figure 8: Solutions of transition metals

Alloys are homogenous mixtures of different metals, and in some instances non-metals, used to make a variety of objects including coins, car wheels and bells.

Common alloys	**Elements used**	**Uses**
Bronze	Copper and tin	Statues
Brass	Copper and zinc	Bells
Steel	Iron, carbon, chromium, nickel, silicon, manganese, boron and others	Structures, buildings, machinery, cutlery
Solder	Tin, lead and antimony	Welding
Alnico	Aluminium, nickel and cobalt	Magnets

Heterogeneous mixtures

A heterogeneous mixture does not have a definite composition. Cereal in milk is an example of a heterogeneous mixture. Soil is another example. Soil has pebbles, plant matter and sand in it. Although you may add one substance to the other, they will stay separate in the mixture. We say that these heterogeneous mixtures are non-uniform, in other words they are not exactly the same throughout.

Figure 9: Milk is a heterogenous mixture, and so is oil and water

Milk is a heterogenous mixture, and so is oil and water. Milk is a colloid of water proteins, fats, lactose, and minerals. The proteins, fats, lactose, and minerals are spread out though the water. The oil and water mixture is also a colloid because the oil and water do not mix and the oil 'sits' on top of the water. A common example of a suspension is muddy water. A suspension is a mixture of solid particles in a liquid which will settle out quickly once the liquid is still.

Figure 10: Muddy water is a suspension because soil particles are suspended in the water and will settle out quite quickly.

Note

Useful things to remember:

- A heterogeneous mixture is a mixture in which the composition is not uniform throughout the mixture.
- Heterogenous mixtures can be made up of substances in different phases.
- A homogeneous mixture is a mixture in which the composition is uniform throughout the mixture.
- Homogenous mixtures are all in the same phase.
- All solutions would be considered homogeneous.

Note

If you need further explanation on homogenous and heterogenous mixtures, you can watch this video: [Robin Reaction: Homogenous and heterogenous mixtures!] (Duration: 7.38).

Summary

In this unit you have learnt the following:

- All the objects and substances that we see in the world are made of matter.
- This matter can be classified according to whether it is a mixture or a pure substance.
- A mixture is a combination of two or more substances, where these substances are not bonded (or joined) to each other and no chemical reaction occurs between the substances. Examples of mixtures are air (a mixture of different gases) and cereal in milk.
- The main characteristics of mixtures are that the substances that make them up are not in a fixed ratio, these substances keep their physical properties, and these substances can be separated from each other using mechanical means.
- A heterogeneous mixture is one that consists of two or more substances. It is nonuniform and the different components of the mixture can be seen. An example would be a mixture of sand and water.
- A homogeneous mixture is one that is uniform, and where the different components of the mixture cannot be seen. An example would be salt in water.
- Pure substances can be further divided into elements and compounds.
- An element is a substance that cannot be broken down into other substances through chemical means.
- All the elements are found on the periodic table. Each element has its own chemical symbol. Examples are iron (Fe), sulfur (S), calcium (Ca), magnesium (Mg) and fluorine (F).
- A compound is a substance made up of two or more different elements that are joined together in a fixed ratio. Examples of compounds are sodium chloride (NaCl), iron sulfide (FeS), calcium carbonate ($CaCO_3$) and water (H_2O).

Unit 2: Assessment

Suggested time to complete: 25 minutes

1. Copy and complete the following table into your notebook.

Substance	**Element, mixture, or compound?**	**Type of mixture (if applicable)**
Water		
Brass		
Jelly		
Aluminium		
Table salt		
Sugar water		
Cooking oil		

2. In your notebook, draw particle diagrams to show an element, a heterogenous mixture and the compound water.
3. Give a one-word term for the following:
    a. a mixture with a uniform composition
    b. a substance made up of only one type of atom
    c. a substance which has a chemical formula
    d. a mixture where undissolved substances are spread throughout the substance

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. compound
2. element
3. mixture
4. compound
5. element
6. mixture

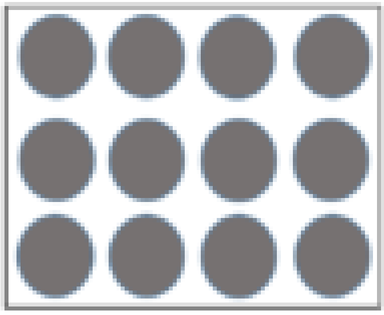
Back to Exercise 2.1

Unit 2: Assessment

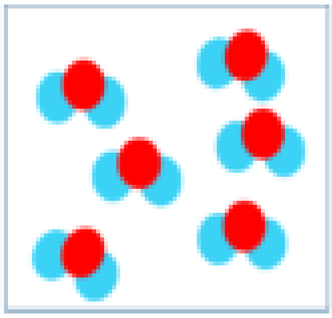
1.

Substance	**Element, mixture, or compound?**	**Type of mixture (if applicable)**
Water	Compound	N/A
Brass	Mixture	homogenous
Jelly	Mixture	heterogenous
Aluminium	Element	N/A
Table salt	Compound	N/A
Sugar water	Mixture	homogenous
Cooking oil	Mixture	homogenous

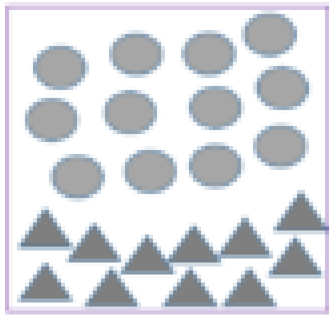
2.



Element



Compound: Water



Heterogenous mixture

3.

   a. homogenous
   b. element
   c. compound
   d. colloid/heterogenous

Back to Unit 2: Assessment

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Unit 3: Bonding

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Identify, define and give examples of:
  - a covalent bond
  - an ionic bond
  - a metallic bond.
- Explain the macroscopic and microscopic properties of bonding.
- Name and write chemical formulae for common substances like:
  - water
  - sodium chloride
  - carbon dioxide
  - sulphuric acid.

What you should know:

Before you start this unit, make sure you can:

- Confidently complete all the work in Subject outcome 5.2.
- Confidently complete all the work in Subject outcome 5.3.
- Confidently complete all the work in Subject outcome 5.4 Unit 1 and Unit 2.

Introduction

In this unit you will learn to identify and describe bonding between elements to form compounds. Bonds formed between metals and non-metals are ionic bonds. Bonds formed between two or more non-metals are covalent bonds. Bonds formed between metals are metallic bonds. You will also learn to write the chemical formulae of commonly used substances like water, carbon dioxide and acids such as sulphuric acid.

Chemical bonding

Atoms seldom exist on their own. More often, the things around us are made up of different atoms that have joined together. They join through chemical bonding. Chemical bonding is one of the most important processes in chemistry because it allows all sorts of different molecules and combinations of atoms to form, which then make up the complex objects in the world around us.

Atoms are more reactive, and therefore more likely to bond, when their outer electron orbitals are not full.

Atoms are less reactive when these outer orbitals contain the maximum number of electrons, in other words when they have a stable electron configuration. This explains why the noble gases do not react.

A chemical bond is formed when atoms are held together by attractive forces. This attraction occurs when electrons are either shared between atoms, or when electrons are exchanged between the atoms that are involved in the bond. The sharing or exchange of electrons takes place so that the outer energy levels of the atoms involved are filled, making the atoms more stable. If an electron is shared, it means that it will spend its time moving in the electron orbitals around both atoms. If an electron is exchanged, it means that it is transferred from one atom to another. In other words, one atom gains an electron while the other atom loses an electron.

A chemical bond is the physical process that causes atoms and molecules to be attracted to each other and held together in more stable chemical compounds.

The type of bond that is formed depends on the elements that are involved:

- non-metals will bond with each other forming covalent bonds.
- non-metals and metals will bond forming ionic bonds.
- metals will bond with metals forming metallic bonds.

Covalent bonding

Covalent bonding occurs between the atoms of non-metals. The outermost energy levels of the atoms overlap so that unpaired electrons in each of the bonding atoms can be shared.

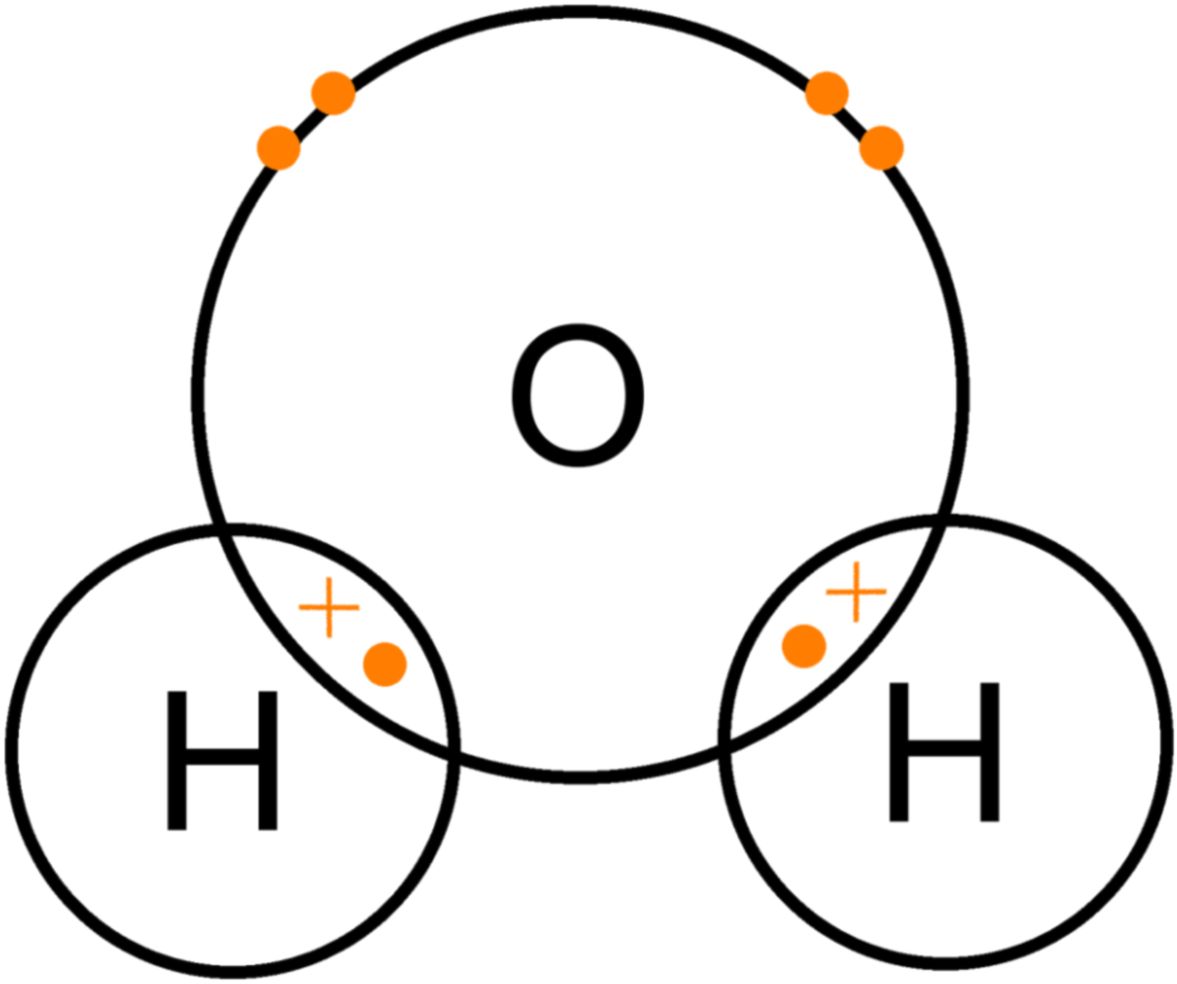


Figure 1: A shell diagram of the covalent bonds in a water molecule

By overlapping orbitals, the outer energy shells of all the bonding atoms are filled. The shared electrons move in the orbitals around both atoms. As they move, there is an attraction between the negatively charged electrons and the positively charged nuclei. This attractive force holds the atoms together in a covalent bond.

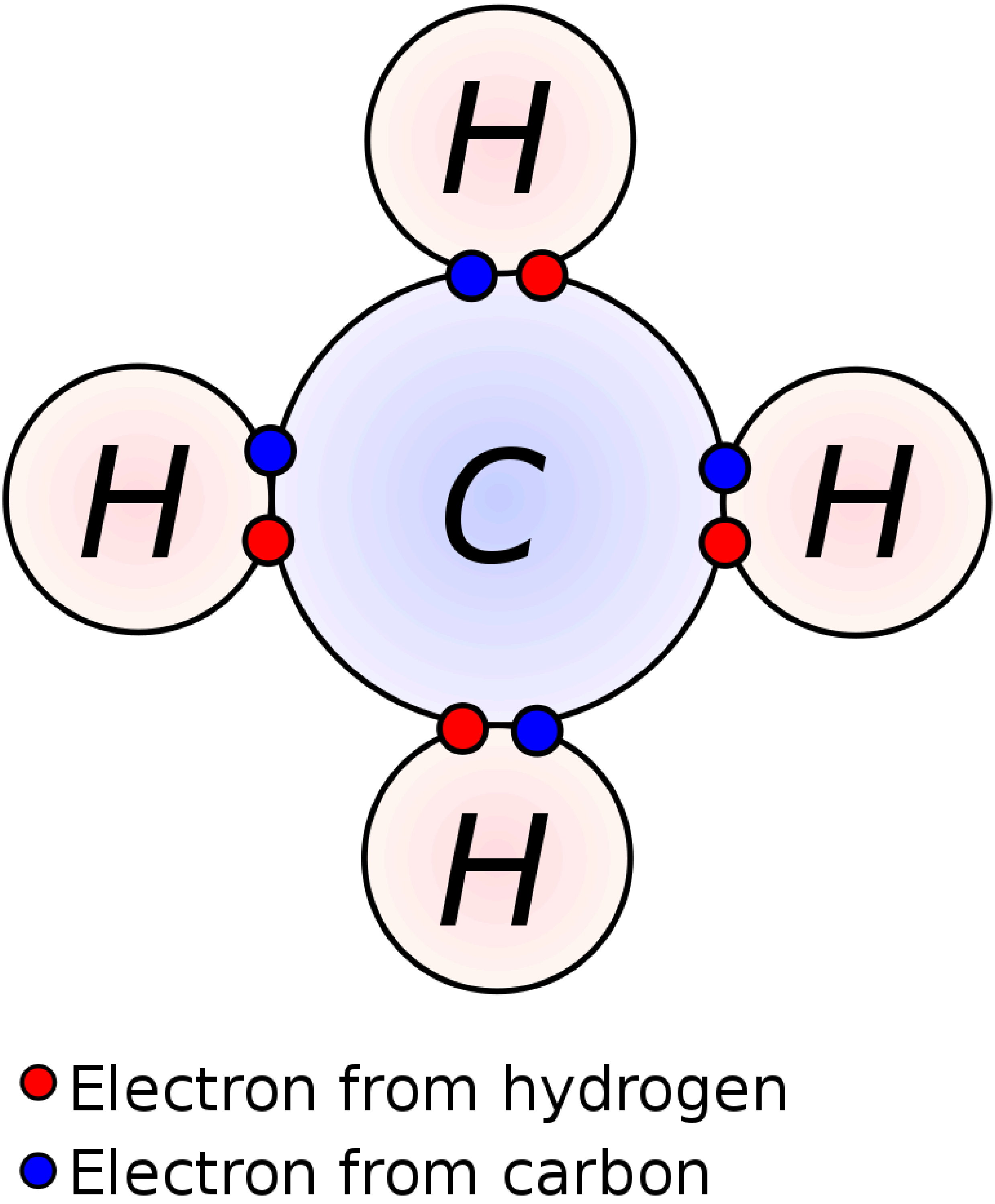


Figure 2: The outer energy shells showing the valence electrons involved in forming the bonds between the 4 hydrogen atoms and 1 carbon atom to form methane.

Example 1

1. Draw a shell diagram to explain the covalent bond in chlorine.
2. Write out the electron configuration for chlorine.
3. Work out how many valence electrons each chlorine atom has.
4. Work out how many electrons each atom needs to have a stable electron configuration.

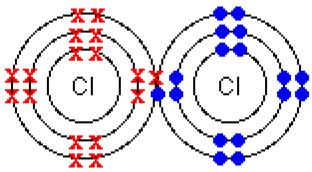
Solutions:

1. Chlorine is diatomic. An atom will form a covalently bonded molecule with another atom, so it becomes more stable.

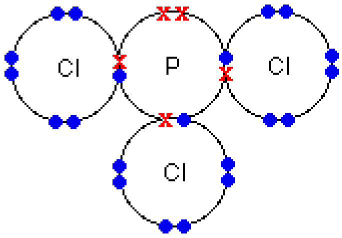
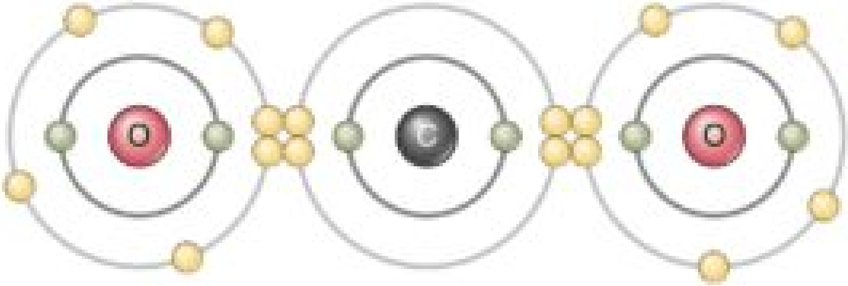
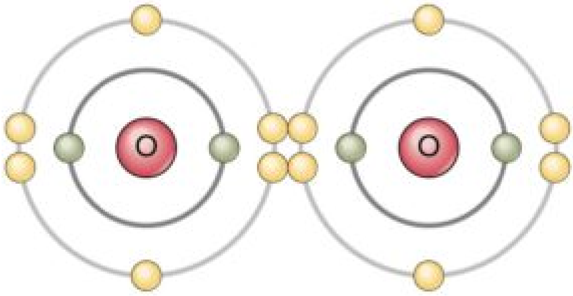
   To draw a diagram like this:

   - Draw the outer energy levels, fill in the electrons. (It is not necessary to draw all of the energy levels, you can just draw the outer energy level with the valence electrons.)
   - Use dots to represent the electrons from one type of atom and use crosses for the other type of atom.
   - Draw the outer most energy levels close together and place the shared electrons where the circles meet.

2. Chlorine's atomic number is 17 so its electron configuration will be $2, 8, 7$.
3. Each atom has 7 valence electrons. Remember, these are the electrons on the outermost energy level, and are the only electrons involved in bonding.
4. Each chlorine atom needs 1 electron to have a full outer most energy level. So, the atoms will 'share' 1 electron. Remember, to be stable, each atom needs either 2 or 8 electrons on its outer most energy level.



Other examples of covalently bonded compounds can be seen in the table below:

	Phosphorus chloride (PCl_3)
	Carbon dioxide (CO_2)
	Oxygen (O_2)

Properties of covalent bonding

Covalent compounds have several properties that distinguish them from ionic compounds and metals.

- The melting and boiling points of covalent compounds are generally lower than those of ionic compounds.
- Covalent compounds are generally more flexible than ionic compounds. The molecules in covalent compounds can move around to some extent and can sometimes slide over each other.
- Covalent compounds are generally not very soluble in water, for example plastics are covalent compounds and many plastics are water resistant.
- Covalent compounds generally do not conduct electricity when dissolved in water, for example iodine dissolved in pure water does not conduct electricity.

Note

If you need further explanation of covalent bonding you can watch this video:
[Fuse Schools: Covalent bonding of hydrogen, oxygen, and nitrogen](#) (Duration: 3.24).

Exercise 3.1

In your notebooks, draw shell diagrams to show the bonding in:

1. Hydrogen (H_2)
2. Hydrogen chloride (HCl)
3. Ammonia (NH_3)

The full solutions are at the end of the unit.

Ionic bonding

In ionic bonding electrons are transferred from one atom to another, unlike in covalent bonds where electrons are shared to achieve a stable electron configuration.

Ionic bonding is the complete transfer of valence electron(s) between atoms and is a type of chemical bond that generates two oppositely charged ions. Metals will donate electrons to non-metals and become positively charge ions and non-metals tend to readily accept electrons to achieve a stable configuration.

Bonding in Sodium fluoride (NaF)

Sodium and fluorine form an ionic bond to become sodium fluoride. Watch the animation to see how.

Sodium has the electron configuration $2, 8, 1$. To achieve a stable electron configuration, it needs to 'lose' 1 electron to have the configuration $2, 8$.

Fluorine has the electron configuration $2, 7$. To achieve a stable configuration it needs to 'gain' 1 electron.

So, sodium will give its electron to fluorine and become a positively charge ion Na^+ and fluorine will become negatively charged F^-.

Bonding in Sodium chloride (NaCl)

Sodium $2, 8, 1$ has 1 electron more than a stable structure $2, 8$. If it gives away that electron it will become more stable.

Chlorine $2, 8, 7$ has 1 electron short of a stable structure $2, 8, 8$. If it gains an electron from somewhere it too will become more stable. So, if a sodium atom gives an electron to a chlorine atom, both become more stable.

$$\mathrm{Na}\ 2,8,1 \rightarrow \mathrm{Na}^{+} 2,8$$
$$\mathrm{Cl}\ 2,8,7 \rightarrow \mathrm{Cl}^{-} 2,8,8$$

You need one sodium atom to provide the extra electron for one chlorine atom, so they combine 1:1. The formula is therefore NaCl.

The sodium atom has lost an electron, so it no longer has equal numbers of electrons and protons. Because it has one more proton than electron, it has a charge of +1. If an atom loses electrons, positive ions are formed. Positive ions are also called cations.

The chlorine atom has gained an electron, so it now has one more electron than protons. It therefore has a charge of –1. If an atom gains electrons, negative ions are formed. A negative ion is also called an anion.

In Sodium Chloride (NaCl), the sodium ions and chloride ions are held together by the strong electrostatic attractions between the positive and negative charges. Ionic substances are a combination of lots of ions bonded together into a giant molecule. The arrangement of ions in a regular, geometric structure is called a crystal lattice. So in fact, NaCl does not contain one Na and one Cl ion, but rather many of these two ions arranged in a crystal lattice where the ratio of Na to Cl ions is 1:1. The structure of the crystal lattice is shown in Figure 4.

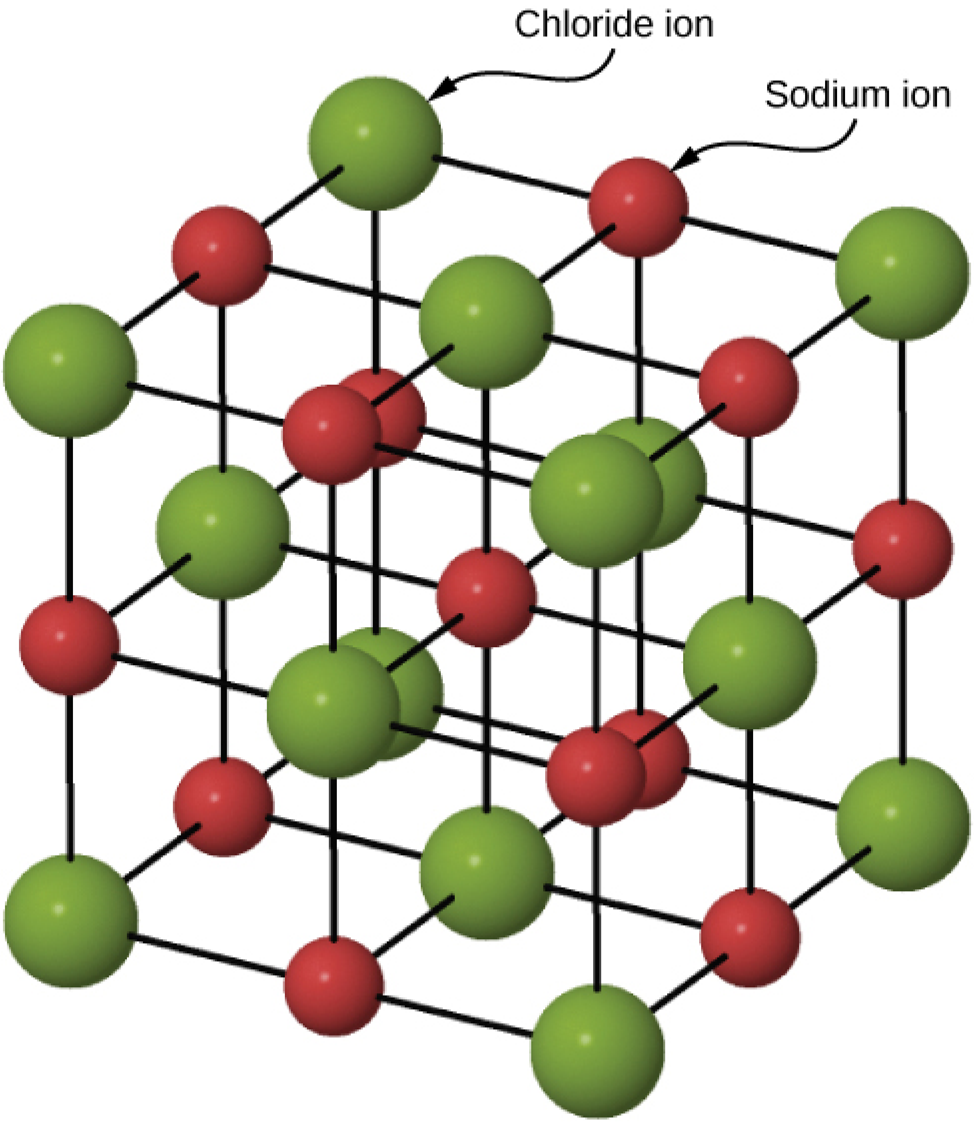


Figure 4: 3D crystal lattice structure of sodium chloride

Bonding in Magnesium Oxide (MgO)

In Magnesium Oxide, the two elements magnesium and oxygen, lose and gain 2 electrons respectively in order to achieve a stable configuration.

$$\begin{aligned} \text{Mg } 2,8,2 &\rightarrow \text{Mg}^{2+} 2,8 \\ \text{O } 2,6 &\rightarrow \text{O}^{2-} 2,8 \end{aligned}$$

The ionic bonding is therefore stronger than in sodium chloride because here you have an ion with a $^{+}2$ charge attracting an ion with a $^{-}2$ charge. The greater the charge, the greater the attraction. The formula of magnesium oxide is MgO.

Properties of ionic compounds

Ionic compounds have several distinguishing properties.

- Ions are arranged in a lattice structure.
- Ionic solids are crystalline at room temperature.
- The ionic bond is a strong electrostatic attraction. This means that ionic compounds are often hard and have high melting and boiling points.
- Ionic compounds are brittle, and bonds are broken along planes when the compound is put under pressure (stressed).
- Solid crystals do not conduct electricity, but ionic solutions do.

Note

If you need further explanation of ionic bonding you can watch this video:
Fuse Schools: What are ionic bonds? (Duration 2:54)

Exercise 3.2

For the following questions, choose the most correct answer:

1. Ionic bonds form because:
   a. two ions of the same charge are attracted to each other.
   b. two ions of different charges are attracted to each other.
   c. two atoms share their electrons.
2. Which of these is a property of an ionic compound?
   a. They have a low melting point.
   b. They are poor conductors of electricity.
   c. They form lattice structures.
3. The symbol Li^{+} means?
   a. That this lithium isotope has 1 positive charge.

b. That this lithium ion has 1 positive charge.
c. That lithium has 1 valance electron.

4. How many chloride ions are needed to cancel the $+2$ charge of magnesium in magnesium chloride?
   a. 1
   b. 2
   c. 3

The full solutions are at the end of the unit.

Metallic bonding

The structure of a metallic bond is quite different to both covalent and ionic bonds. In a metallic bond, the valence electrons are delocalised, meaning that an atom's electrons do not stay around that atom's nucleus. In a metallic bond, the positive atomic nuclei are surrounded by a sea of delocalised electrons which are attracted to the various nuclei.

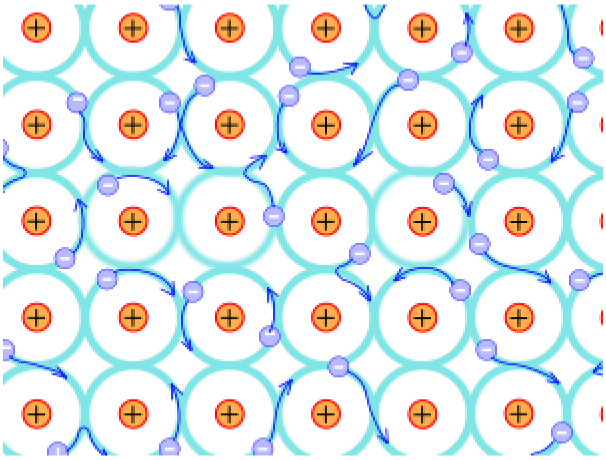


Figure 5: The movement of electrons in metallic bonding

Writing chemical formulae

A chemical formula is a short-hand way of writing out the names of compounds and elements. It is quicker and easier to write HCl than to write out hydrogen chloride. Using chemical formulae also shows how many atoms of a particular element are in different compounds.

The following are some guidelines for naming compounds:

1. The compound name will always include the names of the elements that are part of it.
   - A compound of iron (Fe) and sulfur (S) is iron sulfide (FeS).

- A compound of potassium (K) and bromine (Br) is potassium bromide (KBr).
- A compound of sodium (Na) and chlorine (Cl) is sodium chloride (NaCl).

2. In a compound, the element that is on the left of the periodic table is used first when naming the compound. In the example of NaCl, sodium is a group 1 element on the left-hand side of the table, while chlorine is in group 17 on the right side of the table. Sodium therefore comes first in the compound name. The same is true for FeS and KBr.
3. The symbols of the elements can be used to represent compounds. These are called chemical formulae, for example:
   - FeS – iron sulfide
   - NaCl – sodium chloride
   - H_2O – water.
4. When numbers are written as subscripts in compounds (they are written below and to the right of the element symbol), this tells us how many atoms of that element there are in relation to other elements in the compound, for example:
   - NO_2 (nitrogen dioxide) – there are two oxygen atoms for every nitrogen atom.
   - H_2O (water) – there are two hydrogen atoms for every oxygen atom.
   - CO (carbon monoxide) – there is one oxygen atom for every carbon atom.
   - NO_2 (nitrogen dioxide) – there are two oxygen atoms for every nitrogen atom.
   - SO_3 (sulfur trioxide) – there are three oxygen atoms for every sulfur atom.
   - H_2SO_4 (sulfuric acid) – there are two hydrogen atoms for every one sulfur atom and for every four oxygen atoms.
   - CO_2 (carbon dioxide) – there are two oxygen atoms for every carbon atom.

Example 2

Write the chemical formula for sodium fluoride.

Solution

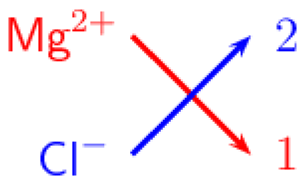
1. List the ions involved: You will need to work out the electron configuration of both sodium and fluorine. From there you should know that sodium needs to lose 1 electron to become stable and fluorine needs to gain 1 electron to become stable. This means that the ions Na^+ and F^- will form.
2. Write down the charges on the ions: The sodium ion has a charge of +1 and the fluoride ion has a charge of −1.
3. Find the right combination: For every plus, we must have a minus. So, the +1 from sodium cancels out the −1 from fluoride. They combine in a 1:1 ratio.
4. Therefore the chemical formula for sodium fluoride is NaF.

Example 3

Write the chemical formula for magnesium chloride.

Solution

1. List the ions involved by working out the electron configuration for magnesium and chlorine, then working out how many electrons they each need to lose or gain to have a stable configuration: Mg^{2+} and Cl^{-}.
2. Find the right combination: Magnesium has a charge of +2 and would need two chlorides to balance the charge. They will combine in a 1:2 ratio. There is an easy way to find this ratio:



3. Draw a cross as above, and then you can see that $Mg^{2+} \rightarrow 1$ and $Cl^{-} \rightarrow 2$.
4. Write down the formula: $MgCl_2$.

Exercise 3.3

1. Write the chemical formula for:
   a. calcium oxide
   b. potassium oxide
2. Explain why carbon tetrafluoride has the chemical formula of CF_4. You may draw a diagram to help with your explanation.

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- A chemical bond is the physical process that causes atoms and molecules to be attracted to each other and held together in more stable chemical compounds.
- Atoms are more reactive, and therefore more likely to bond, when their outer electron orbitals are not full.
- Atoms are less reactive when these outer orbitals contain the maximum number of electrons.
- When atoms bond, electrons are either shared or exchanged.
- Covalent bonding occurs between the atoms of non-metals and involves a sharing of electrons so that the orbitals of the outermost energy levels in the atoms are filled.
- Properties of covalent compounds:
  - low melting and boiling points
  - insoluble in water

    - softer and flexible
    - insulators of electricity and heat.
- An ionic bond occurs between atoms where there is an exchange of electrons. The atoms are held together by the electrostatic force of attraction between the resulting oppositely charged ions.
- Ionic solids are arranged in a crystal lattice structure.
- Properties of ionic compounds:
    - high melting and boiling points
    - soluble in water
    - harder and inflexible
    - good conductors of electricity and heat.
- A metallic bond is the electrostatic attraction between the positively charged nuclei of metal atoms and the delocalised electrons in the metal.
- When naming compounds and writing their chemical formula, it is important to know the elements that are in the compound, how many atoms of each of these elements will combine in the compound and where the elements are in the periodic table.

Unit 3: Assessment

Suggested time to complete: 30 minutes

1. Name the type of bonding in the following compounds or molecules:
    a. nitrogen (N_2)
    b. lithium oxide (Li_2O)
    c. vinegar/acetic acid ($C_2H_4O_2$)

   For questions 2 to 7, choose the most correct answer.
2. A chemical bond in which one atom loses an electron to form a positive ion and the other atom gains an electron to form a negative ion is a/an:
    a. cation
    b. ionic bond
    c. isotope
    d. covalent bond
3. What is a covalent bond?
    a. The transfer of electrons from one atom to another atom.
    b. The sharing of electrons equally between atoms of non-metals to attain a stable electronic configuration.
4. Why do non-metals covalently bond?
    a. They want to create new chemical compounds.
    b. They want full electron shells.
    c. Because it is nature.
5. What type of atoms (or ions) will form an ionic substance?
    a. two non-metals
    b. two metals
    c. a metal ion and a non-metal ion
6. What type of ions do metals form?
    a. Metals form positive cations, for example Na^{1+}.

b. Metals form positive anions, for example: Na^{1+}.
c. Metals form negative anions, for example: Na^{1-}.

7. Ionic bonds form because:
   a. two ions of the same charge are attracted to each other.
   b. two ions of different charges are attracted to each other.
   c. two atoms share their electrons.
   d. two or more atoms share protons.
8. Draw a shell diagram to show the covalent bonding in hydrogen fluoride.
9. Explain why lithium oxide has the chemical formula Li_2O.
10. Copy the following table into your notebook and complete it:

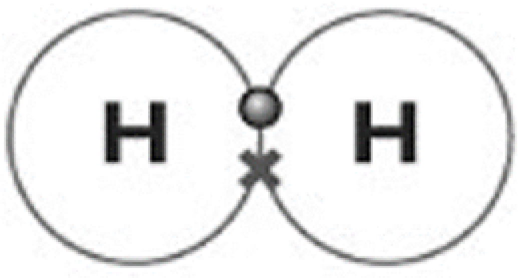
Name of compound	Name and number of elements in the compound
Calcium oxide (CaO)	Element: Number: Element: Number:
Potassium permanganate ($KMnO_4$)	Element: Number: Element: Number: Element: Number:
Nitric acid (HNO_3)	Element: Number: Element: Number: Element: Number:

The full solutions are at the end of the unit.

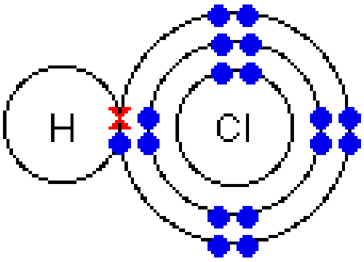
Unit 3: Solutions

Exercise 3.1

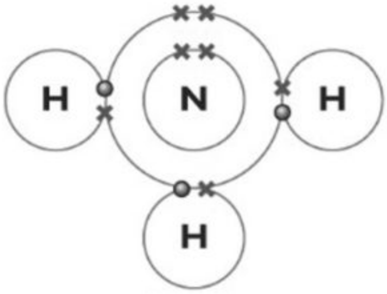
1. Hydrogen. Hydrogen has 1 electron. In order to become stable, it will bond with another atom of hydrogen. The atoms will share the two electrons.



2. Hydrogen chloride. Hydrogen has 1 electron. Chlorine has 7 electrons on its outermost energy level and needs 1 more electron to have a stable electron configuration. It will form a covalent bond with hydrogen by sharing 1 electron and the 1 electron from hydrogen.



3. Ammonia. Nitrogen needs to gain 3 electrons to have a stable configuration so it will bond with 3 hydrogen atoms, which have 1 electron each.



[Back to exercise 3.1]

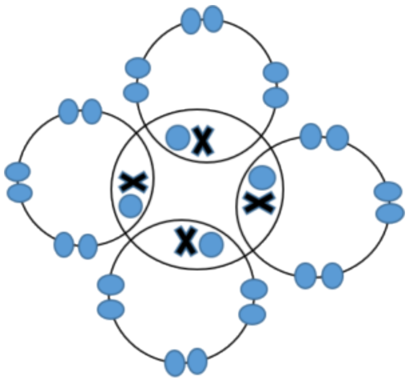
Exercise 3.2

1. b – ionic bonds form between a negatively charged non-metal ion and a positively charged metal ion – opposites attract!
2. c – the ions form a geometric lattice.
3. b – lithium will lose 1 electron and become a positively charged ion.
4. b – each chlorine ion needs to gain 1 electron for a stable configuration, so 2 chlorine ions will be needed to cancel out the $+2$ charge.

[Back to exercise 3.2]

Exercise 3.3

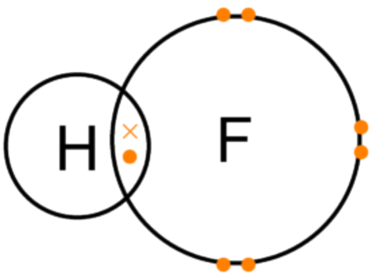
1.
    a. calcium oxide will be CaO. Calcium forms a Ca^{2+} ion. Oxygen forms a O^{2-}, so the ratio of atoms will be 1:1 and the formula will be CaO.
    b. potassium oxide will be K_2O. Potassium forms a K^+ ion because it will readily lose an electron. Oxygen forms a O^{2-} ion so 2 K^+ ions are needed to cancel out the −2 charge of the oxygen.
2. Carbon tetrafluoride is CF_4 because carbon needs 4 electrons for a stable electron configuration and fluorine needs 1 electron for a stable configuration. To fill up the outermost energy level of carbon you will need 4 fluorine atoms:



Back to exercise 3.3

Unit 3: Assessment

1.
    a. covalent
    b. ionic
    c. covalent
2. b
3. b
4. b
5. c
6. a
7. b
8. Shell diagram to show the covalent bonding in hydrogen fluoride:



9. Lithium has 1 valence electron, so will need to lose 1 electron to form a stable electron configuration and will form a Li^{+} ion. Oxygen has 6 valence electrons and needs to gain 2 electrons from lithium to form a stable electron configuration. Because oxygen needs 2 electrons, 2 lithium's are needed, and oxygen will form a O^{2-} ion.
10.

Name of compound	Name and number of elements in the compound
Calcium oxide (CaO)	Element: calcium Number: 1 Element: oxygen Number: 1
Potassium permanganate ($KMnO_4$)	Element: potassium Number: 1 Element: manganese Number: 1 Element: oxygen Number: 1
Nitric acid (HNO_3)	Element: hydrogen Number: 1 Element: nitrogen Number: 1 Element: oxygen Number: 3

Back to Unit 3: Assessment

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SUBJECT OUTCOME XIV

CHEMICAL CHANGE: IDENTIFY, DESCRIBE, AND APPLY PRINCIPLES OF HEAT

Subject outcome

Subject outcome 6.1: Identify, describe, and apply principles of heat.

Learning outcomes

- State the first law of thermodynamics: principle of conservation of energy.
- Define temperature and measure temperature using thermometers (Kelvin and Celsius scales) and colours of heated objects.
- Describe heat and heat transfer (see thermal conductors).
- Define and calculate heat capacity and specific heat.

Unit 1 outcomes

By the end of this unit you will be able to:

- Understand the principle of the conservation of energy which is called the First Law of Thermodynamics.
- Understand that energy cannot be created or destroyed.
- Understand that the amount of energy in a closed system is constant.

Unit 2 outcomes

By the end of this unit you will be able to:

- Understand what heat is.
- Understand the three scales of measurement used to measure heat.
- Understand that heat can be transferred by:
    - convection
    - conduction

- radiation.

Unit 3 outcomes

By the end of this unit you will be able to:

- Understand what specific heat is and how to calculate heat capacity.

Unit 1: First law of thermodynamics

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Understand the principle of the conservation of energy which is called the First Law of Thermodynamics.
- Understand that energy cannot be created or destroyed.
- Understand that the amount of energy in a closed system is constant.

What you should know

Before you start this unit, make sure you can:

- Explain what a force is. To revise this, go to Subject outcome 2.2, Unit 1.
- Define mechanical energy. To revise this, go to Subject outcome 2.3, Unit 1

Introduction

In this unit you learn about the principle of conservation of energy called the first law of thermodynamics. Energy cannot be created or destroyed; it can only be transferred from one form to another. This is the First Law of Thermodynamics and is about the conservation of energy in a system.

The first law of thermodynamics

The first law of thermodynamics states that heat is a form of energy, and thermodynamic processes are therefore subject to the principle of conservation of energy.

This means that heat energy cannot be created or destroyed. It can, however, be transferred from one location to another and converted to and from other forms of energy.

Thermodynamics is taken from the Greek terms thermo meaning heat and dynamis meaning to force, so the word thermodynamics means heat force.

The change in the internal energy (i.e. the total energy) contained within a system is equal to the amount of heat supplied to that system, minus the amount of work performed by the system on its surroundings.

First law of thermodynamics equation

The first law of thermodynamics states that the change in internal energy of a system equals the net heat transfer into the system minus the net work done by the system. In equation form, the first law of thermodynamics is: $\Delta U = q + W$

Where:

ΔU = change in internal energy of the system
q = algebraic sum of heat transfer between system and surroundings
W = work interaction of the system with its surroundings

For an isolated system, energy (E) always remains constant.
Work and heat are due to processes which add or subtract energy, they are not part of the system. While internal energy is a particular form of energy associated with the system; it's a property of the system.

Thermodynamics often divides the universe into two categories: the system and its surroundings. In chemistry, the system almost always refers to a given chemical reaction and the container in which it takes place. In a closed system, the amount of energy in the system will remain constant.

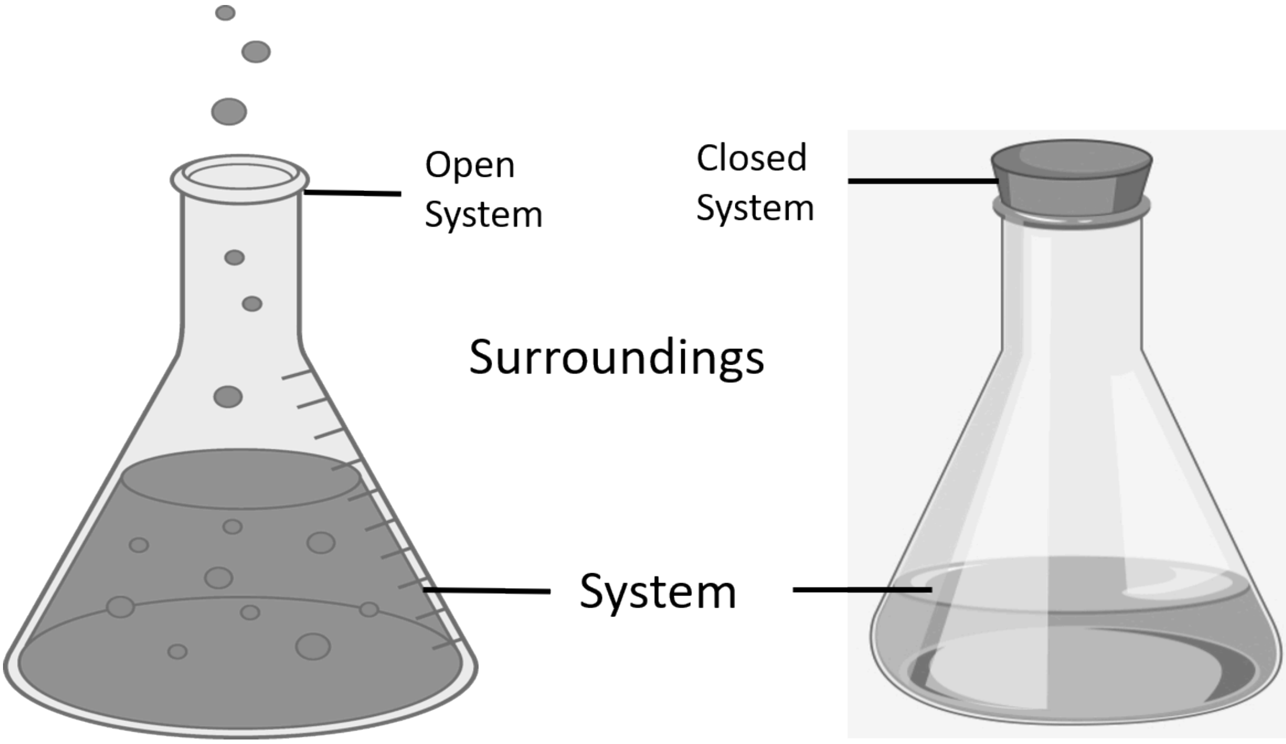

Figure 1: A diagram showing the fundamental distinction between the system and its surroundings in thermodynamics

In chemical reactions, the energy that is absorbed in an endothermic chemical reaction must have been lost from the surroundings. Conversely, in an exothermic reaction, the heat that is released in the reaction is given off and absorbed by the surroundings.

Chemical reactions are often used to do work and exchange heat. For instance, when rocket fuel burns and causes a space shuttle to lift off from the ground, the chemical reaction, by propelling the rocket, is doing work by applying a force over a distance. When plants photosynthesise, they absorb heat energy from the sun to use as the energy needed to convert carbon dioxide and water into glucose and oxygen.

Heat, work, and internal energy

Heat transfer and doing work are the two everyday ways of bringing energy into or taking energy out of a system but the processes are quite different:

Heat transfer is driven by temperature differences.

Work involves a macroscopic force exerted through a distance.

The internal energy of a system is the sum of the kinetic and potential energies of its atoms and molecules. Kinetic plus potential energy is called mechanical energy. Because it is impossible to keep track of all individual atoms and molecules, we must deal with averages and distributions.

Whenever a system goes through any change due to the interaction of heat, work, and internal energy, it is followed by numerous energy transfers and conversions. However, during these transfers, there is no net change in the total energy.

Figure 2: This boiling kettle represents energy in motion

The water in the kettle in Figure 2 is turning to water vapour because heat is being transferred from the stove to the kettle. As the entire system gets hotter, work is done—from the evaporation of the water to the whistling of the kettle.

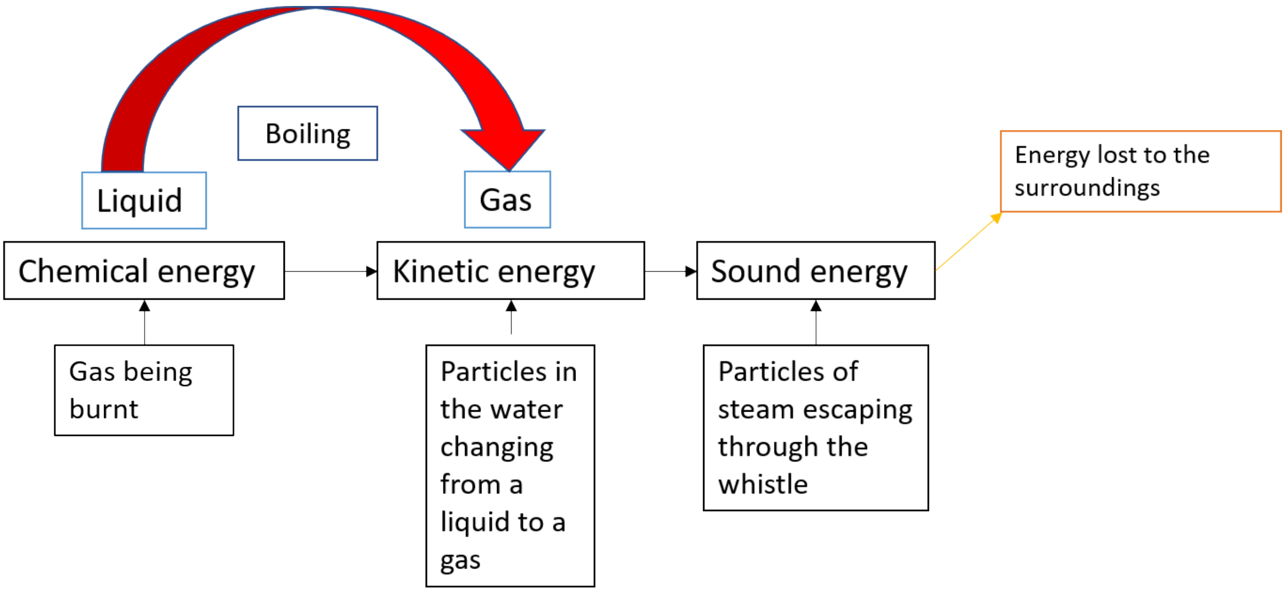

Figure 3: The energy changes that take place when water is boiled in a kettle on a gas stove

When you switch a light on the electrical energy needed comes from burning coal at a power station.

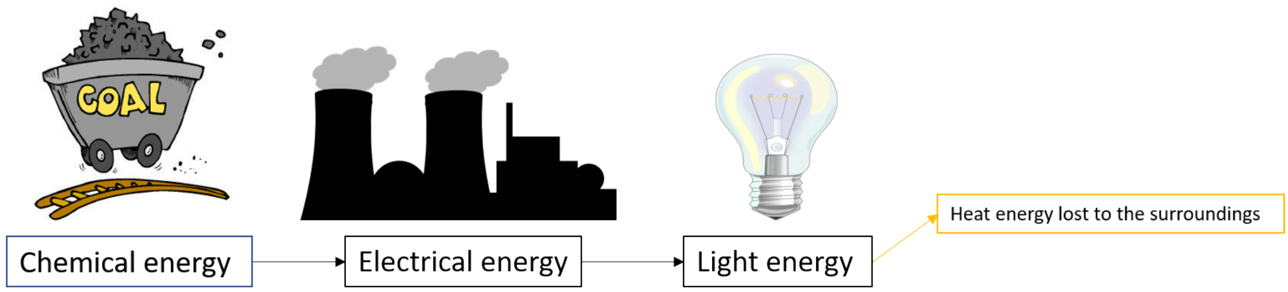

Figure 4: The many energy conversions that happen when we turn on a light bulb

Ice needs to be maintained at a temperature below the freezing point of water to remain solid. On hot summer days, people often use ice to cool beverages. If you put ice in a glass of water and leave it, after a while the ice will have melted, but the temperature of the water will have decreased. This is because the ice has 'pulled' in the heat from the water. Interestingly, the ice and its melt water will stay at $0\ ^{0}\mathrm{C}$ until all of the ice has melted. The total amount of heat in the system has remained the same but has just moved towards a state where both the former ice cube (now water) and the water are the same temperature. As this is not a completely closed system, the water will eventually become warm again, as heat from the surroundings is transferred to the glass and its contents.

When you take a hot bath, the water initially feels very warm. As you soak heat is transferred from the water to you until your body feels like it is the same temperature as the water. Eventually, the water will cool down because heat is lost to the surroundings.

Plants perform one of the most biologically useful transformations of energy on Earth: they convert the energy of sunlight into the chemical energy stored within organic molecules.

Summary

In this unit you have learnt the following:

- First law of thermodynamics states that heat energy in a system is conserved.
- Energy cannot be created or destroyed, it can only be changed from one form to another.
- The thermodynamic equation is $\Delta \mathrm{U} = \mathrm{q} + \mathrm{W}$, where
  - U: internal energy – the sum of the kinetic and potential energies of a system's atoms and molecules.
  - q: heat – energy transferred because of a temperature difference
  - W: work – energy transferred by a force moving through a distance.
- In a closed system, the amount of energy in the system will remain constant, but in an open system, energy will be lost to the surroundings.

Unit 1: Assessment

Suggested time to complete: 15 minutes

1. Which of the following does NOT apply to the first law of thermodynamics?
   a. energy cannot be created
   b. energy cannot be destroyed

   c. energy cannot be transformed from one form to another
   d. the amount of energy within a closed system is constant
2. Which of the following represents the first law of thermodynamics?
   a. While melting, an ice cube remains at the same temperature.
   b. The heat of an object explains how easily it changes temperature.
   c. After falling down the hill, a ball's kinetic energy plus heat energy equals its potential energy.
   d. If a refrigerator is unplugged, eventually everything inside of it will return to room temperature.
3. Explain and/or give definitions for the following:
   a. q (heat)
   b. W (work)
   c. a closed system
   d. internal energy
4. Using the relevant terms from Question 3, briefly explain:
   a. Why your hot cup of tea will cool down if you leave it in a cool room for a period of time.
   b. On a cold winter evening, an ice-cold beer's temperature will not increase as rapidly as an ice-cold beer on a hot summer evening. Explain why.

The full solutions are at the end of the unit.

Unit 1: Solutions

Unit 1: Assessment

1. c
2. d
3.
   a. q is the heat energy that is transferred because of a difference in temperatures.
   b. W is energy transferred by a force moving through a distance.
   c. A closed system is a system where a chemical reaction will take place and the amount of energy in that system will stay the same.
   d. Internal energy is the kinetic and potential energy of the molecules in the system.
4.
   a. The tea in the mug is not a closed system. Because there is a wide difference in temperature between the tea and its surroundings, there will be a loss of heat energy from the tea into its surroundings.
   b. A cold beer in cold conditions will not absorb as much heat energy from its surroundings because there is not such a great difference in the heat energies. Whereas on a hot day, the heat energy difference between the beer and its surroundings is far greater. So, the beer will warm up more quickly because it will absorb more heat energy from the surroundings.

Back to Unit 1: Assessment

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Unit 2: Heat and heat transfer

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Understand what heat is.
- Understand the three scales of measurement used to measure heat.
- Understand that heat can be transferred by:
  - convection
  - conduction
  - radiation.

What you should know

Before you start this unit, make sure you can:

- Summarise the principles of the first law of thermodynamics. To revise this, go to Subject outcome 6.1, Unit 1.
- Explain waves. To revise this, go to Subject outcome 3.1, Unit 1.
- List the wave properties of light. To revise this, go to Subject outcome 3.2, Unit 1.

Introduction

In this unit you will learn what heat is, the different scales used to measure heat and how heat is transferred. Heat is a type of energy that can be transferred in three ways: by convection currents where air rises as it is heated and drops as it cools, by radiation which is direct heating and by conduction which is where heat is spread throughout an object by the movement of particles.

Heat

When you think of heat, you think of a very hot day in the middle of summer. But heat is a type of energy. Heat is energy transfer to or from a thermodynamic system.

In thermodynamics, energy transferred as heat contributes to change in a system's internal energy.

The quantity of energy transferred as heat can be measured by its effect on the states of interacting bodies. For example, heat transfer can be measured by the amount of ice melted, or by change in temperature of a body or in the surroundings of the system.

Heat is caused by the flow of thermal energy from one body to another because there is a difference in temperature. Heat will usually flow from an object with a higher temperature to an object with a lower temperature. Thermal energy always flows from warmer areas to cooler areas. Heat is transferred through conduction, convection, or radiation.

The conventional symbol used to represent the amount of heat transferred in a thermodynamic process is Q. The SI unit of heat is the joule (J).

Note

Temperature is the average kinetic energy of the particles within a given object and is measured by three scales of measurement (Fahrenheit, Celsius, Kelvin).

Thermal energy is defined as the total kinetic energy within a given system.

It is important to remember that *heat* is caused by the flow of thermal energy due to differences in temperature.

Heat and temperature

Temperature is a physical quantity that expresses hot and cold. Thermal energy, present in all matter, is the source of heat, and it flows between bodies when one body comes in contact with another body that is either colder or hotter.

To measure the amount of heat a system has, we can use a thermometer. A thermometer measures the temperature of a system. Thermometers are calibrated in various temperature scales. The most common scales are the Celsius scale (formerly called centigrade, denoted as °C), the Fahrenheit scale (denoted as °F), and the Kelvin scale (denoted as K). The Kelvin scale is predominantly used for scientific purposes according to the International System of Units (SI).

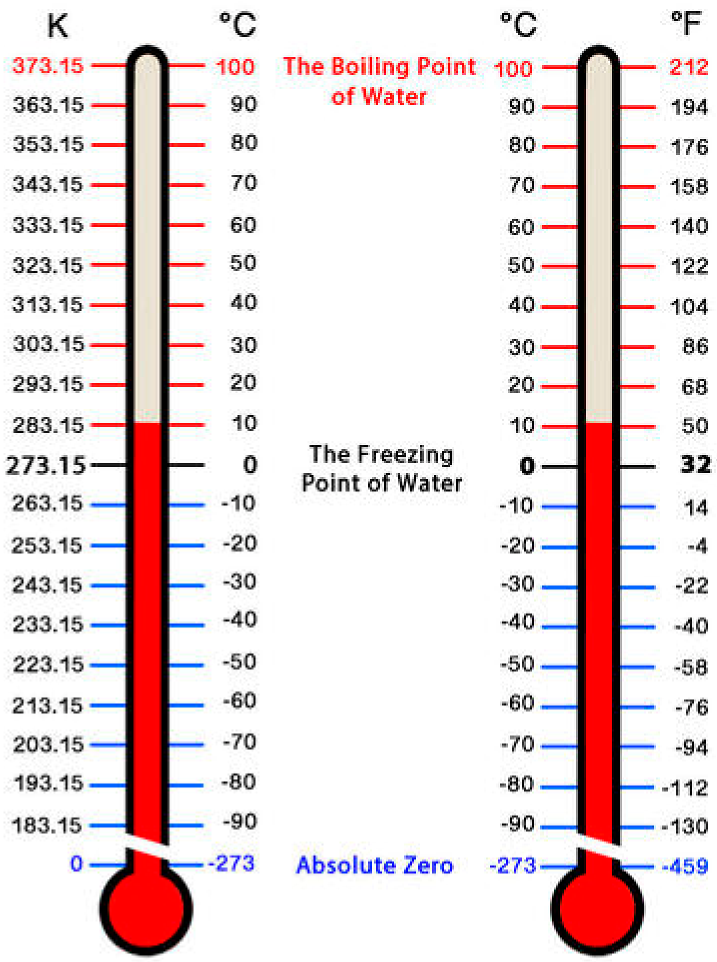

Figure 1: A comparison of Fahrenheit, Celsius, and Kelvin thermometers

Most countries use the Celsius scale. The Celsius scale (symbolised by °C and called "degrees Celsius") defines 0 °C as the freezing point of water and 100 °C as the boiling point of water at sea level. This scale is divided into 100 divisions between these two points but can extend higher and lower.

Other countries, like the United States of America, use the Fahrenheit scale (symbolised by °F and called "degrees Fahrenheit"). On this scale, the freezing point of liquid water is 32 °F, and the boiling point of water is 212 °F.

The fundamental unit of temperature in SI is the Kelvin (K). The Kelvin temperature scale (note that the name of the scale capitalises the word Kelvin, but the unit itself is lowercase) uses units that are the equal to degrees Celsius, but the numerical scale is shifted up by 273.15 units. Note that the Kelvin scale does not use the word degrees; a temperature of 295 K is spoken of as "two hundred and ninety-five kelvin" and not "two hundred and ninety-five degrees Kelvin."

The reason that the Kelvin scale is defined this way is that there exists a minimum possible temperature called absolute zero (zero kelvin). Absolute zero is a theoretical temperature at which an object's particles will have no heat and no movement. The Kelvin temperature scale is set so that 0 K is absolute zero, and the temperature is counted upwards from there. Normal room temperature is about 295 K.

By comparing the Kelvin, Fahrenheit and Celsius scales, a conversion between the three scales can be determined:

$$^{0}\mathrm{C} = (^{0}\mathrm{F} - 32) \times \frac{5}{9}$$

$$^{0}\mathrm{F} = (^{0}\mathrm{C} \times \frac{9}{5}) + 32$$

$$\mathrm{K} = {}^{0}\mathrm{C} + 273$$

Example 2.1

1. What is 98.6 °F in degrees Celsius?
2. What is 25.0 °C in degrees Fahrenheit?

Solutions

1. $^{0}\mathrm{C} = (98.6 - 32) \times \frac{5}{9} = 66.6 \times \frac{5}{9} = 37.0\ ^{0}\mathrm{C}$
2. $^{0}\mathrm{F} = \left(25.0 \times \frac{9}{5}\right) + 32 = 45.0 + 32 = 77.0\ ^{0}\mathrm{F}$

Example 2.2

If the normal room temperature is $72.0\ ^{\circ}\mathrm{F}$, what is room temperature in degrees Celsius and kelvin?

Solution

Step 1: First convert the temperature from Fahrenheit to Celsius:

$$^{0}\mathrm{C} = (72.0 - 32) \times \frac{5}{9} = 40.0 \times \frac{5}{9} = 22.2\ ^{0}\mathrm{C}$$

Step 2: Convert the temperature from Celsius to Kelvin:

$$\mathrm{K} = 22.2^{0}\mathrm{C} + 273 = 295.2\ \mathrm{K}$$

So, room temperature is about 295 K.

Example 2.3

What is 120 K in Celsius?

Solutions

$$^{0}\mathrm{C} = 120 - 273 = -153\ ^{0}\mathrm{C}$$

Exercise 2.1

1. Convert the following:
   a. 0 ^{o}C to Kelvin
   b. 183 K to Celsius
2. In January, the average temperature of eastern Siberia is -50 °C.
   a. Calculate this temperature in Kelvin.
   b. Of the three temperature units, which one is the SI unit for temperature?

The full solutions are at the end of the unit.

Types of heat transfer

Heat can be given off in three different processes: conduction, convection, or radiation.

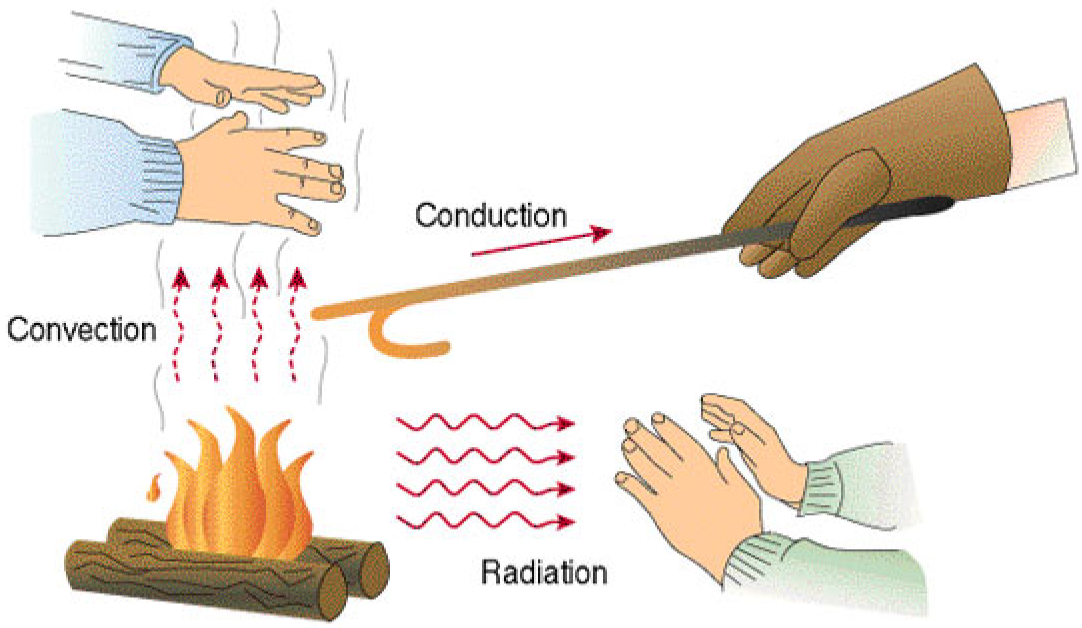

Figure 2: The three ways thermal energy can be transferred

Conduction

Conduction occurs when thermal energy is transferred through the interaction of solid particles. This process often occurs when cooking where the metal pot will be heated by heat coming from the ring on the stove: the boiling of water in a metal pan causes the metal pan to warm up as well.

Conduction is the transfer of heat across a medium or objects that are in physical contact. Conduction can be imagined as the energy transfer from more energetic to less energetic particles (here, molecules) due to interaction between them.

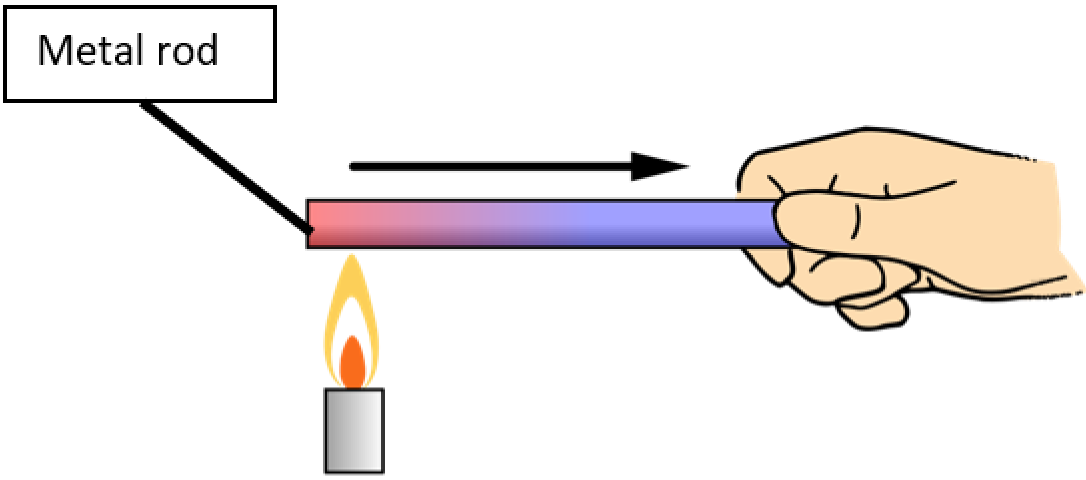

Figure 3: As the metal rod is heated, the thermal energy will travel through the rod until the heat can be felt by the person holding the rod

A hot pan placed on a burner burns your hand if you touch it because conduction of heat takes place between the heated pan and your hand.

Convection

Convection usually takes place in gases or liquids in which the transfer of thermal energy is based on differences in heat. Convection is the transfer of heat from a fluid or gas to a solid surface or within a fluid.

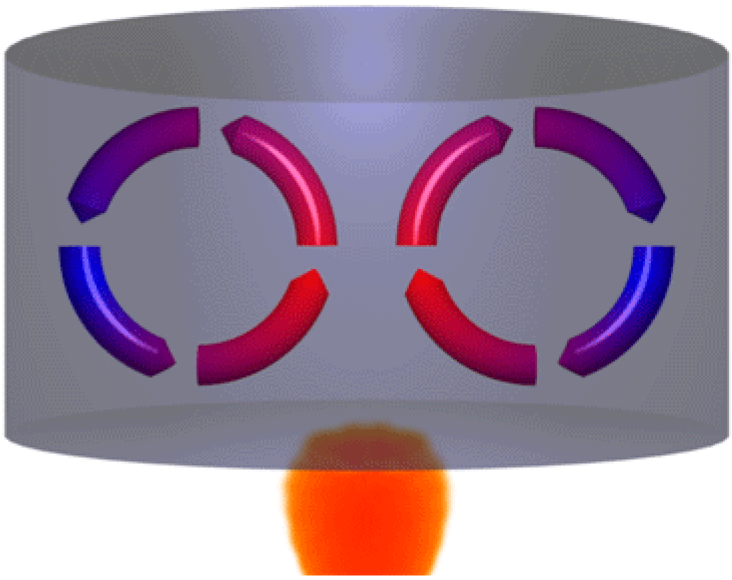

Figure 4: As the water in the pot is heated it rises to the top, cools and drops down to the bottom to be heated again

A convection current is the best example of this mode of heat transfer. When a cast iron skillet containing water is placed on a burner, convection currents are formed in the water. Warmer water, which is less dense moves up while the colder water (more dense), sinks down.

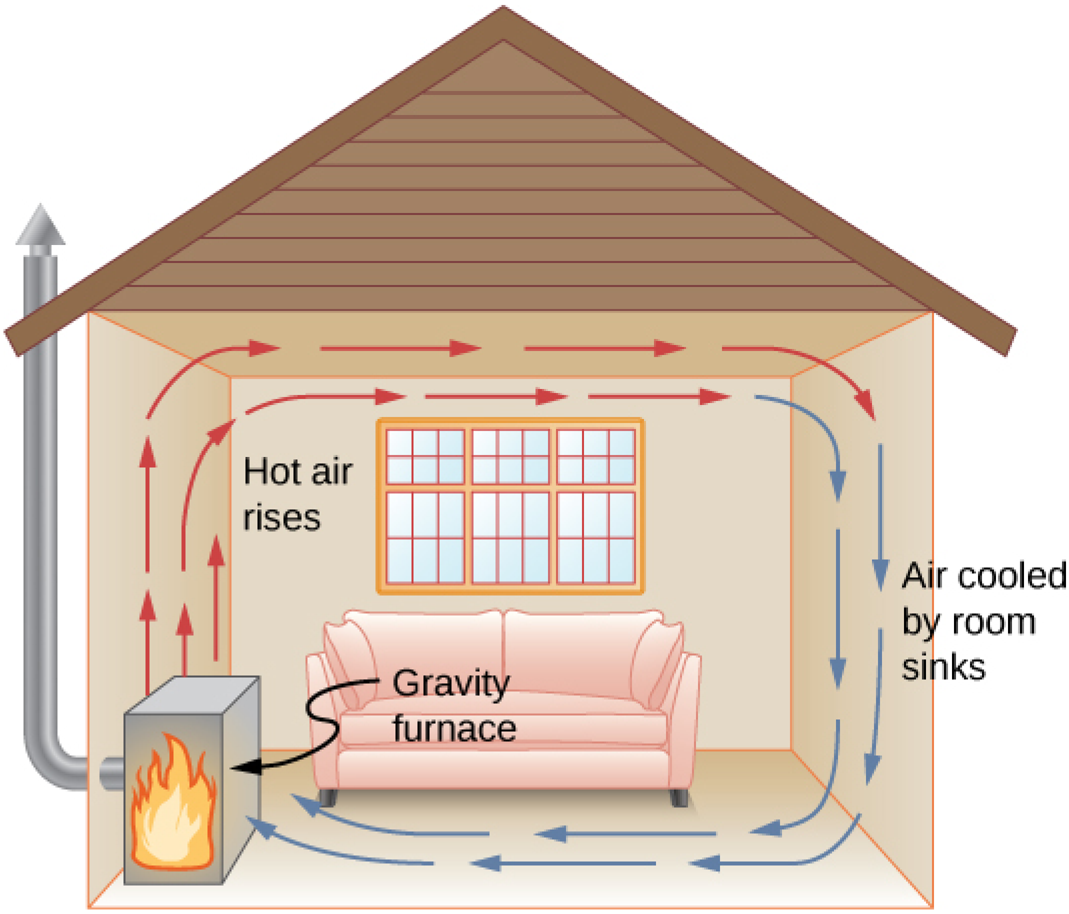

Figure 5: A convection current in a room

The convection currents in a room with a fireplace or heater are shown in Figure 6. The fireplace draws cool air in at the bottom, which is warmed by the flames. The hot air rises from the top keeping the room warm.

There are two types of convection:

- natural convection: this occurs due to a density difference caused by a temperature gradient present between a fluid and a surface
- forced convection: this is externally generated, for example by fans, pumps, and compressors, which are used to set the fluid or gas in motion.

Radiation

Radiation is the transfer of thermal energy through space and is responsible for the sunlight that fuels the Earth. You can feel the heat transfer from the sun on a sunny day.

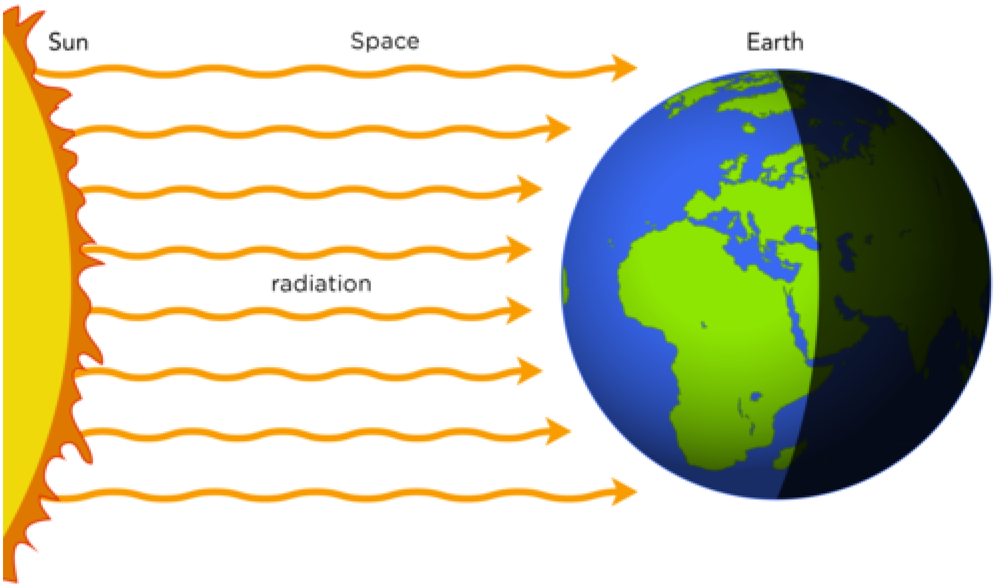

Figure 6: Radiation from the sun warms the surface of the Earth

The space between Earth and the Sun is largely empty, so the sun warms us without any possibility of heat transfer by convection or conduction.

Similarly, you can sometimes tell that an oven being used for cooking is hot without touching its door or looking inside – the air near it may feel warm you as you walk by. In these examples, heat is transferred by radiation. The hot entity emits electromagnetic waves that are absorbed by the skin. No medium is required for electromagnetic waves to be generated.

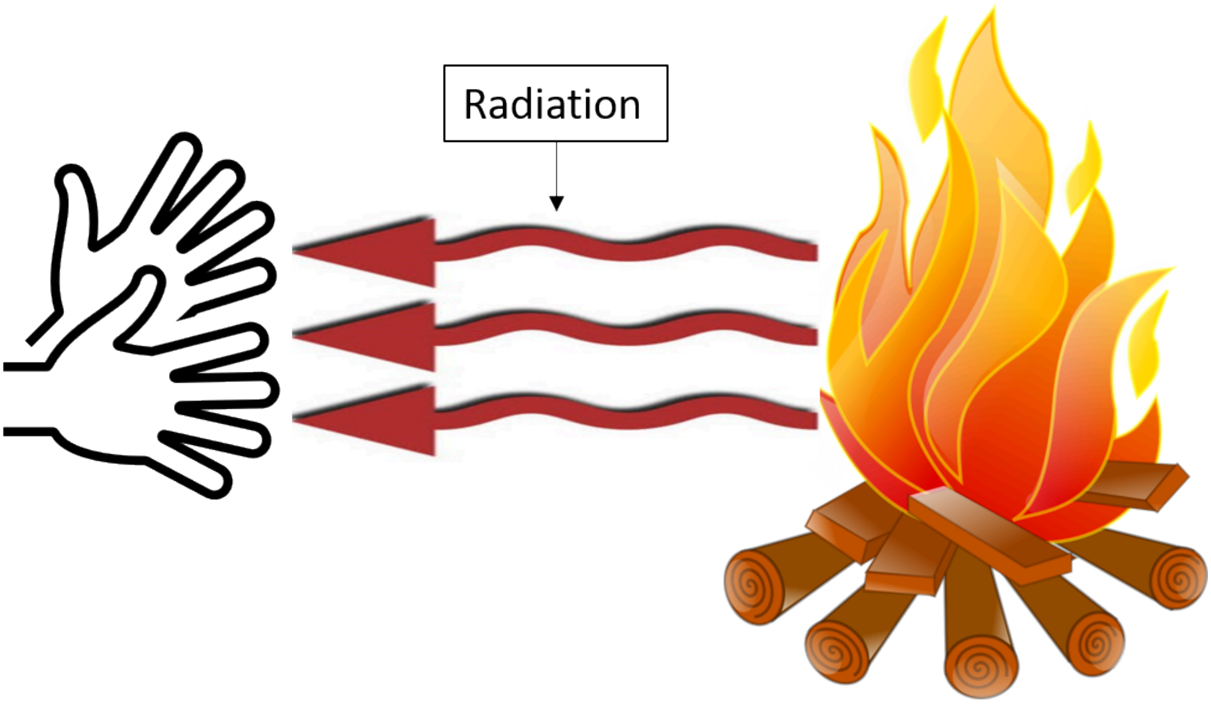

Figure 7: Your hands will get warm near a fire because of the heat emission through radiation

Most of the heat transfer from this fire in Figure 8 to the observers occurs through a type of radiation, called infrared radiation. Infrared radiation is invisible to the naked eye, and the wavelengths are longer than visible red light. A grill cooks food by radiation. A toaster toasts bread by radiation.

Skin is very sensitive to infrared radiation, so you can sense the presence of a fire without looking at it directly.

> **Note**
>
> To consolidate your understanding of heat and heat transfer you can watch this video called [The Physics of heat](), by Crash Course (Duration: 9.15).

Summary

In this unit you have learnt the following:

- Heat is a type of energy.
- Heat can be measured with a thermometer on one of three scales:
  - Celsius
  - Kelvin
  - Fahrenheit.
- Water boils at $100\ ^0\mathrm{C}\ \mathrm{or}\ 373\ \mathrm{K}$ at sea level and freezes at $0\ ^0\mathrm{C}\ \mathrm{or}\ 273\mathrm{K}$.
- Absolute zero is a theoretical temperature set at $-273\ ^0\mathrm{C}\ \mathrm{or}\ 0\ \mathrm{K}$.
- To convert a temperature reading from Celsius to Kelvin, you add 273 to the temperature in Celsius.
- Heat can be transferred by:
  - conduction
  - convection
  - radiation.

Unit 2: Assessment

Suggested time to complete: 20 minutes

1. Convert the following to Kelvin:
   a. $27\ ^0\mathrm{C}$
   b. $-31.2\ ^0\mathrm{C}$
2. Convert the following to Celsius:
   a. $63.2\ \mathrm{K}$
   b. $568.32\ \mathrm{K}$
3. What is the coldest temperature possible? Choose the correct option.
   a. Total zero
   b. Freezing point

c. Complete zero
d. Absolute freezing
e. Absolute zero
4. Gallium is a metal that can melt in your hand at $302.93\ \mathrm{K}$. What is the temperature in Celsius?
5. What does the temperature scale on a thermometer measure?
6. In conduction, heat moves from something hot to ____________________.
7. When water is boiling in a pot (refer to Figure 4 if necessary):
   a. Explain how a convection current is formed.
   b. Which other method of heat transfer is needed to heat the pot?
   c. Explain how the method referred to in b, and convection cause the water in the pot to warm up.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1.
   a. $\mathrm{K} = 0^0\mathrm{C} + 273 = 273\ \mathrm{K}$
   b. ${}^0\mathrm{C} = 183\ \mathrm{K} - 273 = -90^0\mathrm{C}$
2.
   a. $\mathrm{K} = -50\ {}^0\mathrm{C} + 273 = 223\ \mathrm{K}$
   b. Kelvin

Back to Exercise 2.1

Unit 2: Assessment

1.
   a. $\mathrm{K} = 27\ {}^0\mathrm{C}\ +\ 273\ =\ 300\ \mathrm{K}$
   b. $\mathrm{K} = -31.2\ {}^0\mathrm{C}\ +\ 273\ =\ 241.8\ \mathrm{K}$
2.
   a. ${}^0\mathrm{C} = 63.2\ \mathrm{K}$ - $273\ =$ -$209.8\ {}^0\mathrm{C}$
   b. ${}^0\mathrm{C} = 568.32\ \mathrm{K}$ - $273\ =\ 295.32\ {}^0\mathrm{C}$
3. e. Absolute zero
4. ${}^0\mathrm{C} = 302.93\ \mathrm{K}$ - $273\ =\ 29.93^0\mathrm{C}$
5. The scale measures the average kinetic energy of the particles in the object.
6. Something cold.
7. When water is boiling in a pot (refer to Figure 4 if necessary):
   a. A convection current is formed when the water particles are heated and rise, then sink when they have cooled, to be heated again so they can rise again.
   b. Conduction.
   c. Conduction is needed to heat the pot. The stove burner will transfer thermal energy via conduction to the pot. As the pot warms, the pot will heat up the water by convection.

Back to Unit 2: Assessment

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Unit 3: Specific heat capacity

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Understand what specific heat is and how to calculate heat capacity.

What you should know

Before you start this unit, make sure you can:

- define the principles of the first law of thermodynamics, as covered in Subject outcome 6.1, Unit 1.
- explain what heat is and how it is measured and transferred, as covered in Subject outcome 6.1, Unit 2.

Introduction

In this unit you will learn how to calculate heat capacity and specific heat. Specific heat capacity is the amount of heat energy needed to increase the temperature of a substance per unit of mass. The unit joule (J) is used to measure energy. Water has a specific heat capacity of $4.18\ \mathrm{J}$ which means it takes $4.18\ \mathrm{J}$ of energy to raise $1\ \mathrm{g}$ of water by $1^0\mathrm{C}$.

Heat capacity

In basic thermodynamics, the higher the temperature of a material, the more thermal energy it possesses. In addition, at a given temperature, the more of a given substance, the more total thermal energy the material will possess. Heat capacity is the amount of heat required to change the heat content of 1 mole of material by exactly 1°C.

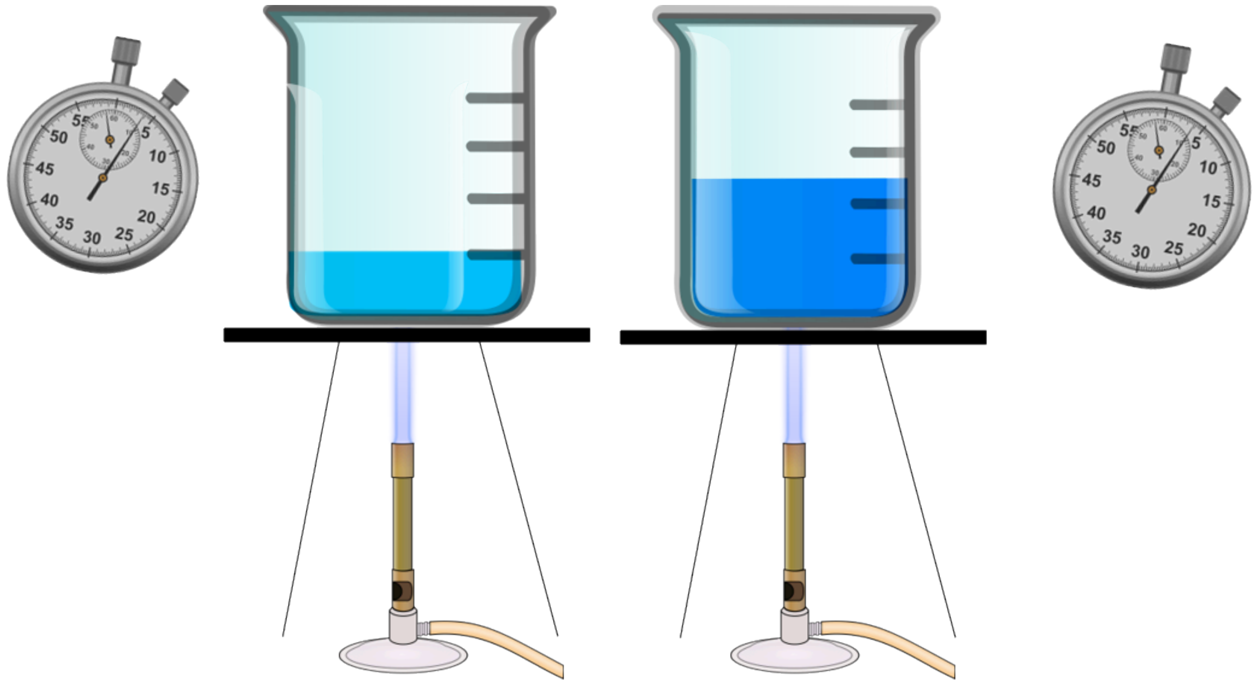


Figure 1: Two beakers of water with different volumes

Look at Figure 1. The beaker on the left has less water. Each beaker of water is being heated with the same amount of thermal energy. Which beaker will boil first?

Obviously, the beaker with the lower volume will boil first. This is because the lower the volume or mass an object has, the less thermal energy it will need to absorb to increase in temperature.

On an atomic level, absorbed heat causes the atoms of a solid to vibrate. As the temperature is raised, the energy of the vibrations increases. In a solid, this is the only motion possible.

In a liquid or gas, absorbed heat causes the atoms in the molecule to vibrate, and the molecules themselves to both rotate and move from place to place. Because there are more "storage" possibilities for energy in liquids and gases, their heat capacities are larger than in solids.

As heat is added uniformly to the same quantities of different substances, their temperatures can rise at different rates. For example, metals, which are good conductors of heat, show fast temperature rises when heated. It is relatively easy to heat a metal until it glows red.

On the other hand, water can absorb a lot of heat with a relatively small rise in temperature. Insulating materials (insulators) are very poor conductors of heat and are used to isolate materials that need to be kept at different temperatures; like the inside of your house from the outside.

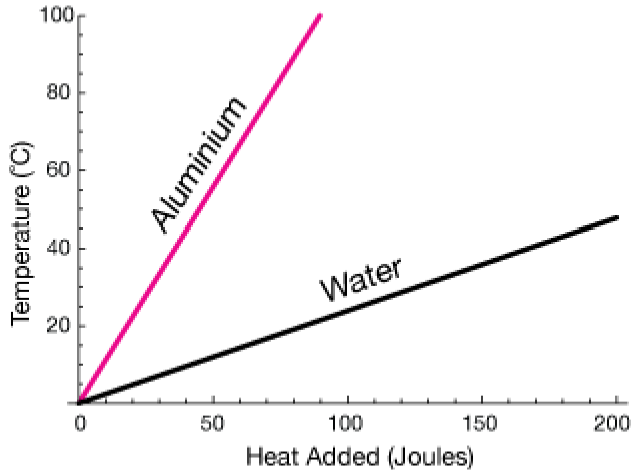


Figure 2: The rise in temperature as heat is added at the same rate to equal masses of aluminium and water

In Figure 2 you can see that the temperature of water rises much more slowly than that of aluminium. This is because all the thermal energy absorbed causes the metal to rise in temperature. Water molecules can rotate and vibrate because water is a liquid. This means that atoms can absorb kinetic energy without reflecting it as a rise in temperature of the substance.

What is specific heat?

Specific heat (C) is the amount of heat required to change the heat content of exactly 1 gram of a material by exactly 1°C.

Note

Specific heat is the heat capacity per unit of mass.

The specific heat of water is $1\ \mathrm{cal/g^0C}\ =\ 4.184\ \mathrm{J/g^0C}$.

We generally choose units of $\mathrm{J/g}$ or $\mathrm{KJ/kg}$. The specific heat of liquid water is $4.184\ \mathrm{J/g}$, which is also $4.184\ \mathrm{KJ/kg}$. The calorie is a unit of heat defined as the amount of heat required to raise the temperature of 1 cm^3 of water by 1 $^\circ$C.

Specific heat values can be determined in the following way: When two materials, each initially at different temperatures, are placed in contact with one another, heat always flows from the warmer material to the colder material until both the materials reach the same temperature. as described by the law of conservation of energy, the heat gained by the initially colder material must equal the heat lost by the initially warmer material.

We know that when heat energy is absorbed by a substance, its temperature increases. If the same quantity of heat is given to equal masses of different substances, it is observed that the rise in temperature for each substance is different. This is due to the fact that different substances have different heat capacities. So the heat capacity of a substance is the quantity of heat required to raise the temperature of the whole substance by one degree. The known heat capacity of a substance is called its specific heat capacity or specific heat, as it is specific to each type of substance.

One of the most interesting and important things about water is its high specific heat compared to other molecules of its size. It is atypically high.

This table lists the specific heats of selected compounds:

Compound	**Spec. Heat J/g·K**
Water ice (H_2O)	2.11
Water liquid	4.184
Water gas	2.08
Aluminium (s) (Al)	0.897
Copper (s) (Cu)	0.385
Iron (s) (Fe)	0.450
Lead (s) (Pb)	0.129
Methanol (l) (CH_3OH)	2.14
Ethanol (l) (C_2H_5OH)	2.44
Ethylene glycol (l) ($C_2O_2H_6$)	2.2
Hydrogen (g) (H_2)	14.267
Benzene (l) (C_6H_6)	1.750
Wood (typical)	1.674
Glass (typical)	0.867

Heat capacity (specific heat if it is per mole or per gram) can change depending on whether the thermodynamic variables of pressure or temperature are held constant during heating or cooling.

Generally in a laboratory we work at constant pressure, atmospheric pressure, so Cp is the most commonly used specific heat. In systems held at constant volume, such as in a gas-cylinder, where pressure can change but volume cannot, we use the heat capacity at constant volume, Cv.

Specific heat of water

For liquid water at room temperature and pressure, the value of specific heat capacity (Cp) is approximately $4.2\ \mathrm{J/g^{\circ}C}$. This implies that it takes $4.2\ \mathrm{J}$ of energy to raise 1 gram of water by 1 degree Celsius. This value for Cp is actually quite large. This is the specific heat of the water as a liquid or specific heat capacity of liquid water.

Substance		C_p in J/g°C	C_p in cal/g°C
Bismuth	Bi	0.123	0.029
Gold	Au	0.126	0.030
Lead	Pb	0.128	0.031
Tungsten	W	0.134	0.032
Mercury	Hg	0.140	0.033
Silver	Ag	0.233	0.056
Brass		0.380	0.091
Copper	Cu	0.386	0.092
Zinc	Zn	0.387	0.092
Granite		0.790	0.189
Glass	SiO_2	0.840	0.201
Aluminium	Al	0.900	0.215
Ice (-10°C)	$H_2O_{(s)}$	2.050	0.490
Ethyl alcohol	C_2H_5OH	2.400	0.574
Water	$H_2O_{(l)}$	4.186	1.000

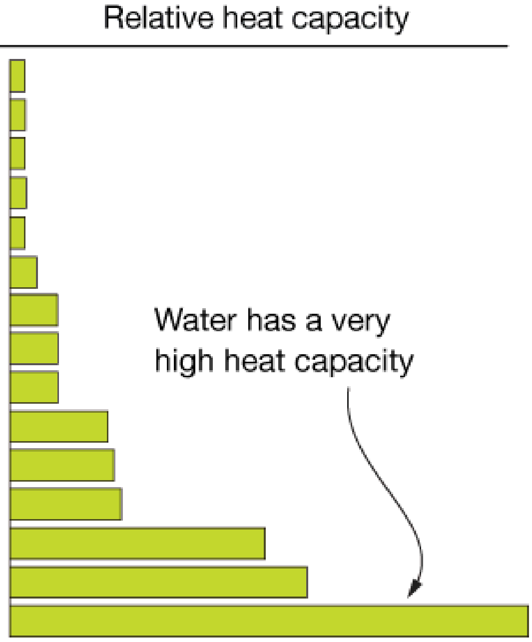


Figure 3: Table showing the heat capacities of different substances

The specific heat capacity of water vapour at room temperature is also higher than most other materials. For water vapour at room temperature and pressure, the value of specific heat capacity (Cp) is approximately $1.9\ \mathrm{J/g^{\circ}C}$.

As with most liquids, the temperature of water increases as it absorbs heat and decreases as it releases heat. However, the temperature of liquid water falls and rises more slowly than most other liquids. We can say that water absorbs heat without an immediate rise in temperature. It also retains its temperature much longer than other substances.

We use this property of water in our body to maintain a constant body temperature. If water had a lower Cp value, then there would be many cases of organisms overheating and underheating.

We can explain the high specific heat of water by the presence of hydrogen bonds. In order to increase the temperature of water, the molecules have to vibrate. Due to the presence of so many hydrogen bonds, a larger amount of energy is required to vibrate the water molecules and break the hydrogen bonds. Similarly, for hot water to cool down, it takes a bit of time. As heat is dissipated, temperature decreases, and the vibrational movement of water molecules slows down.

Specific heat capacity formula

The specific heat of a substance can be used to calculate the temperature change that a given substance will undergo when it is either heated or cooled. The equation that relates heat (Q) to specific heat (C), mass (m), and temperature change (Δt) is as follows:

Where:

energy = mass x specific heat capacity x change in temperature

$$Q = C \text{ x } m \text{ x } \triangle t$$

Q = energy transferred (J)
m = mass of the body (kg)
Δt = rise in temperature (0C)

C = specific heat capacity of a substance (J/kg 0C) (this depends on the nature of the material of the substance)

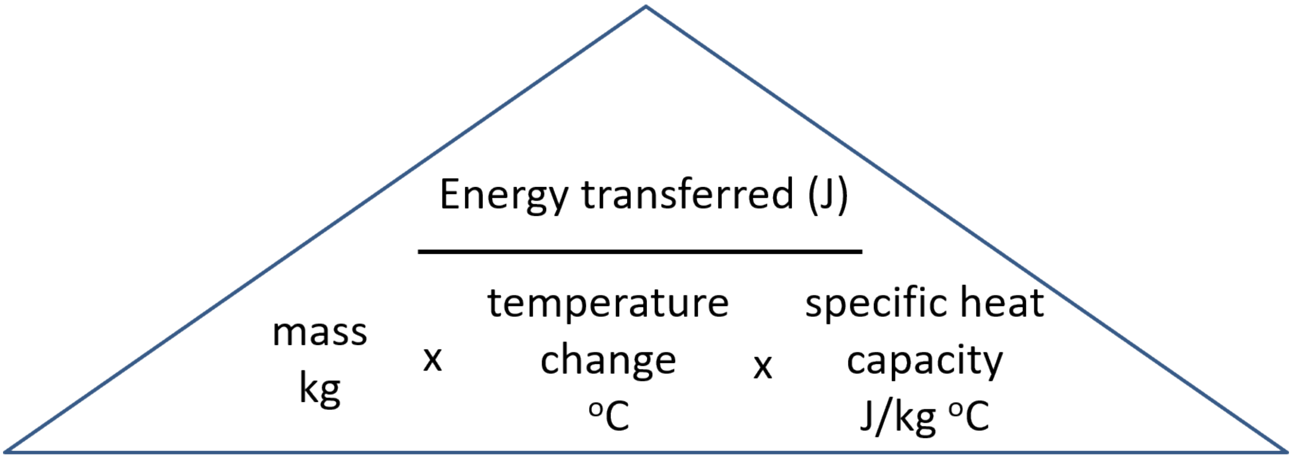
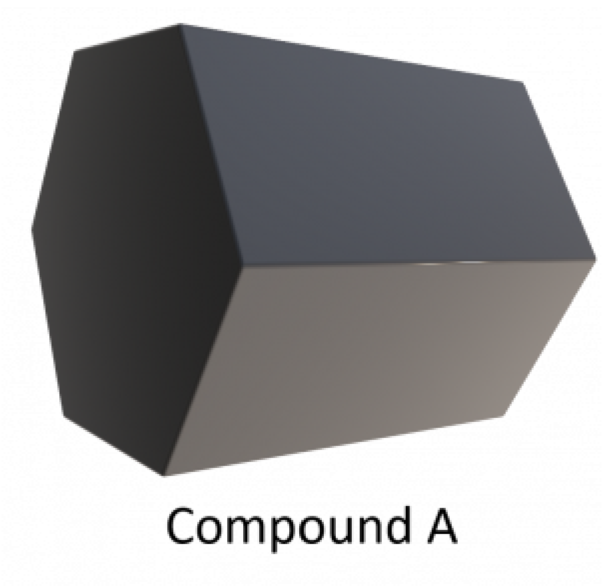


Figure 4: Calculation triangle to calculate C

The heat that is either absorbed or released is measured in joules. The mass is measured in kilograms. The change in temperature is given by $\Delta t = t_f - t_i$, where t_f is the final temperature and t_i is the initial temperature.

Example 3.1

Compound A is an imaginary solid. It has a specific heat capacity of $1\ 000\ \text{J/kg}^{\circ}\text{C}$.



1. A $1\ \text{kg}$ block of Compound A is heated, increasing its temperature by $1\ ^{\circ}\text{C}$. How much energy has been added to the block?
2. A $1\ \text{kg}$ block of Compound A is heated, increasing its temperature by 10°C. How much energy has been added to the block?

3. A 1 kg block of Compound A is heated, increasing its energy by $1\ 000\ \text{J}$. How much warmer does it get?
4. A $1\ \text{kg}$ block of Compound A is heated, increasing its energy by $3\ 000\ \text{J}$. How much warmer does it get?
5. A $1\ \text{kg}$ block of Compound A is cooled, reducing its energy by $1\ 000\ \text{J}$. What is the temperature change?
6. A $1\ \text{kg}$ block of Compound A is at $20\ ^\circ\text{C}$. How much energy is needed to get it to be $30\ ^\circ\text{C}$?

Solutions

1. $1\ 000\ \text{J}$ – *the block has a mass of* $1\ \text{kg}$ *and is being heated by* $1\ ^\circ\text{C}$.
2. $Q = 10\ \text{x}\ 1\ 000 = 10\ 000\ \text{J}$
3. $1\ ^\circ\text{C}$ – *it takes* $1\ 000\ \text{J}$ *to heat the block by* $1\ ^\circ\text{C}$
4. $\triangle\ t = 1\ \text{x}\ 3\ 000 = 3\ ^\circ\text{C}$
5. $\triangle\ t = -1\ ^\circ\text{C}$ – *the block is being cooled by* $1\ 000\ \text{J}$, *so the temperature will decrease by* $1\ ^\circ\text{C}$.
6.

   Step 1: If a $1\ \text{kg}$ block has $1\ 000\ \text{J}$ at $1\ ^\circ\text{C}$ then at $20\ ^\circ\text{C}$ the energy it will have will be:

   $$Q = Cm\ \triangle\ t$$
   $$Q = 1\ 000\ \text{x}\ 1\ \text{x}\ 20 = 20\ 000\ \text{J}$$

   Step 2: So at $30\ ^\circ\text{C}$:

   $$t = 30 - 20 = 10\ ^\circ\text{C}$$
   $$Q = 1\ 000 \times 1 \times 10 = 10\ 000\ \text{J}$$

   Therefore, it will take $10\ 000\ \text{J}$ to raise Compound A from $20\ ^\circ\text{C}$ to $30\ ^\circ\text{C}$.

Example 3.2

A $15.0\ \text{g}$ piece of cadmium metal absorbs $134\ \text{J}$ of heat while rising from $24.0\ ^\circ\text{C}$ to $62.7\ ^\circ\text{C}$. Calculate the specific heat of cadmium.

Solution

Step 1: List the known quantities and plan the problem

Known:

$$Q = 134\ \text{J}$$
$$m = 15.0\ \text{g} = 0.015\ \text{kg}$$
$$\triangle\ t = 62.7 - 24.0 = 38.7\ ^\circ\text{C}$$

Unknown:

C of cadmium

The specific heat equation can be rearranged to solve for the specific heat.

Step 2: Solve

$$C = \frac{Q}{m \times \Delta t} = \frac{134}{0.015 \text{ x } 38.7} = 0.0231 \text{ J/kg }^\circ\text{C}$$

Since most specific heats are known, they can be used to determine the final temperature attained by a substance when it is either heated or cooled.

Example 3.3

Suppose that 60.0 g of water at $23.52 \text{ }^\circ\text{C}$ was cooled by the removal of 813 J of heat.

Calculate the change in temperature using the specific heat equation.

Solution

$60.0 \text{ g} = 0.06 \text{ kg}$

$$\Delta t = \frac{Q}{C \times m} = \frac{813}{4.18 \text{ x } 0.06} = 3.24 \text{ }^\circ\text{C}$$

Since the water was being cooled, the temperature decreases. The final temperature is:

$t_f = 23.52 - 3.24 = 20.28 \text{ }^\circ\text{C}$

Exercise 3.1

1. Write the definitions for the following:
   a. heat capacity
   b. specific heat capacity
2. Write the formula for specific heat capacity, showing the units for each part.
3. The specific heat capacity of copper is $390 \text{ J/kg}^\circ\text{C}$. What does this mean?
4. Calculate the energy transferred when 3 kg of copper is heated from 20 °C to 220 °C.
5. Calculate the energy needed to heat 2 kg of water from 10 °C to 90 °C. The specific heat capacity of water is $4\ 200 \text{ J/kg}^0\text{C}$.

The full solutions are at the end of the unit.

Note

To consolidate your understanding of heat capacity you can watch this video by Fuse Schools, called Heat Capacity (Duration: 3.13).

Summary

In this unit you have learnt the following:

- Heat capacity describes how much heat must be added to a substance to raise its temperature by $1\ ^{\circ}\mathrm{C}$.
- Heat capacity is a measure of how much energy a material can store.
- Specific heat capacity is the energy needed to raise the temperature of 1 kg of a material by $1\ ^{\circ}\mathrm{C}$. It is measured in $\mathrm{J/kg^{\circ}C}$.

Unit 3: Assessment

Suggested time to complete: 25 minutes

1. Use the table below to answer the following questions:

Material	Specific heat capacity ($\mathrm{J/kg^{\circ}C}$)
Water	$4\ 200$
Oil	$2\ 000$
Limestone	910
Glass	840
Iron	460
Copper	390

   a. Which would get hottest? $1\ \mathrm{kg}$ of glass or $1\ \mathrm{kg}$ of iron?

   b. Which would feel colder after 1 hour in the fridge – limestone or copper?

2. Given the equation $Q\ =\ C\ \mathrm{x}\ m\ \mathrm{x}\ \ \triangle t$. How can this be rearranged to solve for C?
3. Use the table below to answer the following questions:

Metal	Specific heat capacity $\mathrm{J/kg^{\circ}C}$
aluminium	910
Brass	380
Copper	390
Iron	460

a. How much energy must be transferred into 1 kg of copper to raise its temperature by $1 \ ^\circ\text{C}$?

b. Suppose you have 1 kg of each metal. Which one will need the most energy to raise its temperature by $1 \ ^\circ\text{C}$?

c. The same amount of energy is transferred into 1 kg of each metal. Which one has the largest temperature rise?

d. How much energy must be transferred into 2 kg of iron to raise its temperature by $5 \ ^\circ\text{C}$?

4. Complete the table by calculating the missing values:

Material	Energy transfer (J)	Mass (kg)	Temperature rise (°C)	Specific heat capacity $\text{J/kg}^\circ\text{C}$
A		4	6	$4\ 000$
B	$6\ 000$	1		$2\ 000$
C	$8\ 000$		4	$1\ 000$
D		12	24	500
E	$2\ 500$	2	5	

5. What is the specific heat of a 250 g block if the temperature goes up $25 \ ^\circ\text{C}$ when 836 J of heat is added?

The full solutions are at the end of the unit.

Unit 3: Solutions

Exercise 3.1

1.

a. Heat capacity is the amount of heat added to a substance to raise its temperature by 1 degree Celsius.

b. Specific heat is the amount of heat required to change the heat content of exactly 1 gram of a material by exactly 1 °C.

2. $Q = C\,m\,\triangle t$
Q is measured in Joules (J)
C is the heat capacity measured in $\text{J/kg}^\circ\text{C}$
m is measured in kg
Δt is measured in ^{0}C

3. $390 \text{ J/kg}^\circ\text{C}$ is the amount of energy needed to heat 1 kilogram of copper by 1 degree Celsius.

4. $\triangle t = 220 - 20 = 200 \ ^\circ\text{C}$
$Q = 3 \text{ x } 200 \text{ x } 390 = 234 \text{ KJ}$

5. $\triangle t = 90 - 10 = 80 \ ^\circ\text{C}$
$Q = 2 \text{ x } 80 \text{ x } 4\ 200 = 672 \text{ KJ}$

Back to Exercise 3.1

Unit 3: Assessment

1.

a. glass

b. copper

2.

$$Q = C\ m\ \triangle t$$

$$C = \frac{Q}{m \triangle t}$$

3.

a. 390 J

b. Aluminium

c. Brass

d.

$$Q = C\ m\ \triangle t$$

$$Q = 2 \text{ x } 5 \text{ x } 460 = 4.6 \text{ KJ}$$

4.

Material	Energy transfer (J)	Mass (kg)	Temperature rise (^{o}C)	Specific heat capacity $\text{J/kg}^{\circ}\text{C}$
A	$9\ 600$	4	6	$4\ 000$
B	$6\ 000$	1	3	$2\ 000$
C	$8\ 000$	2	4	$1\ 000$
D	$14\ 410$	12	24	500
E	$2\ 500$	2	5	250

5.

$$Q = C\ m\ \triangle t$$

$$C = \frac{Q}{m \triangle t}$$

$$C = \frac{836}{0.25 \text{ x } 25} = 133.76 \text{ J/kg }^{\circ}\text{C}$$

Back to Unit 3: Assessment

Media Attributions

SUBJECT OUTCOME XV

CHEMICAL CHANGE: DIFFERENTIATE BETWEEN PHYSICAL AND CHEMICAL CHANGE

Subject outcome

Subject outcome 6.2: Differentiate between physical and chemical change

Learning outcomes

- Identify and distinguish between physical and chemical changes and give examples.
- Identify and apply physical and chemical methods of separating mixtures (solids, liquids, and gases).

Range: Separation methods are manual, magnetic, filtration, fractional distillation, using a separating funnel, precipitation reactions and chromatography.

Unit 1 outcomes

By the end of this unit you will be able to:

- Identify and distinguish between both a chemical change and a physical change.
- Give examples of both.
- Understand conservation of mass.
- Write chemical equations.

Unit 2 outcomes

By the end of this unit you will be able to:

- Separate a mixture by using either chemical or physical methods, such as:
    - manual methods
    - filtration

- magnetism
- chromatography
- fractional distillation
- precipitation reactions
- separating funnel.

Unit 1: Chemical and physical change

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Identify and distinguish between both a chemical change and a physical change.
- Give examples of both.
- Understand conservation of mass.
- Write chemical equations.

What you should know:

Before you start this unit, make sure you can:

Confidently complete all the work in Subject outcome 5.4 Unit 1: Particles.
Confidently complete all the work in Subject outcome 5.4 Unit 2: Elements, mixtures and compounds.

Introduction

In this unit you will learn about chemical and physical changes and understand examples of both. A chemical change occurs because of a chemical reaction. The new substances formed are not easily separated into the elements from which they are composed. A physical change is a change of state, such as between solid, liquid or gas, and is easily reversed.

Physical changes

A physical change is a change in which the particles of the substances that are involved do not change in any way. When water is heated, for example, both the temperature and energy of the water molecules increase, and the liquid water evaporates to form water vapour. When this happens, change has taken place, but the molecular structure of the water has not changed. This is an example of a physical change. All changes in state are physical changes.

$H_2O_{(l)} \rightarrow H_2O_{(g)}$

Conduction (the transfer of energy through a material) is another example of a physical change. As energy is transferred from one material to another, the energy of each material is changed, but not its chemical makeup.

Dissolving one substance in another is also a physical change.

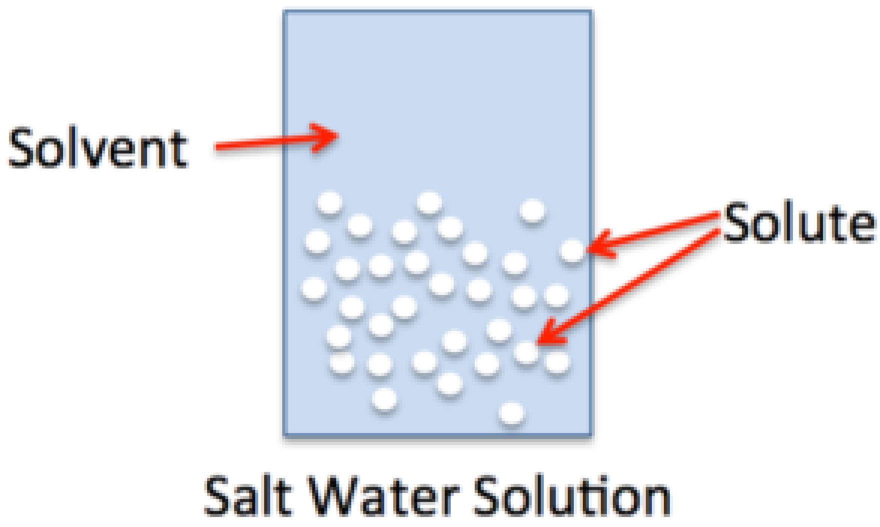


Figure 1: When salt is dissolved into water it does not change chemically

There are some important things to remember about physical changes in matter:

1. Arrangement of particles

   When a physical change occurs, the particles of the substance may re-arrange themselves, but the bonds between the atoms in the particles will not break. For example, when liquid water boils, the molecules will move apart but the molecule itself will stay intact. In other words, water will not break up into hydrogen and oxygen atoms.

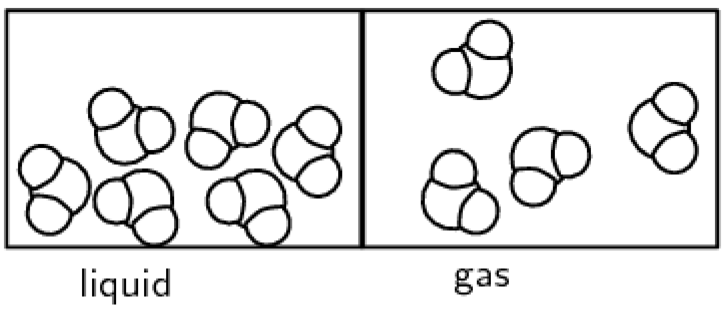


Figure 2: Water molecules move apart when heated but do not change their structure

2. Conservation of mass

   In a physical change the total mass, the number of atoms and the number of molecules will always stay the same. In other words, you will always have the same number of molecules or atoms at the end of the change as you had at the beginning.

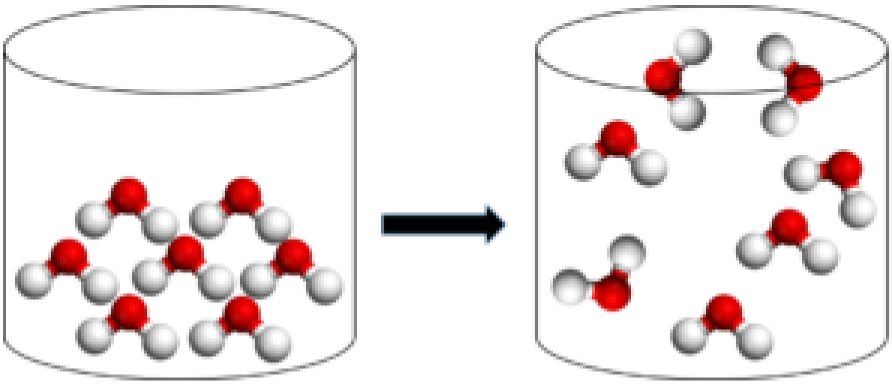


Figure 3: When water is heated, and it changes to a gas, the number of molecules in the system does not change when the state changes

3. Energy changes

   Energy changes may take place when there is a physical change in matter, but these energy changes are normally smaller than the energy changes that take place during a chemical change.

4. Reversibility

   Physical changes in matter are usually easier to reverse than chemical changes. Methods such as filtration and distillation can be used to reverse the change. Changing the temperature is another way to reverse a physical change. For example, a mixture of salt dissolved in water can be separated by filtration, and ice can be changed to liquid water and back again by changing the temperature.

Chemical changes

A chemical change is the result (product) of a reaction between two or more substances (reactants). There are several ways chemical changes occur:

Name of reaction	Reaction	General equation
Combination/ Synthesis	Two or more elements combine to form one compound.	$\mathrm{A+B \rightarrow AB}$ Example: $\mathrm{Sodium+Chlorine \rightarrow Sodium\ chloride}$ $\mathrm{2Na+Cl_2 \rightarrow 2NaCl}$
Decomposition	The opposite of a combination reaction. A complex molecule breaks down to make simpler ones.	$\mathrm{AB \rightarrow A+B}$ Example: $\mathrm{Calcium\ carbonate \rightarrow Calcium\ oxide+Carbon\ dioxide}$ $\mathrm{CaCO_3 \rightarrow CaO+CO_2}$
Precipitation	Two solutions of soluble salts are mixed resulting in an insoluble solid (precipitate) forming.	$\mathrm{soluble\ salt A+\ B \rightarrow precipitate\ +\ soluble\ salt\ C}$ Example: $\mathrm{Sodium\ chloride+Silver\ nitrate \rightarrow Silver\ chloride+Sodium\ nitrate}$ $\mathrm{NaCl+AgNO_3 \rightarrow AgCl+NaNO_3}$
Neutralisation	An acid and a base react with each other. Generally, the product of this reaction is a salt and water.	Acid + Base → Salt + Water Example: $\mathrm{Hydrochloric\ acid+Sodium\ hydroxide \rightarrow Sodium\ chloride+water}$ $\mathrm{HCl+NaOH \rightarrow NaCl+H_2O}$
Combustion	Oxygen combines with a compound to form carbon dioxide and water. These reactions are exothermic, meaning they give off heat.	$\mathrm{A+O_2 \rightarrow H_2O+CO_2}$ Example: $\mathrm{Glucose+oxygen\ Carbon\ dioxide+water}$ $\mathrm{C_6H_{12}O_6+6O_2 \rightarrow 6CO_2+6H_2O}$
Displacement	One element takes the place of another element in a compound.	$\mathrm{A+BC \rightarrow AC+B}$ $\mathrm{Zinc+Copper\ sulphate \rightarrow Zinc\ sulphate+copper}$ $\mathrm{Zn+CuSO_4 \rightarrow ZnSO_4+Cu}$

Figure 4: Burning magnesium to form magnesium oxide is an example of a chemical change

When a chemical change takes place, new substances are formed in a chemical reaction. These new products may have very different properties from the substances that were there at the start of the reaction. For example:

1. Light emission – certain chemical reactions produce light because of the reaction.
2. Bubbles – when a chemical change occurs in a liquid solution, and a gas is produced, bubbles can be seen in the liquid.

3. Change of colour – a substance changing in colour is an excellent indication that some form of chemical change has happened. Colour changes are particularly noticeable in transition metals. An example of how a change in colour indicates a chemical change is when copper (which is an orange-brown colour) oxidises (reacts with oxygen) to produce copper oxide (which is a greenish colour).
4. Odour change – chemical reactions can release molecules with certain smells, this is especially true of volatile chemicals.
5. Change of temperature – chemical reactions necessitate a shift in the energy of an object, and this energy change is frequently detectable as a change in temperature.
6. Formation of precipitate – precipitate refers to solid particles that are suspended in a solution and cause a clear solution to become cloudy.
7. Irreversible changes – while physical changes can often be easily reversed, chemical changes are generally more difficult to reverse and seldom occur spontaneously in nature.
8. Change in general form or composition – substantial changes in the composition or makeup of the substance often indicate chemical changes, such as when a wooden log turns into ash as it burns.
9. Mass is conserved – the mass of a closed system of substances will remain constant, regardless of the processes acting inside the system. Matter can change form but cannot be created or destroyed. This is known as the conservation of mass and applies to physical and chemical changes.

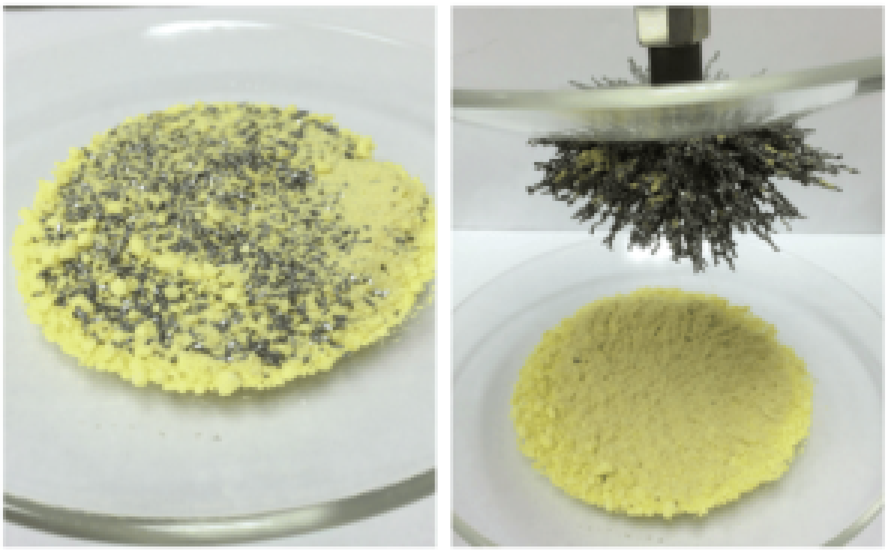
Example 1

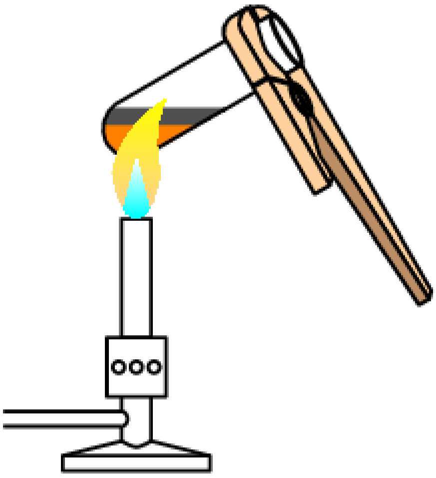
Explain the formation of iron sulfide.

Solution

Iron is a dull grey metal which is magnetic. Sulfur is a yellow non-metal which is not magnetic.

When iron and sulfur are mixed, they can easily be separated by using a magnet:





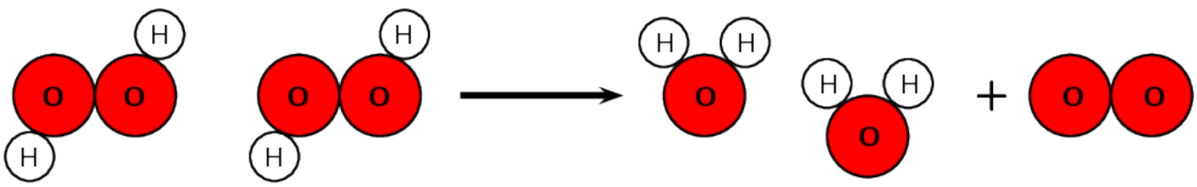
When the mixture is heated, the sulfur will change into an orange/brown liquid and give off a smell similar to rotting eggs. As heating continues the mixture will glow bright red and once sufficiently heated, the sulfur will react with the iron to form iron sulfide. Iron sulfide is a black solid which is not magnetic.

Example 2

Explain the decomposition of hydrogen peroxide.

Solution

The decomposition of hydrogen peroxide to form water and oxygen gas is an example of a chemical change.



The chemical bonds between O and H in H_2O_2 are broken down, and new bonds between H and O are formed (to form H_2O) and between O and O are formed (to form O_2).

When this is done in a laboratory, a catalyst is used to speed up the reaction and during the reaction oxygen bubbles are released.

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

Molecules	two molecules ($2H_2O_2$)	three molecules ($2H_2O+O_2$)
Energy changes	energy taken in when bonds are broken	energy given off when new bonds are formed
Atoms are conserved	4 oxygen atoms, 4 hydrogen atoms	4 oxygen atoms, 4 hydrogen atoms

You can watch a video of this reaction by jlambbio. (Duration: 1.56)

Activity 1: Make elephant toothpaste

What you need:

- ½ cup 6% hydrogen peroxide
- 1 teaspoon yeast
- 2 tablespoons hot water in a small dish
- 1 drop of food colouring
- washing-up liquid
- an small, empty, disposable plastic soda or water bottle
- a tray to stand the bottle on to catch the foam
- a funnel

What to do:

1. Pour the hydrogen peroxide into the bottle.
2. Mix the yeast in the water.
3. Add the washing up liquid and food colouring to the hydrogen peroxide in the bottle.
4. Add the yeast mixture to the bottle.
5. Stand back and admire the reaction! This reaction is exothermic (it gives out heat), so do not hold the bottle or stand too close during the reaction.
6. Record your observations.

What did you find:

When the yeast is added to the hydrogen peroxide, it foams rapidly and erupts out of the bottle. This is because hydrogen peroxide naturally breaks down over time into water and oxygen. Catalase, the enzyme in yeast, acts as a catalyst to speed up the reaction. The oxygen produced causes the washing up liquid to foam, and the food colouring just makes the whole thing look even cooler!

Note

Watch amazing chemical reactions. (Duration: 4.11)

Exercise 1.1

For each of the following, state whether a chemical or a physical change occurs.

1. Melting candle wax.
2. Frying an egg.
3. Mixing hydrochloric acid (HCl) and magnesium ribbon (Mg) to form magnesium chloride ($MgCl_2$).
4. Dissolving salt in water.

5. Melting ice cream.

The full solutions are at the end of the unit.

Note

For further explanation on chemical and physical changes watch this video by Chem Academy.

Physical vs. Chemical Changes – Explained (Duration: 7.40).

Representing chemical change by writing chemical equations

To represent chemical changes, we can write chemical equations.

For example, the reaction between iron and sulfur to form iron sulfide is:

$Fe + S \rightarrow FeS$

The decomposition of hydrogen peroxide is:

$2H_2O_2 \rightarrow 2H_2O + O_2$

In this equation you will notice that there is a 2 in front of the H_2O_2 and the H_2O. This number represents the number of molecules of the substance in the reaction.

The subscript numbers on the H and O in the equation represents the number of atoms of the element in each molecule.

Summary

In this unit you have learnt the following:

- Matter does not stay the same. It may undergo physical or chemical changes.
- A physical change is a change that can be seen or felt, but that does not involve the breaking of bonds of the particles in the reaction. During a physical change, the form of matter may change, but not its identity.
- During a physical change, the arrangement of particles may change but the mass, number of atoms and number of molecules will stay the same.
- Physical changes involve small changes in energy and are easily reversible.
- A chemical change occurs when one or more substances change into other substances. A chemical reaction involves the formation of new substances with different properties. For example, hydrogen and oxygen react to form water.
- A chemical change may involve a decomposition or synthesis reaction. During a chemical change, the

mass and number of atoms is conserved, but the number of molecules is not always the same.

Unit 1: Assessment

Suggested time to complete: 15 minutes

1. Which of the following statements is incorrect for a chemical reaction?
   a. Heat may be given out but never absorbed.
   b. Sound may be produced.
   c. A colour change may take place.
   d. A gas may be given off.
2. Which of the following is a physical change?
   a. Rusting of iron
   b. Combustion of magnesium ribbon
   c. Burning of candle
   d. Melting of wax
3. Which of the following is a chemical change?
   a. Twinkling of stars
   b. Cooking of vegetables
   c. Cutting of fruit
   d. Boiling of water
4. Sugar is dissolved into a mug of tea. What type of change is this?
   a. Chemical
   b. Physical
   c. Both chemical and physical
   d. Neither chemical nor physical
5. For each of the following definitions give one word or term:
   a. A change that can be seen or felt, where the bonds in the particles involved are not broken.
   b. The formation of new substances in a chemical reaction.
   c. A reaction where a new product is formed from elements or compounds.
6. For the following equations, state what kind of chemical change has occurred:
   a. $\text{Magnesium} + \text{oxygen} \rightarrow \text{magnesium oxide}$
   b. $\text{Hydrochloric acid} + \text{potassium hydroxide} \rightarrow \text{water} + \text{potassium chloride}$
   c. $\text{Magnesium} + \text{copper sulphate} \rightarrow \text{copper} + \text{magnesium sulphate}$

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

1. Physical change – as soon as the wax cools down it will change back into a solid.
2. Chemical change – the egg white has changed from a colourless liquid to a white solid.
3. Chemical change – a new substance is formed. The mixture will give off bubbles (this is the hydrogen).
4. Physical change – the salt can be separated from the water easily by evaporation.
5. Physical change – the ice cream has changed state. It will be able to go back to being a solid when the temperature is reduced.

Back to Exercise 1.1

Unit 1: Assessment

1. a
2. d
3. a
4. b
5.
    a. physical change
    b. chemical change
    c. chemical change
6.
    a. synthesis/combination
    b. neutralisation
    c. displacement

Back to Unit 1: Assessment

Media Attributions

Unit 2: Separating mixtures

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Separate a mixture by using either chemical or physical methods, such as:
    - manual methods
    - filtration
    - magnetism
    - chromatography
    - fractional distillation
    - precipitation reactions
    - separating funnel.

What you should know:

Before you start this unit, make sure you can:

- Confidently complete all the work in Subject outcome 5.4 Unit 1: Particles.
- Confidently complete all the work in Subject outcome 5.4 Unit 2: Elements, mixtures and compounds.

Introduction

In this unit you will learn about both the physical and chemical separation of mixtures. Physical separation does not change the chemical composition of the substances being separated. Physical separation can involve a change of state. Chemical separation occurs as a result of a chemical reaction.

Separating mixtures

A mixture is a made up of different elements and/or compounds which are not chemically joined and so they can be separated into different substances. Mixtures can be sorted physically or chemically.

Physical separation techniques

There are a few different ways that mixtures can be separated using physical methods.

Filtration

Filtration involves separating an insoluble solid from a mixture, for example sand and water, mud and water, tea leaves from water.

Swimming pool water is filtered through a sand filter to remove insoluble debris and air can be filtered through membranes to remove dust and other particles.

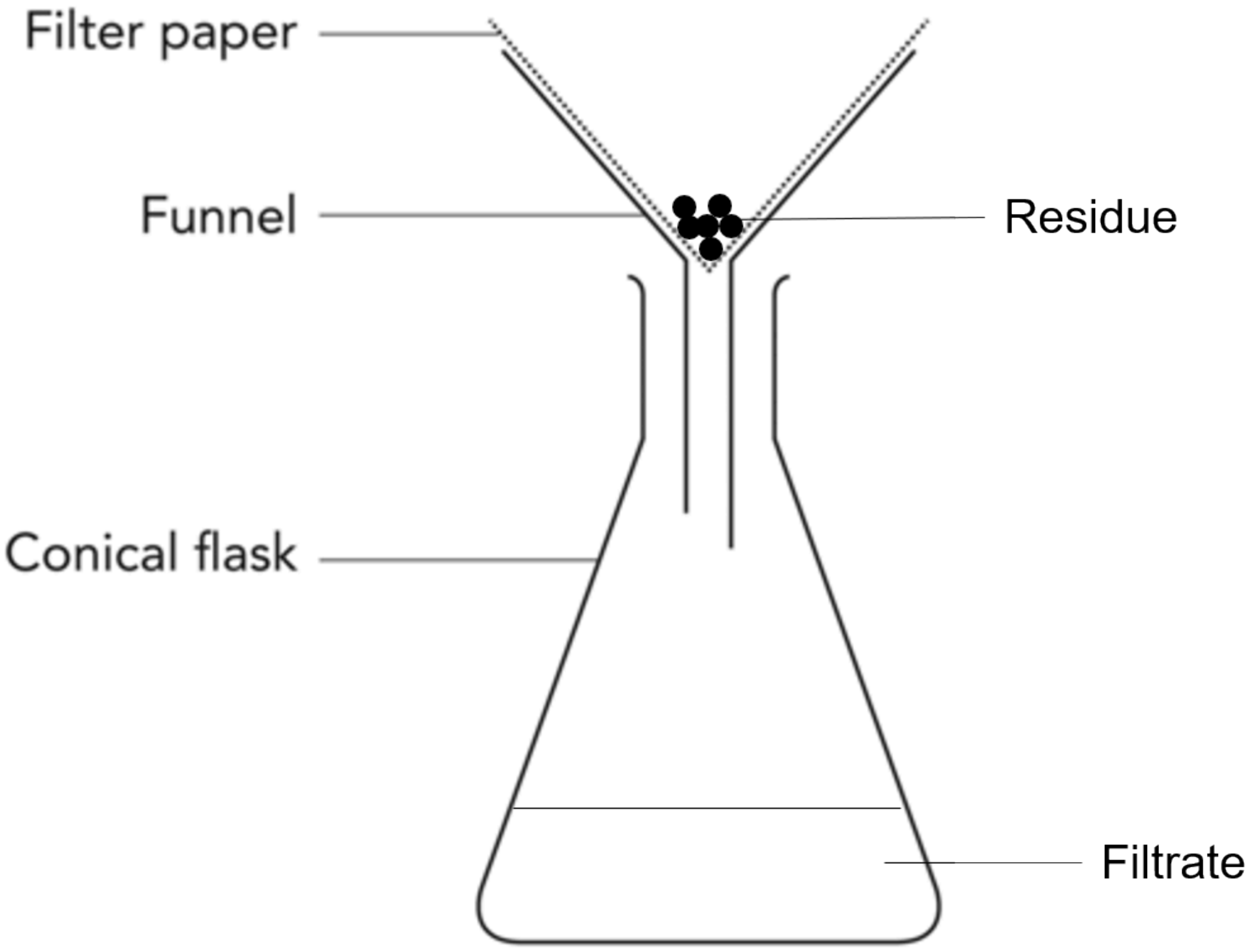


Figure 1: Apparatus that can be used for filtration

Magnetism

Magnetism involves separating a magnetic substance from a non-magnetic one using a magnet.

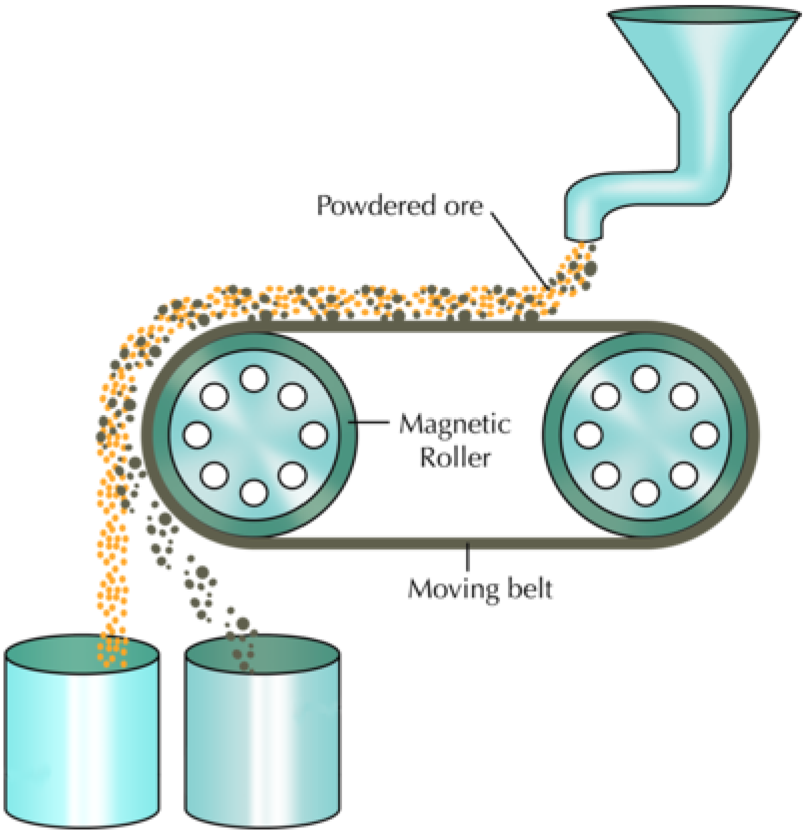


Figure 2: Magnetism is used in mining to separate metal ore from soil and rocks

Evaporation

Evaporation involves separating a soluble solid from a liquid, for example salt from sea water.

Evaporation works by allowing the liquid to change into a gas leaving the solid that was dissolved behind. Using heat will speed up the process.

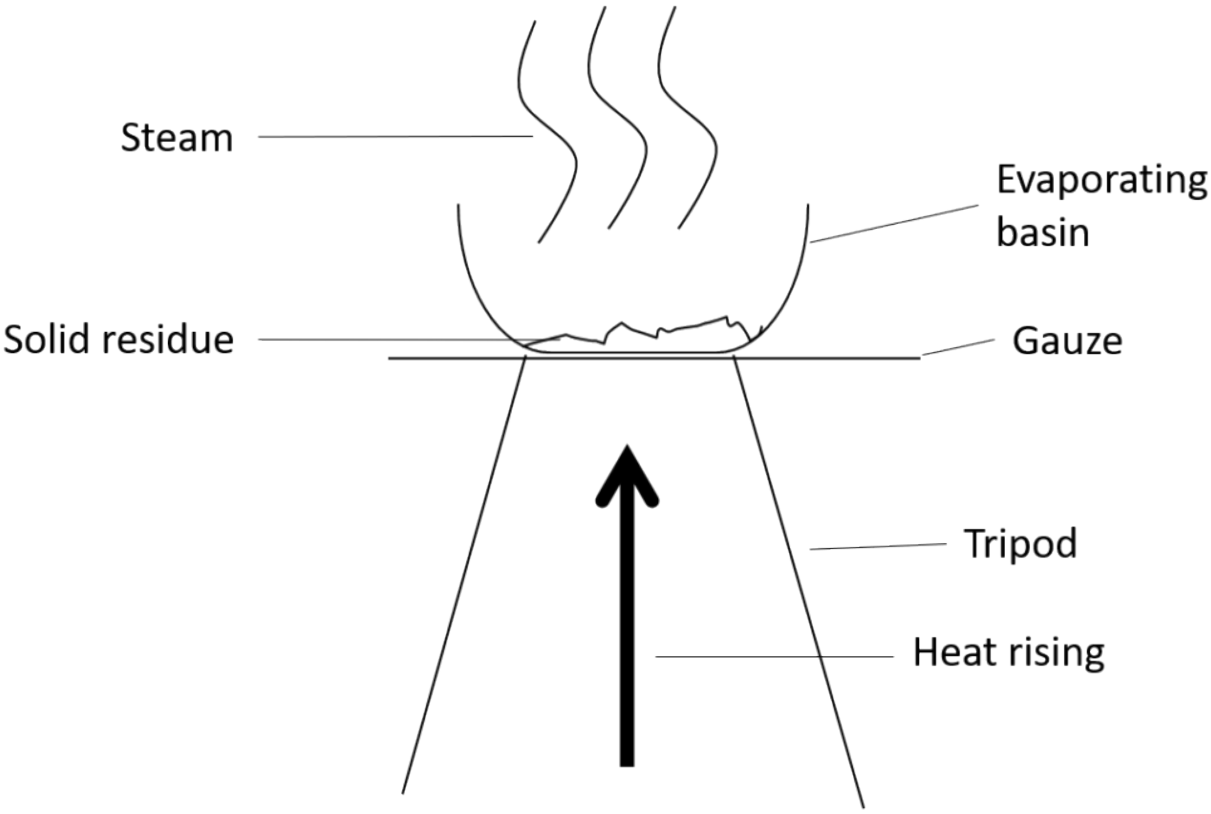


Figure 3: Apparatus that can be used for evaporation

Figure 4: Sea water is pumped into shallow ponds from where the water evaporates and salt is left behind

Simple distillation

Simple distillation is the separation of a mixture of liquids with different boiling points. The liquid with the lowest boiling point will boil off first, leaving behind the liquid with the higher boiling point.

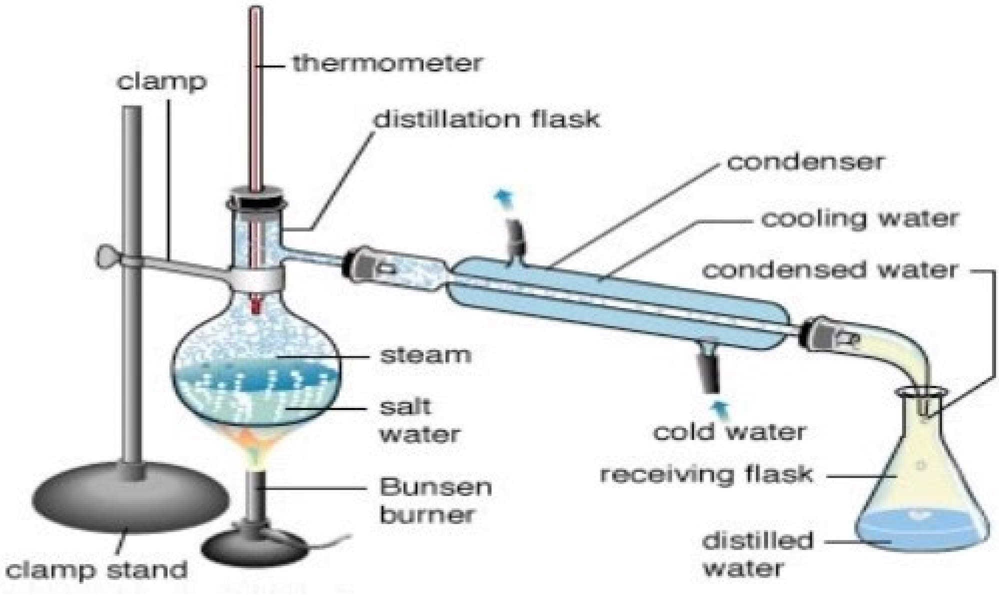


Figure 5: Simple distillation apparatus

The simple distillation process:

A mixture of liquids is put into the round bottomed flask

↓

Temperature is maintained at that of the substance with the lower boiling point.

↓

The liquid with the lowest boiling point will boil first – changing from a liquid to a gas.

↓

The gas will then travel down the Liebig Condenser. Cold water runs around the Liebig Condenser to cool the gas, which will condense back into a liquid and drip into the receiving flask.

Alcoholic drinks such as whiskey and brandy are distilled to separate the alcohol from water. Alcohol has a lower boiling point than water. Many distilleries use huge copper vats called stills to boil off the alcohol from the mixture.

Figure 6: The copper stills at the Glenfiddich Distillery in Scotland

Fractional distillation

Fractional distillation separates a mixture into several different parts, called fractions.

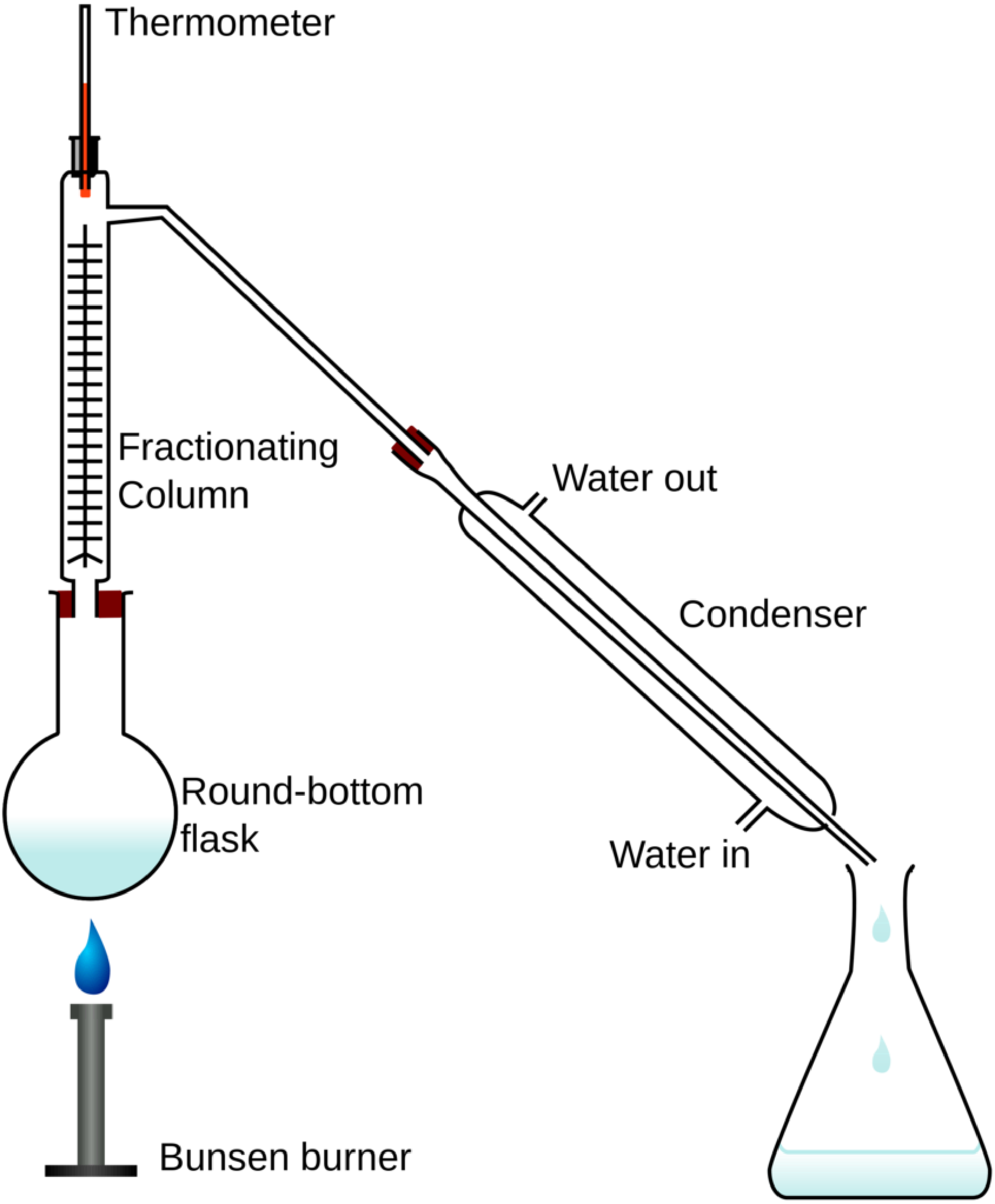


Figure 7: Laboratory apparatus used to separate more than one liquid from a mixture

Crude oil is distilled using fractional distillation. Crude oil is a mixture consisting of chains of carbon atoms of different lengths. The length of the carbon chain determines its boiling point. The crude oil is evaporated, and its vapours condense at different temperatures in the fractionating column. Each fraction contains hydrocarbon molecules with a similar number of carbon atoms and a similar range of boiling points.

A tall fractionating column is fitted above the heated mixture, with several condensers coming off at different heights. The column is hot at the bottom and cool at the top. Substances with high boiling points, those with longer carbon chains, condense at the bottom and substances with lower boiling points, those with shorter carbon chains, continue to rise and condense at various other points along the condenser.

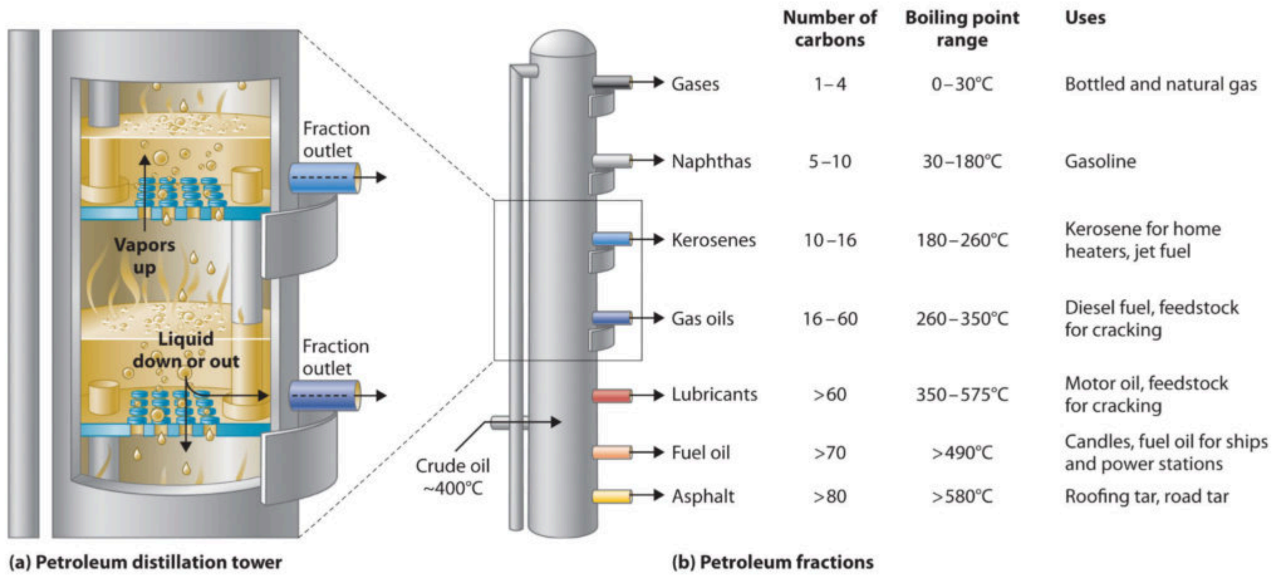


Figure 8: The separation of crude oil in a fractionating column

Note

For further explanation about fractional distillation, watch this video:
Fuse Schools: Fractional Distillation (Duration:4.05).

Separating funnel

A separating funnel can be used to separate two immiscible liquids.

A separating funnel is a glass funnel with a tap at the bottom. The mixture of liquids is placed inside the separating funnel. The liquid with the lower density floats on top. When the tap is opened, the liquid with the higher density starts to flow through the separating funnel into the container. The tap is closed when the transition point between the two layers is just above the tap. Using another container, the rest of the top layer and the first part of the second layer is allowed to run through the tap. This sample is discarded. The rest of the second liquid is then allowed to run into a third container.

In Figure 10 you can see that 1 shows the less dense liquid and 2 shows the denser liquid that can be removed first.

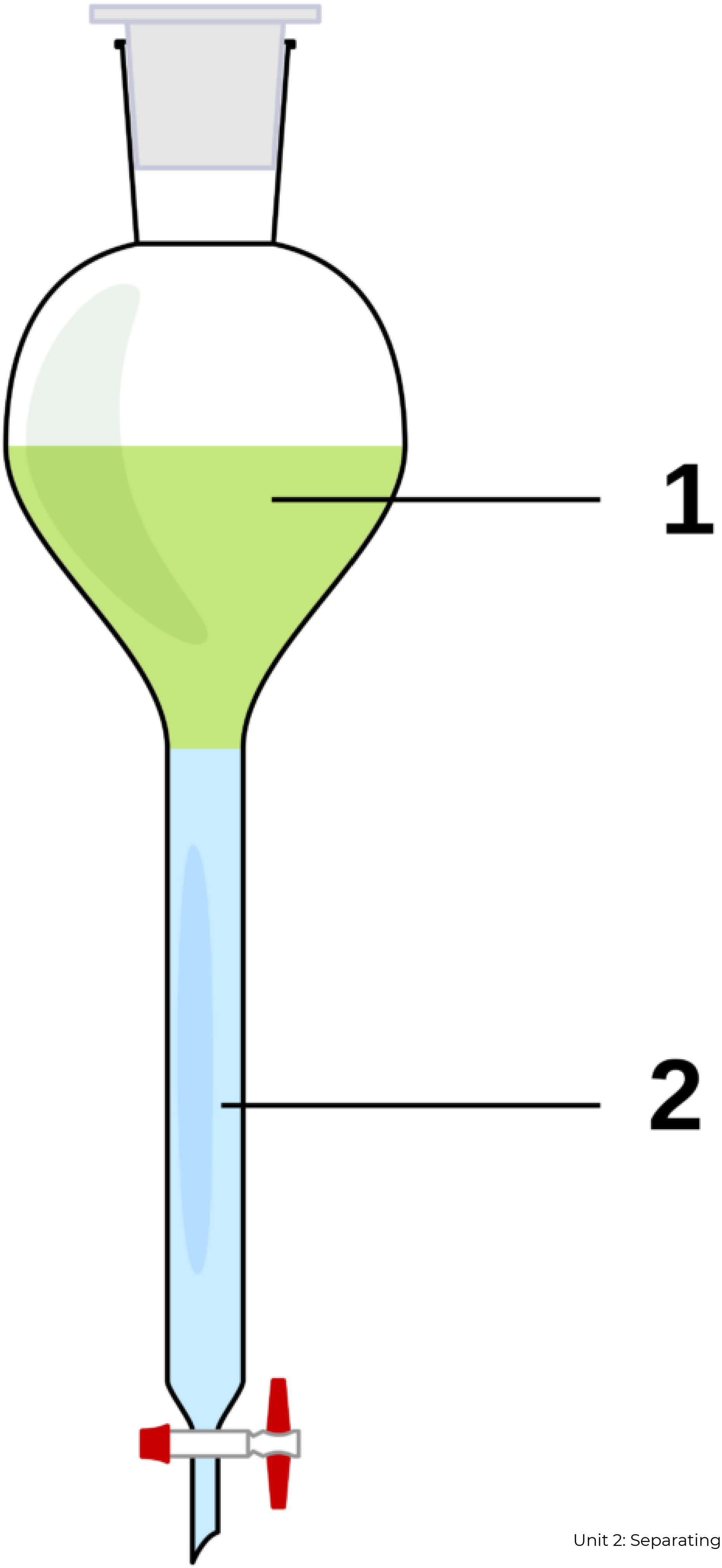

1
2

Figure 10: A separating funnel

Exercise 1.1

1. In a coffee machine, the ground coffee is separated from the coffee solution by using:
   a. toilet paper
   b. tissue paper
   c. filter paper
   d. sandpaper
2. Evaporation is used to:
   a. separate solids of different particle size.
   b. obtain the solute from the solution.
   c. separate liquids of different boiling points.
   d. separate the dyes in a marker.
3. Water and alcohol are easily separated by distillation because of their:
   a. different colours
   b. different boiling points
   c. different melting points
   d. different densities.
4. Which one of the following pairs of separation techniques will BOTH separate salt from a mixture of salt and water?
   a. decanting and filtration
   b. distillation and evaporation
   c. decanting and distillation
   d. chromatography and evaporation.
5. Which one of the following is a disadvantage of evaporation?
   a. the solvent is not recovered
   b. it always requires heat
   c. it cannot be used for insoluble solids
   d. all the solute is recovered

The full solutions are at the end of the unit.

Chemical separation techniques

Chemical separation is when you use a chemical substance to separate a mixture.

A primary way that mixtures can be separated using chemical separation. This is called precipitation. A precipitation reaction is the formation of an insoluble salt when two solutions containing soluble salts are combined. The insoluble salt that settles in a solution is known as the precipitate. The solids produced in precipitate reactions are crystalline solids and can be suspended throughout the liquid or settle at the bottom of the solution. The remaining fluid is called supernatant liquid. The two components of the mixture (precipitate and supernate) can be separated by various methods, including filtration.

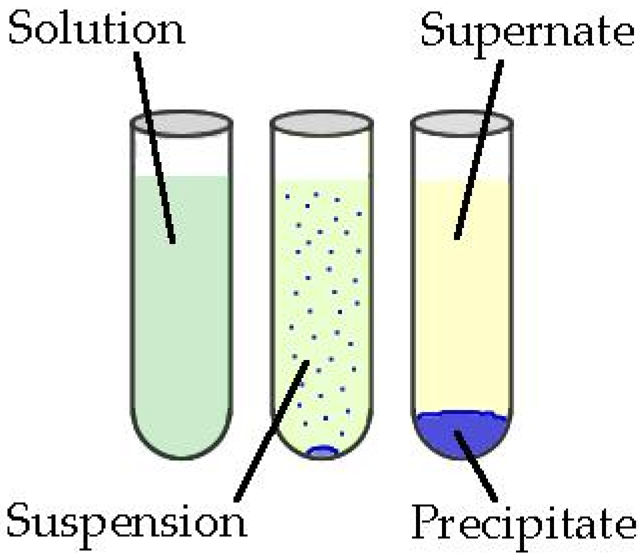


Figure 11: The formation of a precipitate is a chemical separation technique

The following reaction between silver nitrate and copper is a common precipitation reaction:

$Cu + 2AgNO_3 \rightarrow 2Ag + Cu(NO_3)_2$

A piece of copper suspended in aqueous silver nitrate will cause the silver to precipitate out of the solution and form on the wire. The solution will go blue because the copper reacts with the nitrate ions $(NO_3)^-$ to form copper nitrate. Copper is more reactive than silver which is why it will displace the silver from the solution.

Figure 12: The precipitation reaction between silver nitrate and copper

Activity 1: Precipitation of copper

Time required: 15 minutes

What you need:

- 25 g copper sulfate
- 2 iron nails
- hot water
- a glass or transparent beaker
- string
- a pencil or stick

What to do:

1. Dissolve 25g of copper sulfate into 100 ml of hot water in the glass.
2. Stir the mixture until it has dissolved.
3. Tie the two iron nails together with the string and suspend them from the pencil or stick lying on top of the glass. The nails must be suspended in the copper sulfate solution.
4. Leave the reaction for 24 hours and note your observations.

What did you find?

Copper is a reddish-brown colour, and it will precipitate out of the solution and begin to form on the nails. The solution will also change colour from blue to a greenish colour as the iron dissolves into the solution to form iron sulfate. This precipitation reaction happens because copper is less reactive than iron.

Chromatography

Chromatography is used to separate a mixture according to the solubility of the dissolved molecules. Paper chromatography has two phases, the stationary phase which is the paper and the mobile phase which is the solvent being used. The mixture is placed on the paper a little way from the edge and then the lower edge of the paper is placed in the solvent. The components of the mixture will separate on the paper and show up as different spots. This is called a chromatogram. An impure substance will therefore produce a chromatogram with more than one spot. If two or more mixtures have the same components, they will produce identical chromatograms.

The solvents used in chromatography are water, if the substance you are separating is water soluble, and if the substance is insoluble then ethanol is used.

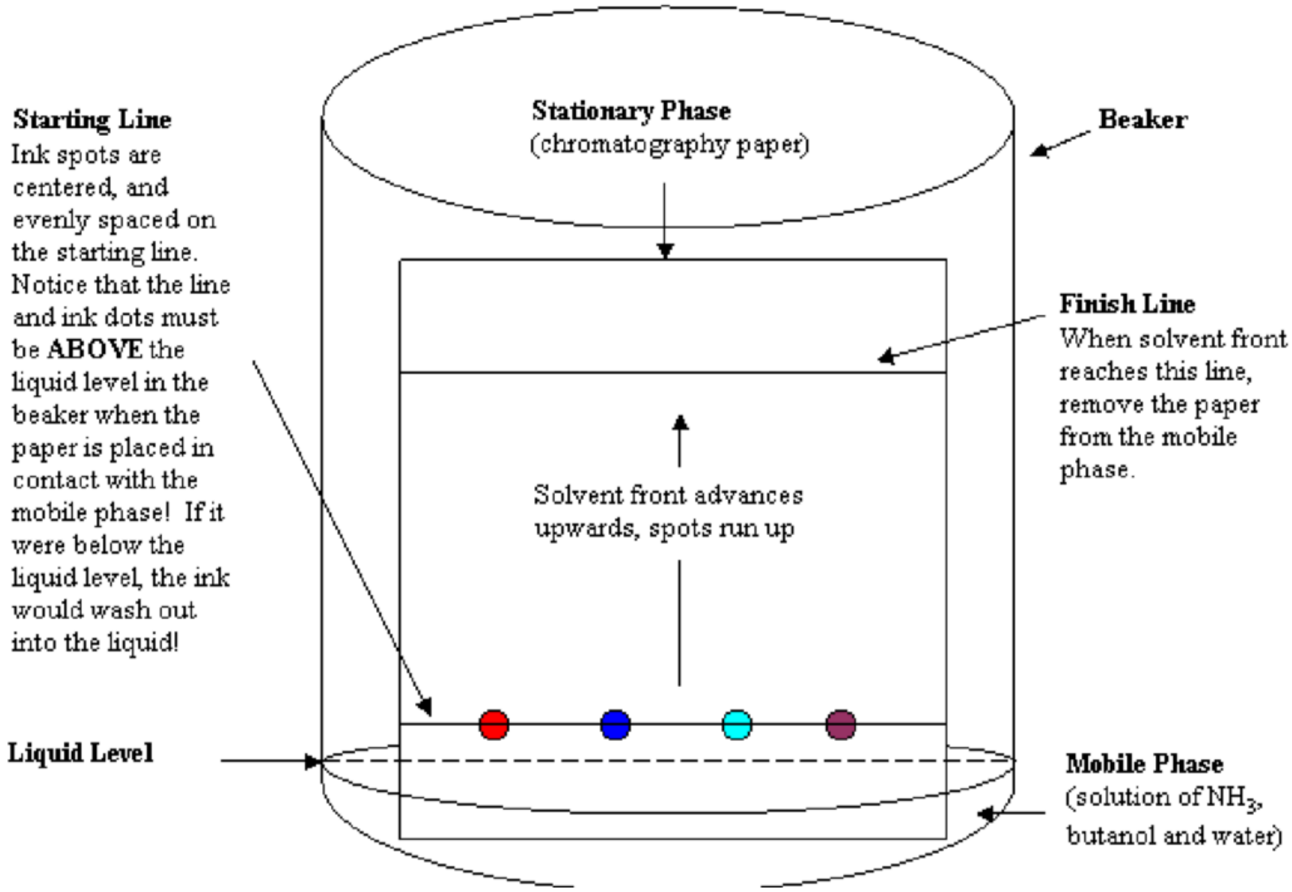


Figure 9: Paper chromatography being used to separate the colours in ink

The unknown components of mixtures can be identified by comparing them with chromatograms of known substances.

Paper chromatography is carried out on the unknown sample and a sample of a known compound. This is done simultaneously on the same paper using the same solvent. If the resulting spot(s) are at the same height, then the substance being tested is the same as the known substance.

Activity 1: Separating inks in kokis

Time required: 30 minutes

What you need:

- different coloured kokis or food colouring (hint: Black, brown, green, dark blue and purple are the most successful colours to use)
- white coffee filters
- a medicine dropper
- transparent glass
- water
- scissors
- a pencil
- sticky tape

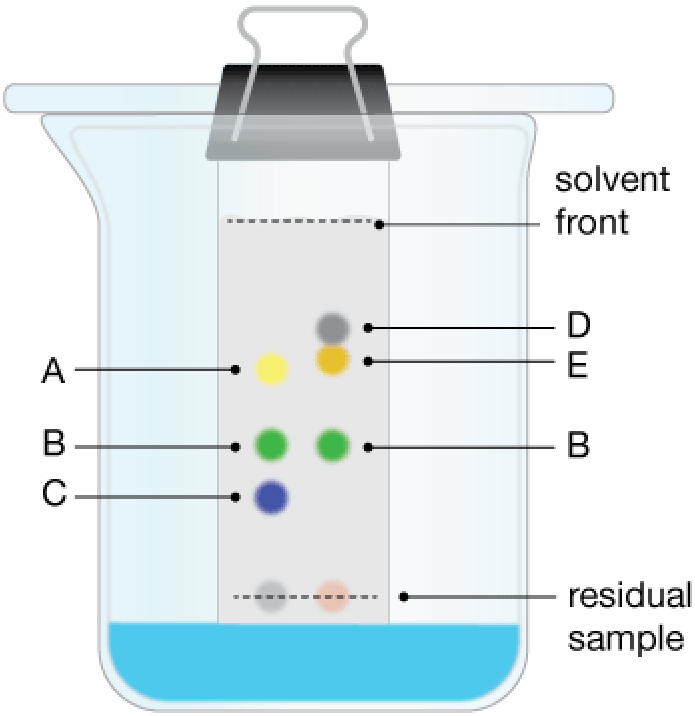
What to do:

Part 1:

1. Take 1 coffee filter, in the centre draw a blob of ink using a koki or a drop of food colouring.
2. Place it over the glass.
3. Using the medicine dropper, carefully drop 1 drop of water on the centre of the ink blob.
4. Add a further drop of water once the ink has stopped moving and continue until the ink does not move anymore. Be careful to only add the water to the centre of the ink blob.

Part 2:

1. Fill the glass with approximately 1 centimetre of water.
2. Cut a long thin strip of filter paper. Draw a pencil line approximately 1 centimetre from the bottom of the paper.
3. Draw a blob of ink on the pencil line using a koki or a drop of food colouring.
4. Secure the top of the piece of paper around the pencil with tape and hang the paper in the glass making sure the paper reaches the water but the water must not touch the ink.



What did you find?

As the ink dissolves in the water soaking the filter paper, it begins to spread out along the filter paper. This is because the ink is soluble in the water and the ink will separate out into the different coloured inks it is made of according to the solubility of the particles. The further the particles travel the more soluble they are in the solvent.

Summary

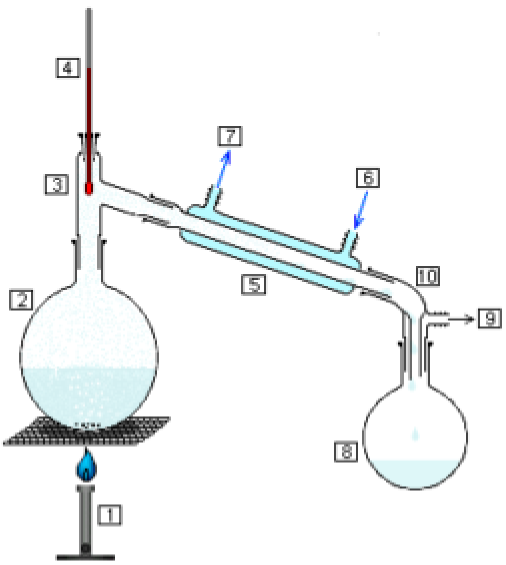
In this unit you have learnt the following:

- Chemical reactions involve large changes in energy. Chemical reactions are not easily reversible.
- Mixtures can be separated physically or chemically.
- Chemical methods of separation include precipitation reactions.
- Physical methods of separation include:
  - chromatography
  - simple and fractional distillation
  - evaporation
  - filtration
  - magnetic separation.

Unit 2: Assessment

Suggested time to complete: 20 minutes

1. Think carefully about the following statements. Are they true or false?
   a. In filtration, the filtrate is always a pure liquid.
   b. Drinking water can only be obtained from seawater by distillation.
   c. The fractional distillation of liquids is only possible if the liquids have different boiling points.
   d. Paper chromatography is a physical method of separating mixtures.
   e. Mixtures have fixed melting and boiling points.
2. Name the technique most suited to separate the following mixtures:
   a. To obtain drinking water from muddy water.
   b. To separate petrol from crude oil.
   c. To obtain pure sugar from a solution.
   d. To determine whether the colouring in a fruit juice is a single substance or a mixture of coloured substances.
3. Distillation can be used to separate a mixture of liquids with different boiling points, or a solid from a liquid where the solvent is recovered.



   a. Name the separation process shown in the diagram.
   b. Explain the benefit of using distillation to separate a soluble solid from a liquid, as opposed to

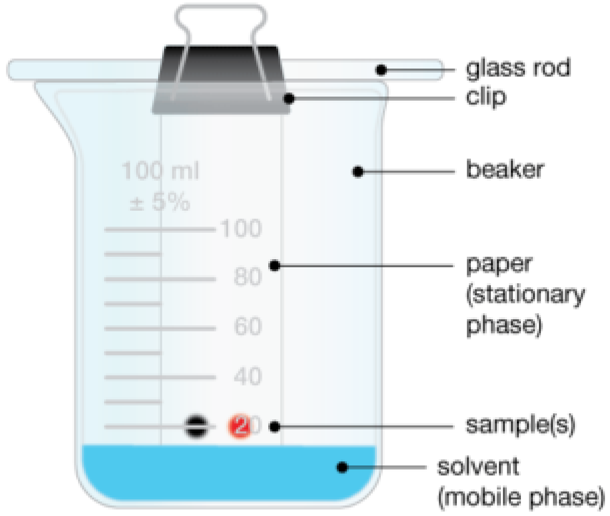
evaporation.

c. Name the item labelled 5 in the diagram.

d. Identify the part 6 or 7 of item 5 which is connected to the cold tap.

e. How could you show that the water collected contains no salt?

4. Paper chromatography can be used to separate the dyes in a sample of ink.



a. The ink spot is placed on the chromatography paper just above the level of the solvent. Why?

b. What happens to the ink spot as the water moves up the paper?

c. What would happen to a spot of water-soluble ink consisting of a single-coloured dye if it were used in the above experiment?

5. Is a precipitation reaction a chemical or physical change? Explain your answer.

The full solutions are at the end of the unit.

Unit 2: Solutions

Exercise 2.1

1. c
2. b
3. b
4. b
5. a

Back to Exercise 2.1

Unit 2: Assessment

1.
   a. false
   b. true
   c. true

d. true
e. false

2.
a. distillation/filtration
b. fractional distillation
c. evaporation
d. chromatography

3.
a. simple distillation
b. the solvent is recovered
c. condenser
d. water in
e. boil the water; if the water is pure then it will boil at 100 ^{o}C at sea level

4.
a. so the ink does not flood into the water
b. the ink dissolves into the solvent and is carried up the paper
c. it would only make 1 spot on the paper

5. Displacement reactions are chemical changes because a new substance is made.

Back to Unit 2: Assessment

Media Attributions

SUBJECT OUTCOME XVI

CHEMICAL CHANGE: IDENTIFY, DESCRIBE, AND APPLY PRINCIPLES OF CHEMICAL REACTIONS (ELECTROLYTES)

Subject outcome

Subject Outcome 6.3: Identify, describe, and apply principles of chemical reactions (electrolytes)

Learning outcomes

- Identify and describe electrolytes.
- Describe hydrolysed salts as sources of electrolytes and determine the solubility of salts as measured by conductivity of solution.
- Identify acids as potential sources of electrolyte.
- Identify the interaction (displacement reactions) and effect of ions in aqueous solutions (e.g. corrosive).

Unit 1 outcomes

By the end of this unit you will be able to:

- Give a definition of an electrolyte and identify them.
- Identify salts which are sources of electrolytes.
- Determine their solubility by how much electricity they conduct.
- Identify acids which are sources of electrolytes.
- Identify the effects of ions in an aqueous solution.

Unit 1: Principles of chemical reactions

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Give a definition of an electrolyte and identify them.
- Identify salts which are sources of electrolytes.
- Determine their solubility by how much electricity they conduct.
- Identify acids which are sources of electrolytes.
- Identify the effects of ions in an aqueous solution.

What you should know:

Before you start this unit, make sure you can:

- Confidently complete all the work in Subject outcome 5.4 Unit 2: Elements, mixtures, and compounds.
- Confidently complete all the work in Subject outcome 6.2 Unit 1: Chemical and physical change.
- Confidently complete all the work in Subject outcome 6.2 Unit 2: Separating mixtures.

Introduction

Some chemical substances can conduct electricity when they are solid like metals. Other chemical substances can conduct electricity when they have been dissolved in a liquid. For a substance to conduct electricity, it must contain charged particles that are free to move. Metals, for example, conduct electricity because the valence electrons are free to move.

Solutions can conduct electricity if they contain ions, as these are charged particles and they are free to move in the solution. These substances are called electrolytes. Examples of electrolytes include acids, bases, and salt solutions.

Activity 1.1: Dissolving compounds

Time required: 10 minutes

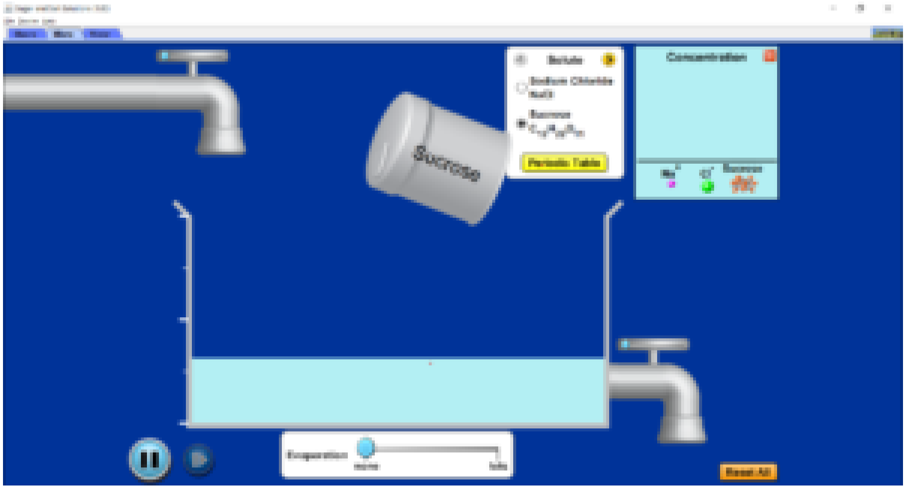
What you need:

- a computer with JAVA installed

What to do:

1. Open the Sugar and Salt Solutions simulation.

2. On the top left-hand corner, press the 'micro' tab.



3. Select sucrose as the solute, and then add sucrose to the water by shaking (clicking and dragging) the container over the water.
4. What do you notice about the sucrose molecules in the water?
5. Press the reset all button.
6. Change the solute to sodium chloride and shake it into the solvent.
7. What do you notice about the sodium chloride? How does this compare to the sucrose?
8. Press the tab which says water. Add the sodium chloride.

What did you find?

Sucrose is a covalently bonded substance. The molecules are neutral. When added to water, the molecules move around in the water, but they are still neutral. Sucrose solution will not conduct electricity and is therefore not an electrolyte.

Sodium chloride has ionic bonds. In the solid phase it is made up of sodium ions (Na^+) and chloride ions (Cl^-) tightly packed together in a crystal lattice. When a NaCl solid dissolves in water the ions separate and are free to move around in the solution. This process is called dissociation. Because the ions are now free to move, the solution can conduct electricity. Sodium chloride solution is therefore an electrolyte.

Electrolytes

Electrolytes are substances that contain free ions and behave as electrically conductive media. As we learnt in Activity 1.1, sodium chloride solution is an electrolyte because sodium chloride dissolves in water leaving the ions free to move around. So, the ions dissociate from one another.

The equation for the dissociation is:

$$\text{Sodium chloride} \rightarrow \text{sodium ions} + \text{chloride ions}$$

$NaCl_{(s)} \rightarrow Na^{+}_{(aq)} + Cl^{-}_{(aq)}$

When sodium metal bonds ionicly to chlorine, the sodium atoms lose electrons and form positively charged cations (Na^{+}) and the chlorine atoms gain electrons to form negative anions (Cl^{-}).

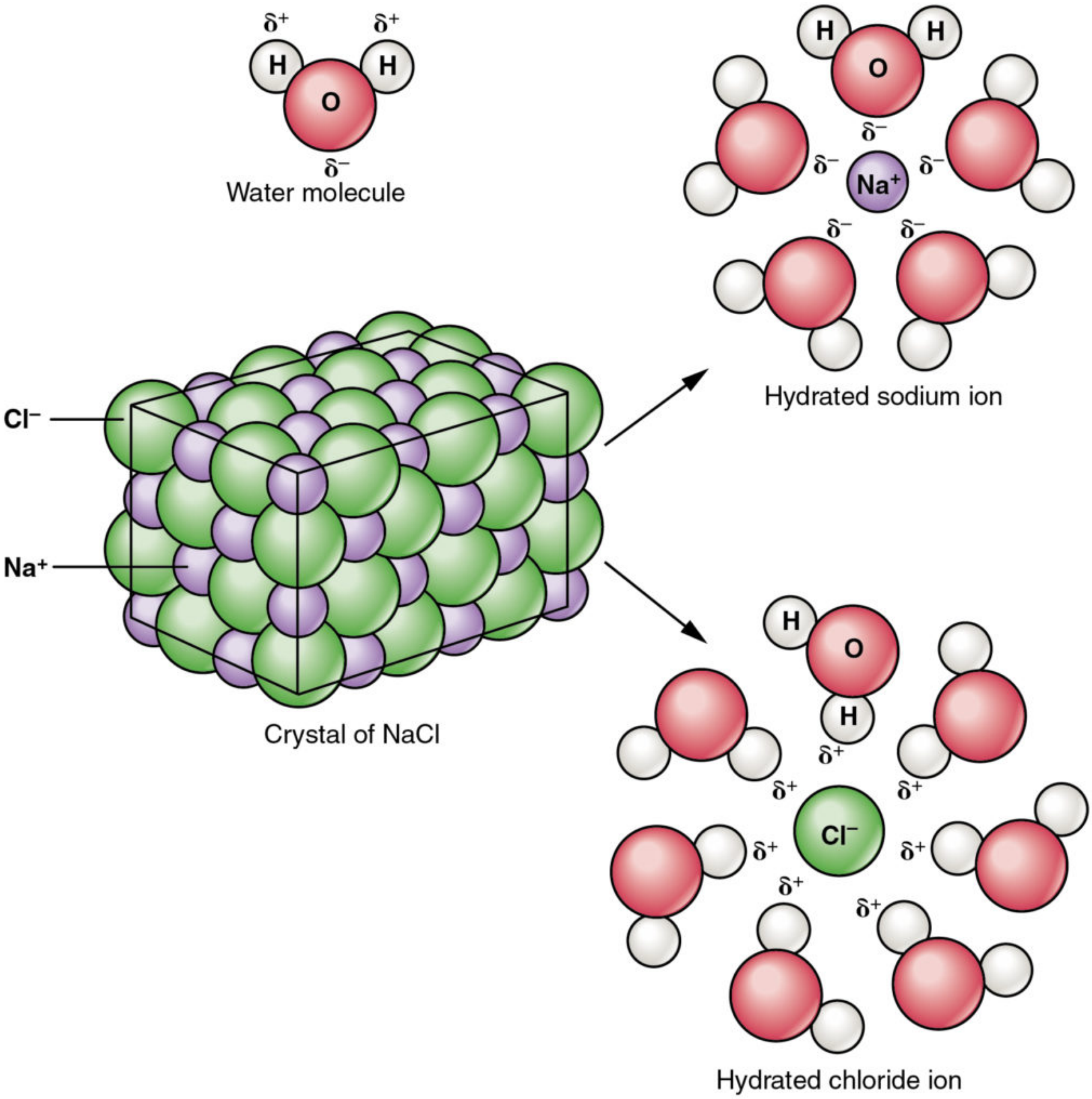


Figure 1: When a sodium chloride crystal is placed in water, the ions can move apart and move freely

We say that dissolution of a substance has occurred when a substance dissociates or dissolves. Dissolving is a physical change that takes place. It can be reversed by evaporating off the water.

Most ionic compounds (salts) will dissociate in water. The metal ions of the salt are always positively charged (cations) and the non-metals ions are negatively charged (anions).

Some salts contain groups of atoms that are covalently bonded together and behave as a single unit. They can be positively or negatively charged and are called polyatomic ions. The most common ones are listed below with their name and formula:

Ammonium: NH_4^+

Nitrate: NO_3^-

Carbonate: CO_3^{2-}

Oxide: O^{-2}

Permanganate: MnO_4^-

Phosphate: PO_4^{3-}

Sulphate: SO_4^{2-}

Hydroxide: OH^-

Hydronium: H_3O^+

Acids as electrolytes

Acids will dissociate in water and form electrolytes. Weak acids form weak electrolytes and strong acids will form strong electrolytes.

For example, carbonic acid is a weak acid:

$$H_2CO_{3(aq)} \rightleftharpoons H^+_{(aq)} + HCO^-_{3(aq)}$$

Note

The $\rightleftharpoons$ arrows indicate that the reaction is reversible.

A strong acid, for example hydrochloric acid, will dissociate easily and readily form hydronium ions (H_30^+). These are strong electrolytes.

$$HCl_{(aq)} + H_2O_{(l)} \rightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$$

Chemical equations for dissociation

Chemical equations are written to show the amounts of substances involved and to show the compounds formed because of a chemical change.

Ionic equations such as: $NaCl_{(s)} \rightarrow Na^+_{(aq)} + Cl^-_{(aq)}$ are written to show the dissociation of the ionic compound in water. The + and – symbols show what charge the ions have when in an aqueous solution. The bracketed subscript (s) are state symbols; they show what state the compound or ions are in.

(s) = solid, (l) = liquid, (g)= gas, (aq) = aqueous

The dissolution of potassium sulfate into potassium and sulfate ions is shown below as another example:

$$\text{Potassium sulfate} \rightarrow \text{potassium ions} + \text{sulfate ions}$$

$$K_2SO_{4(s)} \rightarrow 2K^+_{(aq)} + SO^{-2}_{4(aq)}$$

Ionisation

Molecular substances (covalent compounds) may also dissolve, but most will not form ions. One example is glucose:

$\text{Glucose} \rightarrow \text{Glucose}$

$C_6H_{12}O_{6(s)} \rightarrow C_6H_{12}O_{6(aq)}$

These solutions will not conduct electricity because there are no free-moving charged particles (ions). They are not electrolytes.

Some covalently bonded substances, however, will form ions when they dissolve by reacting with water molecules. This process is called ionisation. Hydrogen chloride, for example, can ionise to form hydrogen and chloride ions.

$\text{hydrogen chloride+water} \rightarrow \text{hydronium ions} + \text{chloride ions}$

$HCl_{(g)} + H_2O_{(l)} \rightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$

This solution will conduct electricity because there are now free-moving ions. It is an electrolyte.

$HCl_{(aq)} + H_2O_{(l)} \rightarrow H_3O^+_{(aq)} + Cl^-_{(aq)}$

Below is an example of how to work with dissociation equations.

Example 1

1. Write the chemical equation that represents the dissociation of the compound potassium bromide. (KBr)
2. Write the chemical equation that represents the dissociation of the sodium sulphate (Na_2SO_4).

Solutions:

1. KBr is an ionic compound and will completely dissociate when it is dissolved into water:

   $KBr_{(s)} \rightarrow K^+_{(aq)} + Br^-_{(aq)}$

2. The two sodium ions will dissociate from the compound and go their own way, but the sulfate ion will stay together.

   The dissolving equation is therefore $Na_2SO_{4(s)} \rightarrow 2Na^+_{(aq)} + SO^{2-}_{4(aq)}$

Exercise 1.1

1. For each of the following, say whether the substance is ionic or molecular.
   a. potassium nitrate (KNO_3)

   b. ethanol (C_2H_5OH)
   c. sucrose ($C_{12}H_{22}O_{11}$)
   d. sodium bromide ($NaBr$)
2. Sodium hydroxide will dissociate in water to form sodium and hydroxide (OH) ions.
   a. Identify the:
      i. cations
      ii. anions
   b. Write an ionic equation to show the dissociation. Do not forget to include state symbols.
3. Write dissociation equations for the following:
   a. iron sulfate ($FeSO_{4(s)}$)
   b. zinc chloride ($ZnCl_{2(s)}$)
   c. sodium hydroxide ($NaOH_{(s)}$)

The full solutions are at the end of the unit.

Electrolytes and conductivity

A strong electrolyte is one where many ions are in high concentration in the solution and a weak electrolyte is one where ions are in low concentration. Strong electrolytes are good conductors of electricity and weak electrolytes are weak conductors of electricity. Non-electrolytes do not conduct electricity at all.

Conductivity in aqueous solutions is a measure of the ability of water to conduct an electric current. The more ions there are in the solution, the higher its conductivity. The more ions there are in solution, the stronger the electrolyte.

Factors that affect the conductivity of electrolytes

The conductivity of an electrolyte is affected by the following factors:

1. The concentration of ions in a solution. The higher the concentration of ions in a solution, the higher its conductivity will be.
2. The type of substance that dissolves in water. Whether a material is a strong electrolyte (for example potassium nitrate, (KNO_3), a weak electrolyte (for example acetic acid, CH_3COOH) or a non-electrolyte (for example sugar, alcohol or oil) will affect the conductivity of water because the concentration of ions in a solution will be different in each case. Strong electrolytes form free-moving ions easily, weak electrolytes do not form ions easily and non-electrolytes do not form ions in a solution.
3. Temperature. The warmer the solution, the higher the solubility of the material being dissolved and therefore the higher the conductivity as well.

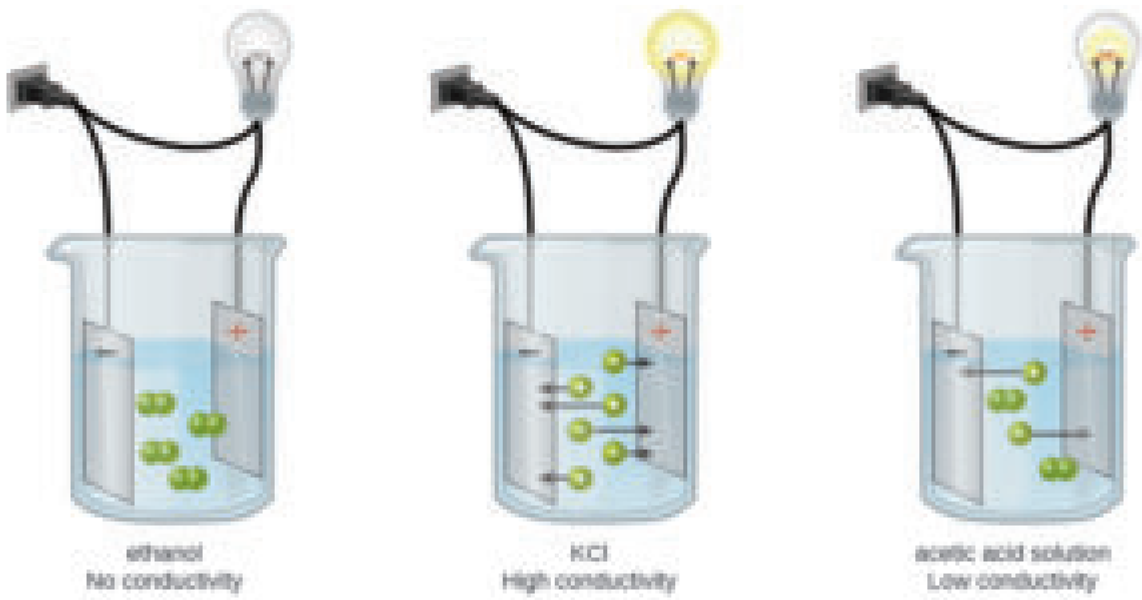


Figure 2: Solutions with varying levels of conductivity

Solutions of non-electrolytes such as ethanol do not contain dissolved ions and cannot conduct electricity. Solutions of electrolytes contain ions that permit the passage of electricity. The conductivity of an electrolyte solution is related to the strength, concentration, and temperature of the electrolyte.

Activity 1.2: Conduction of electricity in a solution

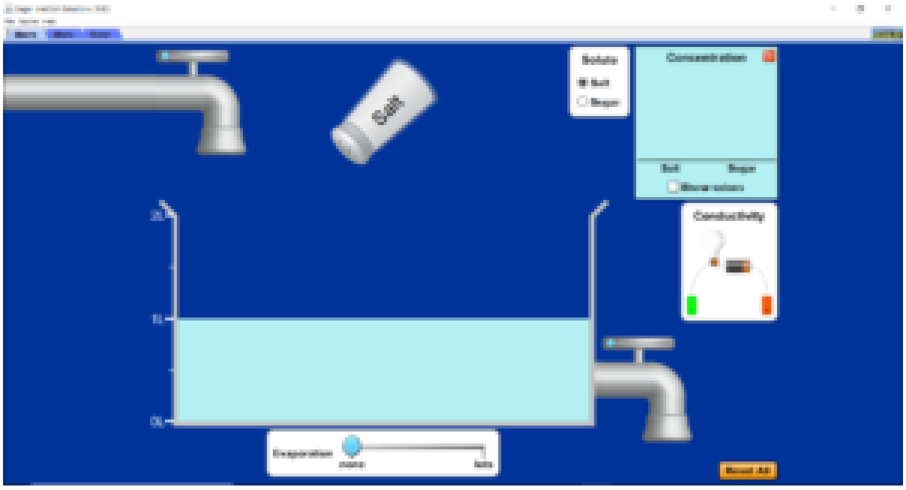
Time required: 10 minutes

What you need:

- a computer with JAVA installed

What to do:

1. Open the Sugar and Salt Solutions simulation.
2. On the top left-hand corner, press the 'macro' tab.



3. Drag the conductivity apparatus into the water.
4. Add salt to the water by shaking the salt cellar with your mouse.
5. What do you notice about the brightness of the bulb?
6. Press the reset all button.
7. Add the conductivity apparatus, select sugar as the solute add sugar to the water with your mouse.
8. What do you notice about how the sugar effects the bulb? How does this compare to the salt (sodium chloride)?

What did you find?

The salt (sodium chloride) dissociates into sodium and chlorine ions when it dissolves in the water, and the bulb lights up. The more sodium chloride you add, the brighter the bulb becomes. This is because an electrolyte can conduct electricity. If you were to replace the bulb with an ammeter, you would be able to read the current flowing through the solution.

The bulb did not light up when using the sugar (sucrose) solution. It is therefore not an electrolyte and does not conduct electricity. Sucrose is a covalent compound that does not ionise in a solution.

Note

Remember:

- For electricity to flow, there needs to be a movement of charged particles, e.g. ions.
- Distilled water, oil and alcohol do not conduct a current because they are covalent compounds and do not ionise in a solution.
- The concentration of the ions in a solution affects the amount of current flowing through the solution. The higher the concentration the higher the current, and vica versa.

Exercise 1.2

Use the information in the table below to answer the following questions:

Salt	Amount of salt dissolved g/l	Current (A)
Sodium chloride	0.5	0.15
Sodium chloride	1.0	0.36
Potassium nitrate	0.5	0.2
Potassium nitrate	1.0	0.45
Hydrogen chloride	0.5	0.05
Hydrogen chloride	1.0	0.09

Assuming the temperature of the water is at 15 °C for all the above.

1. Use the information to draw a bar graph of the results.
2. Which substance is the strongest electrolyte? Explain your answer.
3. Explain why the currents recorded for both solutions of hydrogen chloride are less than that of sodium chloride.
4. List two factors which could be changed to increase the conductivity of a solution of sodium chloride.

The full solutions are at the end of the unit.

Displacement of ions in an aqueous solution

When a solid metal is placed in a salt solution, a reaction will happen if the solid metal is more reactive than the metal ions in the salt solution. The positive metal ions in the solution gain electrons to become a solid, and the solid metal atoms lose electrons and go into the solution as ions. This process is called displacement; one metal element has taken the place of another (less reactive) metal element in the solution. In this process a solid metal corrodes away (the more reactive metal) and the metal that had ions in the solution forms a solid.

Therefore, salt solutions can be described as corrosive.

Iron corrodes in the presence of water and oxygen and this type of corrosion is called rusting. Rusting requires both oxygen and water, and it is usually sped up by acids, strains in the iron, contact with less-active metals, and the presence of rust itself. Iron objects will rust very quickly in the presence of salt water.

The equation for this is:

$$\text{Iron+hydrogen+oxygen} \rightarrow \text{Iron oxide} + \text{water}$$

Figure 5: An iron chain which has begun to rust

Rust is porous and is a flaky red solid. Once an iron object starts rusting, measures need to be taken to remove the rust and prevent further corrosion.

Aluminium metal reacts with oxygen in the air to form aluminium oxide. This kind of corrosion causes a protective layer to form on the aluminium and prevents any further corrosion.

$\text{aluminium} + \text{oxygen} \rightarrow \text{aluminium oxide}$

The same process also occurs to copper. The Statue of Liberty in New York City has a copper skin and was a brown colour when it was first delivered to the USA in 1885. It now a green colour, due to the corrosion of the copper skin in the presence of carbon dioxide and water. This has formed a protective layer of copper carbonate on the statue.

Figure 6: The Statue of Liberty is now protected by a layer of corroded copper

Summary

In this unit you have learnt the following:

- Dissociation is a general process in which ionic compounds separate into smaller ions when dissolved in water.
- Conductivity is a measure of a solution's ability to conduct an electric current.
- An electrolyte is a substance that contains free ions and is therefore able to conduct an electric current.
- Electrolytes can be divided into strong and weak electrolytes, based on the concentration of ions in the solution.
- A non-electrolyte cannot conduct an electric current because it does not contain free ions.
- The type of substance, the concentration of ions and the temperature of the solution affect the conductivity of an electrolyte.

Unit 1: Assessment

Suggested time to complete: 20 minutes

1. Give a definition for the following terms:

a. an electrolyte
b. a strong electrolyte
c. a weak electrolyte
2. What factors affect the conductivity of ions in water?
3. For each of the following substances state whether they are molecular or ionic.
a. methane (CH_4)
b. potassium bromide (KBr)
c. carbon dioxide (CO_2)
d. hexane (C_6H_{14})
e. lithium fluoride (LiF)
f. magnesium chloride ($MgCl$)
4. Write equations to show how each of the following ionic compounds dissociate in water.
a. sodium sulphate (Na_2SO_4)
b. potassium permanganate ($KMnO_4$)
c. sodium phosphate (Na_3PO_4)

The full solutions are at the end of the unit.

Unit 1: Solutions

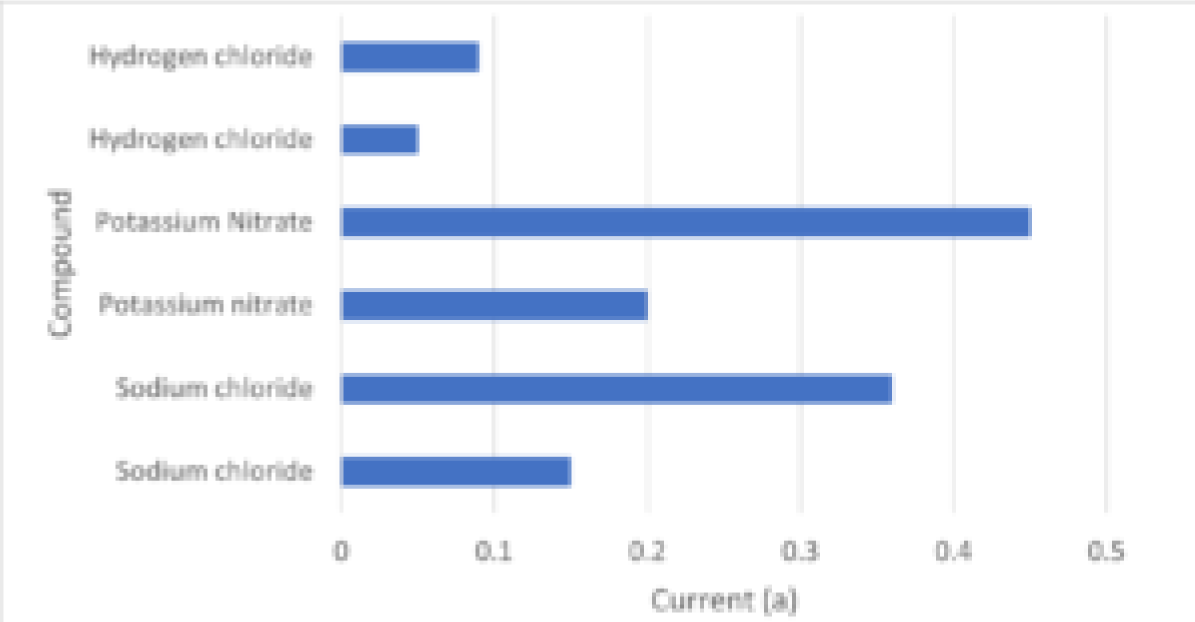
Exercise 1.1

1.
a. potassium nitrate (KNO_3) is an ionic compound because there is a metal bonded to non-metals
b. ethanol (C_2H_5OH) is a molecular compound because there are no metals in the compound only non-metals
c. sucrose ($C_{12}H_{22}O_{11}$) is a molecular compound because there are no metals in the compound only non-metals
d. sodium bromide ($NaBr$) is an ionic compound because there is a metal bonded to a non-metal
2.
a.
i. cations – sodium ions. Sodium is a metal so it will form positively charged ions.
ii. anions – hydroxide ions. They are non-metals so will form negatively charged ions.
b. $NaOH_{(s)} \rightarrow Na^+_{(aq)} + OH^-_{(aq)}$ Sodium will form positively charged ions in an aqueous solution and hydroxide will form a negatively charged ion.
3.
a. $FeSO_{4(s)} \rightarrow Fe^{2+}_{(aq)} + SO^{2-}_{4(aq)}$
b. $ZnCl^2_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2Cl^-_{(aq)}$
c. $NaOH_{(s)} \rightarrow Na^+_{(aq)} + OH^-_{(aq)}$

Back to Exercise 1.1

Exercise 1.2

1.



Graph to show the size of the current dependending on the amount and type of electrolyte

2. Potassium nitrate is the strongest electrolyte because when 1g/l is dissolved it produces the highest current.
3. Hydrogen chloride is a weak electrolyte compared to sodium chloride.
4. – Increase the concentration of sodium chloride in the solution.
   – increase the temperature of the aqueous solution.

[Back to Exercise 1.2]

Unit 1: Assessment

1.
   a. an electrolyte – a solution that will conduct electricity
   b. a strong electrolyte – a solution with a high centration of ions and will therefore conduct electricity well
   c. a weak electrolyte – a solution with a low concentration of ions and will therefore not conduct electricity very well
2. Temperature, concentration, and type of substance
3.
   a. molecular
   b. ionic
   c. molecular
   d. molecular
   e. ionic
   f. ionic
4.
   a. $\mathrm{Na_2SO_{4\,(s)}} \rightarrow \mathrm{Na}^{+}_{(aq)} + SO^{-2}_{4(aq)}$

b. $\mathrm{KMnO_{4\,(s)}} \rightarrow K^{+}_{(aq)} + MnO^{-}_{4(aq)}$

c. $\mathrm{Na_3PO_{4\,(s)}} \rightarrow \mathrm{3Na^{+}{}_{(aq)}} + \mathrm{PO^{-3}_{4(aq)}}$

Back to Unit 1: Assessment

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SUBJECT OUTCOME XVII

CHEMICAL CHANGE: DETERMINE THE QUANTITATIVE ASPECTS OF CHANGE

Subject outcome

Subject Outcome 6.4: Determine the quantitative aspects of change

Learning outcomes

Identify and distinguish between physical and chemical changes and give examples.
Identify and apply physical and chemical methods of separating mixtures (solids, liquids, and gases).

Range: Separation methods are manual, magnetic, filtration, fractional distillation, using a separating funnel, precipitation reactions and chromatography.

Unit 1 outcomes

By the end of this unit you will be able to:

- Calculate atomic mass.
- Calculate molecular mass.
- Calculate formula mass.
- Calculate the amount of a substance in moles and grams.
- Calculate the concentration of a solutions.

Unit 1: Quantitative aspects of change

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Calculate atomic mass.
- Calculate molecular mass.
- Calculate formula mass.
- Calculate the amount of a substance in moles and grams.
- Calculate the concentration of a solution.

What you should know:

Before you start this unit, make sure you can:

- Identify and describe intermolecular bonding referring to covalent, ionic, and metallic bonding covered in Subject outcome 5.4 Unit 3: Bonding
- Explain macroscopic properties in terms of chemical bonding (microscopic properties) covered in Subject outcome 5.4 Unit 3: Bonding
- Name and write chemical formulae of generally used substances covered in Subject outcome 5.4 Unit 3: Bonding

Introduction

In this unit you will learn how to calculate atomic, formula and molecular mass, calculate the concentrations of solutions and calculate the amount of a substance in moles and grams.

Quantitative aspects of change

An equation for a chemical reaction can provide us with a lot of useful information. It tells us what the reactants and the products are in the reaction, and it also tells us the ratio in which the reactants combine to form products. Look at the equation below:

$\mathrm{Fe} + \mathrm{S} \rightarrow \mathrm{FeS}$

In this reaction, every atom of iron (Fe) will react with a single atom of sulphur (S) to form a molecule of iron sulphide (FeS). However, what the equation does not tell us, is the quantity or the amount of each substance that is involved. You may for example be given a small sample of iron for the reaction. How will you know how many atoms of iron are in this sample? Or how many atoms of sulphur you will need for the reaction to use up all the iron you have? Is there a way of knowing what mass of iron sulphide will be produced at the end of the reaction? These are all important questions, especially when the reaction is an industrial one, where it is important to know the quantities of reactants that are needed, and the quantity of product that will be formed.

Relative atomic mass

Atomic mass (symbol: ma) is the mass of a single atom of a chemical element. It includes the masses of the protons and neutrons found in the atom.

Atomic mass can be expressed in grams. However, because each atom has a small mass, this is not helpful. Instead, atomic mass is expressed in unified atomic mass units (unit symbol: u).

1 u has a value of $1.7 \text{ x } 10^{24} \text{ g or } 0.0000000000000000000000017 \text{ g or } 1.7 \text{ x } 10^{27} \text{ kg}$

A carbon-12 atom has a mass of 12u. The mass of a carbon-12 atom is made of 6 protons and 6 neutrons. The mass of the electrons is not included because they are so insignificant. The masses of protons and neutrons are almost the same, so we can say that both protons and neutrons have a mass of roughly 1 u. Hence, we can get a rough value of an atom's mass in atomic mass units by working out the sum of the number of protons and the number of neutrons in the nucleus, which is called the mass number.

The atomic mass unit is defined as $\frac{1}{12}$ of the mass of a single carbon-12 atom.

The mass of other atoms is expressed relative to this. Magnesium atoms have twice the mass of carbon, so a magnesium atom has a relative atomic mass of 24 u. A uranium atom has a relative atomic mass of 238 u which is equivalent to almost 20 carbon atoms.

Relative molecular mass

The formula of a covalent compound gives the number and kind of atoms in a molecule; therefore it can be used to calculate the relative molecular mass. This is done by adding the relative atomic masses together.

The relative molecular mass of hydrogen, which is a diatomic molecule with the formula H_2, is calculated by adding the masses of two hydrogen atoms together. The mass of each atom of hydrogen is 1 u. Therefore, the molecular mass of H_2 is $1 + 1 = 2 \text{ u}$.

Example 1.1

Calculate the relative molecular mass of water (H_2O).

Solution

Step 1: Find the relative atomic mass for hydrogen and oxygen.

Hydrogen has a relative atomic mass of 1 u.

Oxygen has a relative atomic mass of 16 u.

Step 2: Add the relative atomic masses together, not forgetting to add twice the relative atomic mass of hydrogen because the formula is H_2O.

$1 + 1 + 16 = 18 \text{ u}$

The relative molecular mass of water is 18 u.

Example 1.2

Calculate the relative molecular mass of carbon dioxide (CO_2).

Solution

The relative atomic mass of carbon is $12\ \text{u}$.

The relative atomic mass of oxygen is $16\ \text{u}$.

There are 2 atoms of oxygen, so the relative molecular mass of carbon dioxide (CO_2) is: $12 + (16 + 16) = 44\ \text{u}$.

Example 1.3

Calculate the relative molecular mass of sucrose ($C_{12}H_{22}O_{11}$).

Solution

Step 1: Find the atomic masses.

Carbon is 12, oxygen is 16 and hydrogen is 1

Step 2: $(12\text{x}12)\ +\ (22\text{x}1)\ +\ (11\text{x}16)\ =\ 342\ \text{u}$

The relative molecular mass of sucrose ($C_{12}H_{22}O_{11}$) is $342\ \text{u}$.

Exercise 1.1

Give the relative molecular mass of each of the following elements:

1. hydrogen gas
2. nitrogen gas
3. bromine

The full solutions are at the end of the unit.

Relative formula mass

Relative formula mass is the mass of one formula unit of an ionic compound. It is calculated in the same way as the relative molecular mass, as the formula gives the ratio of the ions in the compound.

The relative formula mass of lithium fluoride (LiF) is 26 $(7 + 19 = 26)$.

The relative formula mass of iron oxide (FeO) is $56 + 16 = 72$.

Exercise 1.2

Calculate the relative formula or molecular mass for the following:

1. Hydrogen chloride (HCl)
2. Sodium chloride ($NaCl$)
3. Nitric acid (HNO_3)
4. Aluminium oxide (Al_2O_3)

The full solutions are at the end of the unit.

Molar mass

When the relative atomic, molecular or formula mass is expressed in grams, the amount is referred to as one mole of that substance.

Molar mass (M) is the mass of 1 mole of a chemical substance. The unit for molar mass is grams per mole or $g.mol^{-1}$.

It is worth noting the following: on the periodic table, the relative atomic mass that is shown can be interpreted in two ways.

1. Relative atomic mass (no units used)
   The average mass of a *single* atom of all the isotopes of that element relative to the mass of one atom of carbon-12.
2. Molar mass (using grams as the unit)
   The mass of *one mole of the element*.

Element	Relative atomic mass (u)	Molar mass $(g \cdot mol^{-1})$	Mass of one mole of the element (g)
Magnesium	24.3	24.3	24.3
Lithium	6.94	6.94	6.94
Iron	55.8	55.8	55.8

The molar mass of any substance is its relative atomic, molecular or formula mass, as read from the periodic table, in grams. So:

Substance (formula)	Atomic, molecular or formula mass (u)	Molar Mass $(g.mol^{-1})$
Iron (Fe)	58.9 (atomic mass)	58.9
Helium (He)	4.0026 (atomic mass)	4.0026
Ethanol (C_2H_5OH)	46.069 (molecular mass)	46.069
Calcium phosphate $Ca_3(PO_4)_2$	310.177 (formula mass)	310.177

You may sometimes see the molar mass written as Mm. We use M in this book, but you should be aware of the alternative notation.

Example 1.4

Calculate the number of moles of iron (Fe) in an $111.7\ g$ sample.

Solution

Step 1: Find the molar mass of iron.

If we look at the periodic table, we see that the molar mass of iron is $55.8\ g.mol^{-1}$. This means that 1 mole of iron will have a mass of $55.8\ g$.

Step 2: Find the number of moles (n) of iron.

If 1 mole of iron has a mass of $55.8\ g$, then the number of moles of iron in $111.7\ g$ must be:

$$n = \frac{111.7\ g}{55.8\ g.mol^{-1}}$$

$$n = \frac{111.7\ g.mol}{55.8\ g}$$

$$n = 2\ mol$$

There are 2 moles of iron in the sample.

Example 1.5

You have a sample that contains 5 moles of zinc. Calculate the mass of zinc in the sample from moles.

Solution

Step 1: Find the molar mass of zinc from the periodic table.

The molar mass of zinc is $65.4\ g.mol^{-1}$, meaning that 1 mole of zinc has a mass of $65.4\ g$.

Step 2: Find the mass.

If 1 mole of zinc has a mass of $65.4\ g$, then 5 moles of zinc have a mass of $65.4\ g \times 5\ mol = 327\ g$.

Exercise 1.3

Calculate the number of moles in each of the following samples:

1. 5.6 g of calcium
2. 0.02 g of manganese
3. 40 g of aluminium

The full solutions are at the end of the unit.

Molar mass of compounds

So far, we have only discussed moles and molar mass in relation to elements. But what happens if we are dealing with a compound? Do the same concepts and rules apply? The answer is yes. However, you need to remember that all your calculations will apply to the whole compound. So, when you calculate the molar mass of a covalent compound, you will need to consider the number and kind of each element in the compound.

For example, if you have one mole of nitric acid (HNO_3) the molar mass is: $1 + 14 + (16 \text{ x } 3) = 63 \text{ g.mol}^{-1}$.

The molar mass of methane (CH_4) is 12 for the carbon plus $4 \text{ x } 1$ for the four hydrogens, for a total of 16. Therefore, the molar mass of methane is 16 g.mol^{-1}.

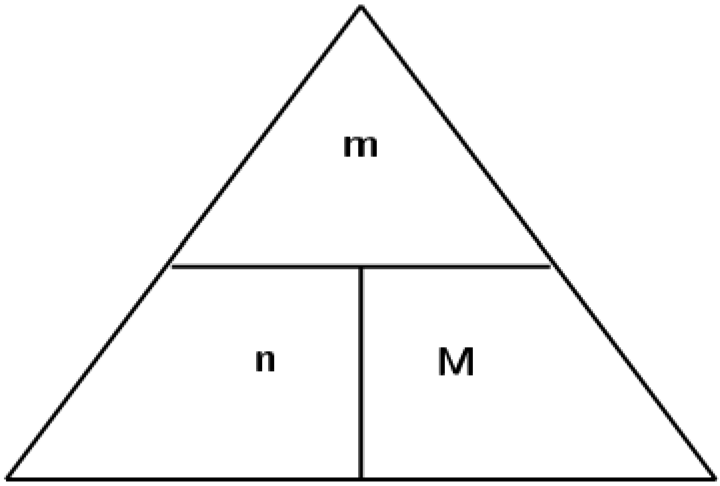


Figure 1: The relationship between molar mass (M), mass (m) and amount (n) of a pure substance

$$n = \frac{m}{M}$$

M = molar mass of the pure substance (measured in g.mol^{-1})

m = mass of the pure substance (measured in grams, g)

n = amount of the pure substance (measured in moles, .mol^{-1})

To use the diagram, place your thumb over the variable you are trying to calculate. This will leave the other two variables, either side by side or one above the other. If they are side by side, you will need to multiply those numbers together. If one is above the other, then you will divide.

Remember that when you use the equation $n = \frac{m}{M}$, the mass is always in grams (g) and the molar mass is always in grams per mol (g.mol^{-1}). Always write the units next to any number of the answer.

Example 1.6

Calculate the number of moles of copper there are in a sample with a mass of 127 g.

Solution

Step 1: Write down the equation.

$$n=\frac{m}{M}$$

Step 2: Find the moles.

$$n=\frac{127}{63.5}=2 \text{ mol}$$

There are 2 moles of copper in the sample.

Example 1.7

Calculate the molar mass of the compound sulfuric acid (H_2SO_4).

Solution

Step 1: Give the molar mass for each element.

Hydrogen = 1.01 g.mol^{-1}

Sulphur = 32.1 g.mol^{-1}

Oxygen = 16.0 g.mol^{-1}

Step 2: Work out the molar mass of the compound:

$$M_{H_2SO_4}=(1.01 \text{ x } 2)+32.1+(16 \text{ x } 4)=98.12 \text{ g.mol}^{-1}$$

Example 1.8

Calculate the number of moles in 1 kg of magnesium chloride ($MgCl_2$).

Solution

Step 1: Convert the mass into grams.

$$m=1 \text{ kg}\times\frac{1000\text{g}}{1\text{kg}}=1\ 000 \text{ g}$$

Step 2: Calculate the molar mass.

$$M_{(MgCl_2)}=24.3+2(35.45)=95.2 \text{ g.mol}^{-1}$$

Step 3: Find the number of moles.

$$n = \frac{1000\ g}{95.2\ g.mol^{-1}}$$

$$n = 10.5\ mol$$

There are 10.5 moles of magnesium chloride in a $1\ kg$ sample.

Exercise 1.4

1. You have a $46\ g$ sample of nitrogen dioxide (NO_2). How many moles of NO_2 are there in the sample?
2. What is the difference between a mole and a molecule?
3. Calculate the molar mass of the following chemical compounds:
   a. KOH
   b. $FeCl_3$
   c. $Mg(OH)_2$

The full solutions are at the end of the unit.

Molar concentrations of liquids

A typical solution is made by dissolving a solid substance in a liquid. The amount of substance that is dissolved in a given volume of solution is known as the concentration of the liquid. Mathematically, concentration (C) is defined as moles of solute (n) per unit volume (V) of solution.

$$C = \frac{n}{V}$$

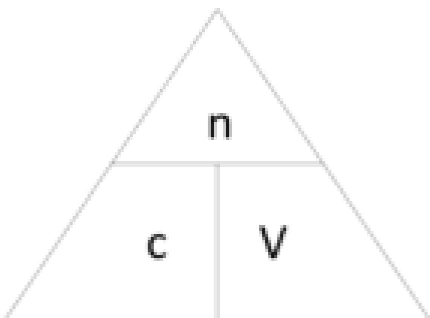


Figure 2: The relationship between concentration (C), moles (n) and per unit volume (V) of a solution

In Figure 2 you can see the relationship of the following variables:

c = concentration of solution in $mol.dm^{-1}$

V = volume of the solution in $1\ dm^3$ (this is not the volume of liquid added, but the volume of the final solution)

n = moles of the substance being dissolved/moles of the solute in mol.

Concentration of solutions

Concentration is a measure of the amount of solute that is dissolved in a given volume of solution. It is measured in $mol.dm^{-3}$. This is called the molarity of a solution. The following examples help you work through some concentration calculations.

Example 1.9

If $3.5\ g$ of sodium hydroxide ($NaOH$) is dissolved in $2.5\ dm^{-3}$ of water, what is the concentration of the solution in $mol.dm^{-3}$?

Solution

Step 1: Find the number of moles of sodium hydroxide.

$$n = \frac{m}{M}$$
$$n = \frac{3.5}{40.01}$$
$$n = 0.0875\ mol$$

Step 2: Calculate the concentration.

$$c = \frac{n}{V}$$
$$c = \frac{0.0875}{2.5}$$
$$c = 0.035\ mol.d^{-3}$$

The concentration of the solution is $0.035\ mol.dm^{-3}$.

Example 1.10

You have a $1\ dm^3$ container in which to prepare a solution of potassium permanganate ($KMnO_4$). What mass of $KMnO_4$ is needed to make a solution with a concentration of $0.2\ mol.dm^{-3}$?

Solution

Step 1: Calculate the number of moles.

$n = c \times V$ therefore:

$n = 0.2 \times 1$

$n = 0.2 \text{ mol}$

Step 2: Find the mass.

$m = nM$

$m = 0.2 \text{ x } 158$

$m = 31.6 \text{ g}$

The mass of $KMnO_4$ that is needed is 31.6 g.

Example 1.11

How much sodium chloride (in g) is needed to prepare 500 cm^3 of solution with a concentration of 0.01mol.dm^{-3}?

Solution

Step 1: Convert the given volume to the correct units.

$$V = 500 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.5 \text{ dm}^3$$

Step 2: Find the number of moles.

$n = c \text{ x } V$

$n = 0.01 \text{ x } 30.5$

$n = 0.30 \text{ mol}$

Step 3: Find the mass.

$m = nM$

$m = (0.30)(58.45)$

$m = 17.54 \text{ g}$

The mass of sodium chloride needed is 17.54 g.

Example 1.12

A solution is prepared by bubbling 1.56 g of hydrochloric acid in water. Here, the volume of the solution is 26.8 cm^3. Calculate the molarity of the solution.

Solution

Step 1: Find the molecular mass of HCl (hydrochloric acid).

$M_{HCl} = 35.5 + 1 = 36.5 \text{ g.mol}^{-1}$

Step 2: Find the number of moles of HCl.

$$n = \frac{m}{M}$$
$$n = \frac{1.56}{36.5}$$
$$n = 0.042 \text{ mol}$$

Step 3: Convert the volume to dm^3.

$$V = 26.8 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.0268 \text{ dm}^3$$

Step 4: Calculate the molarity of the solution.

$$c = \frac{n}{V}$$
$$c = \frac{0.042}{0.0268}$$
$$c = 1.56 \text{ mol.dm}^{-3}$$

Exercise 1.5

1. 5.95 g of potassium bromide is dissolved in 400 dm^3 of water. Calculate its concentration.
2. 100 g of sodium chloride ($NaCl$) is dissolved in 450 cm^3 of water.
   a. How many moles of $NaCl$ are present in the solution?
   b. What is the volume of water (in dm^3)?
   c. Calculate the concentration of the solution.
3. What is the molarity of the solution formed by dissolving 80 g of sodium hydroxide ($NaOH$) in 500 cm^3 of water?

The full solutions are at the end of the unit.

Summary

In this unit you have learnt the following:

- The mole (n) (abbreviation mol) is the SI (Standard International) unit for amount of substance.
- The molar mass (M) is the mass of one mole of a substance and is measured in grams per mole or $g.mol^{-1}$. The numerical value of a substance's relative atomic, molecular or formula mass is expressed in grams and is the substance's molar mass. For a covalent compound, the molar mass has the same numerical value as the relative molecular mass of that compound. For an ionic substance, the molar mass has the same numerical value as the relative formula mass of the substance.
- The relationship between moles (n), mass in grams (m) and molar mass (M) is defined by the following equation: $n = \frac{m}{M}$.
- In a balanced chemical equation, the number in front of the chemical symbols describes the mole ratio of the reactants and products.
- The empirical formula of a compound is an expression of the ratio of each type of atom in the compound.

- The molecular formula of a compound describes the actual number of atoms of each element in a molecule of the compound.
- We can use the products of a reaction to determine the formula of one of the reactants.
- The concentration of a solution can be calculated using the following equation: $c = \frac{n}{v}$, where c is the concentration ($mol.dm^{-3}$), n is the number of moles of solute dissolved in the solution and V is the volume of the solution (in dm^{-3}).
- The concentration is a measure of the amount of solute that is dissolved in a given volume of solution. This is called the molarity of a solution.
- The concentration of a solution is measured in $mol.dm^{-3}$.

Unit 1: Assessment

Suggested time to complete: 45 minutes

1. Calculate the formula mass of:
   a. $Ca(NO_3)_2$
   b. H_2SO_4
   c. C_6H_5Cl
2. Copy the following table into your notebook and complete it:

Element	**Relative atomic mass (u)**	**Sample mass (g)**	**Number of moles in the sample**
Hydrogen	1	2	
Magnesium	24.3	24.3	
Carbon	12.0	84	
Chlorine	35.5	213	
Nitrogen	14.0	56	

3. Calculate the mass of each of the following samples:
   a. 2.5 mol magnesium
   b. 12 mol lithium
   c. 3 mol of NH_4OH
   d. 4.2 mol of $Ca(NO_3)_2$
   e. 5.2 mol of helium
   f. 0.05 mol of copper (II) chloride ($CuCl_2$)
4. Calculate the number of moles in each of the following samples:
   a. 21.6 g of boron (B)
   b. 54.9 g of manganese oxide (MnO_2)
   c. 100.3 g of mercury (Hg)
   d. 50 g of barium sulphate ($BaSO_4$)
   e. 9.6 kg of titanium tetrachloride ($TiCl_4$)
5. What mass (g) of hydrogen chloride (HCl) is needed to make up $1\ 000\ cm^3$ of a solution of concentration $1\ mol.dm^{-3}$?

6.
   a. How many moles of H_2SO_4 are there in $250\ cm^3$ of a $0.8\ mol.dm^{-3}$ sulphuric acid solution?
   b. What mass of acid is in this solution?
7. $300\ cm^3$ of a $0.1\ mol.dm^{-3}$ solution of sulphuric acid is added to $200\ cm^3$ of a $0.5\ mol.dm^{-3}$ solution of sodium hydroxide. Calculate the number of moles of sulphuric acid which were added to the sodium hydroxide solution.
8. A learner is asked to make $200\ cm^3$ of sodium hydroxide ($NaOH$) solution with a concentration $0.5\ mol.dm^{-3}$.
   a. Determine the mass of sodium hydroxide pellets he needs to use to do this.
   b. Using an accurate balance the learner accurately measures the correct mass of the $NaOH$ pellets. To the pellets he now adds exactly $200\ cm^3$ of pure water. Will his solution have the correct concentration? Explain your answer.
   c. The learner then takes $300\ cm^3$ of a $0.1\ mol.dm^{-3}$ solution of hydrochloric acid (H_2SO_4) and adds it to $200\ cm^3$ of a $0.5\ mol.dm^{-3}$ solution of $NaOH$. Calculate the number of moles of H_2SO_4 which were added to the $NaOH$ solution.

The full solutions are at the end of the unit.

Unit 1: Solutions

Exercise 1.1

Remember that these elements are diatomic so:

1. hydrogen gas = $H_2 = 1.0 + 1.0 = 2.0$
2. nitrogen gas = $N_2 = 14 + 14 = 28$
3. bromine gas = $Br_2 = 80 + 80 = 160$

Back to Exercise 1.1

Exercise 1.2

1. Hydrogen chloride (HCl)

   $H=1$
   $Cl=17$
   $17+1=18$

2. Sodium chloride ($NaCl$)

   $Na = 23$
   $Cl = 17$
   $23 + 17 = 40$

3. Nitric acid (HNO_3)
   Remember you must multiply the relative atomic mass by the number of atoms in the molecule so in this instance, the oxygen needs to be multiplied by 3.

$$\begin{aligned}
H &= 1 \\
N &= 14 \\
O &= (16x3) \\
&= 1 + 14 + (16x3) \\
&= 63
\end{aligned}$$

4. Aluminium oxide (Al_2O_3)

$$\begin{aligned}
Al &= (27x2) \\
O &= (16x3) \\
&= 54 + 48 \\
&= 102
\end{aligned}$$

Back to Exercise 1.2

Exercise 1.3

1. 5.6 g of calcium

   Molar mass of $Ca = 40 \text{ g.mol}^{-1}$

$$n = \frac{5.6}{40}$$
$$n = 0.14 \text{ mol}$$

2. 0.02 g of manganese

   Molar mass of $Mn = 55 \text{ g.mol}^{-1}$

$$n = \frac{0.02}{55}$$
$$n = 0.00036 \text{ mol}$$

3. 40 g of aluminium

   Molar mass of $Al = 27 \text{ g.mol}^{-1}$

$$n = \frac{40}{27}$$
$$n = 1.48 \text{ mol}$$

Back to Exercise 1.3

Exercise 1.4

1. Molar mass of $M_{NO_2} = 14 + (16x2) = 46 \text{ g.mol}^{-1}$:

   Number of moles of NO_2

$$n = \frac{46}{46}$$
$$n = 1 \text{ mol}$$

2. A molecule is made up of two or more atoms joined together. A mole is a measure of large quantities of particles such as molecules or atoms.

3.

a. $\mathrm{M_{KOH}} = 39 + 16 + 1 = 56\ \mathrm{g.mol^{-1}}$

b. $\mathrm{M_{FeCl_3}} = 56 + (17x3) = 107\ \mathrm{g.mol^{-1}}$

c. $\mathrm{M_{Mg(OH)_2}} = 23 + (16\ x\ 2) + (1\ x\ 2) = 57\ \mathrm{g.mol^{-1}}$

Back to Exercise 1.4

Exercise 1.5

1. First find the molar mass of potassium bromide:

   $\mathrm{M_{KBr}} = 39 + 80 = 119\ \mathrm{g.mol^{-1}}$.

   Then find the number of moles of KBr.

   $$\mathrm{n} = \frac{\mathrm{m}}{\mathrm{M}}$$
   $$\mathrm{n} = \frac{5.95}{119}$$
   $$\mathrm{n} = 0.05\ \mathrm{mol}$$

   Then find the concentration

   $$\mathrm{c} = \frac{\mathrm{n}}{\mathrm{V}}$$
   $$\mathrm{c} = \frac{0.05}{400}$$
   $$\mathrm{c} = 0.00012\ \mathrm{mol.dm^{-3}}$$

2.

a.

$\mathrm{M_{NaCl}} = 23 + 17 = 40\ \mathrm{g.mol^{-1}}$

$$\mathrm{n} = \frac{\mathrm{m}}{\mathrm{M}}$$
$$\mathrm{n} = \frac{100}{40}$$
$$\mathrm{n} = 2.5\ \mathrm{mol}$$

b.

$$\mathrm{V} = 450\ \mathrm{cm^3} x \frac{1\ \mathrm{dm^3}}{1000\ \mathrm{cm^3}} = 0.450\ \mathrm{dm^3}$$

c.

$$\mathrm{c} = \frac{\mathrm{n}}{\mathrm{V}}$$
$$\mathrm{c} = \frac{2.5}{0.450}$$
$$\mathrm{c} = 5.55\ \mathrm{mol.dm^{-3}}$$

3. Molecular mass of NaOH:$\mathrm{M_{NaOH}} = 23 + 16 + 1 = 40\ \mathrm{g.mol^{-1}}$

   Number of moles of NaOH:

$n = \frac{m}{M}$

$n = \frac{80}{40}$

$n = 2 \text{ mol}$

Volume = $V = 500 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.5 \text{ dm}^3$

Molarity:

$c = \frac{n}{V}$

$c = \frac{2}{0.5}$

$c = 4 \text{ mol.dm}^{-3}$

Back to Exercise 1.5

Unit 1: Assessment

1.
    1. $Ca(NO_3)_2 = 40 + (14x2) + (16x6) = 164 \text{ g.mol}^{-1}$
    2. $H_2SO_4 = (1x2) + 32 + (16x4) = 98 \text{ g.mol}^{-1}$
    3. $C_6H_5Cl = (12x6) + (1x5) + 35.5 = 112.5 \text{ g.mol}^{-1}$
2.

Element	**Relative atomic mass (u)**	**Sample mass (g)**	**Number of moles in the sample**
Hydrogen	1	2	1
Magnesium	24.3	24.3	1
Carbon	12.0	84	7
Chlorine	35.5	213	6
Nitrogen	14.0	56	4

3.
    a. 2.5 mol magnesium
    $m = nM$
    $m = 2.5 \text{ x } 24$
    $m = 60 \text{ g}$
    b. 12 mol lithium
    $m = nM$
    $m = 12 \text{ x } 23$
    $m = 276 \text{ g}$
    c. 3 mol of NH_4OH
    Molar mass = $14 + (1x4) + 16 + 1 = 35 \text{ g.mol}^{-1}$
    $m = nM$
    $m = 3 \text{ x } 35$
    $m = 105 \text{ g}$
    d. 4.2 mol of $Ca(NO_3)_2$
    Molar mass = $40 + (14x2) + (16x6) = 164 \text{ g.mol}^{-1}$

$m = nM$
$m = 4.2 \text{ x } 164$
$m = 688.8 \text{ g}$

e. 5.2 mol of helium
$m = nM$
$m = 5.2 \text{ x } 4$
$m = 20.8 \text{ g}$

f. 0.05 mol of copper (II) chloride ($CuCl_2$)
Molar mass = $63.5 + (35.5 \text{ x } 2) = 134.5 \text{ g.mol}^{-1}$
$m = nM$
$m = 0.05 \text{ x } 134.5$
$m = 6.73 \text{ g}$

4.

a. 21.6 g of boron (B)
$n = \frac{m}{M}$
$n = \frac{21.6g}{11}$
$n = 1.96 \text{ mol}$

b. 54.9 g of manganese oxide (MnO_2)
Molar mass = $55 + (16x2) = 87 \text{ g.mol}^{-1}$
$n = \frac{m}{M}$
$n = \frac{54.9}{87}$
$n = 0.63 \text{ mol}$

c. 100.3 g of mercury (Hg)
$n = \frac{100.3 \text{ g}}{200.6 \text{ g.mol}^{-1}}$
$n = 0.5 \text{ mol}$

d. 50 g of barium sulphate ($BaSO_4$)
Molar mass = $137 + 32 + (16x4) = 233 \text{ g.mol}^{-1}$
$n = \frac{m}{M}$
$n = \frac{50}{233}$
$n = 0.21 \text{ mol}$

e. 9.6 kg of titanium tetrachloride ($TiCl_4$)
Molar mass = $204 + (35.5 \text{ x } 4) = 346 \text{ g.mol}^{-1}$
$n = \frac{m}{M}$
$n = \frac{9600}{346}$
$n = 27.75 \text{ mol}$

5.

$n = cV$
$n = 1 \text{ x } 1$
$n = 1 \text{ mol}$

Molar mass of $HCl = 1+35.5 = 36.5 \text{ g.mol}^{-1}$

$m = nM$

$m = 1 \text{ x } 36.5$

$m = 36.5 \text{ g}$

6.

a. $V = 250 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.25 \text{ dm}^3$

$n = cV$

$n = 0.8 \text{ x } 0.25$

$n = 0.2 \text{ mol}$

b. $M_{H_2SO_4} = (1+1) + 32 + (16\text{x}4) = 98 \text{ g.mol}^{-1}$

$m = nM$

$m = 0.2 \text{ x } 98$

$m = 19.6 \text{ g}$

7. $V = 300 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.3 \text{ dm}^3$

$n = cV$

$n = 0.1 \text{ x } 0.3$

$C = 0.03 \text{ mol}$

8.

a. $V = 200 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000 \text{ cm}^3} = 0.2 \text{ dm}^3$

$n = cV$

$n = 0.5 \text{ x } 0.2$

$n = 0.1 \text{ mol}$

$M_{NaOH} = 23+16+1 = 40 \text{ g.mol}^{-1}$

$m = nM$

$m = 0.1 \text{ x } 40$

$m = 4 \text{ g}$

b. His solution will not have the correct concentration, because the volume of the solution will be greater than 200 cm^3 once the $NaOH$ pellets have been added and therefore the concentration will be less than 0.5 mol.dm^{-3}.

c. $V = 300 \text{ cm}^3 \times \frac{1 \text{ dm}^3}{1000\text{cm}^3} = 0.3 \text{ dm}^3$

$n = cV$

$n = 0.1 \text{ x } 0.3$

$n = 0.03 \text{ mol}$

Back to Unit 1: Assessment

Media Attributions

SUBJECT OUTCOME XVIII

CHEMICAL SYSTEMS AND INDUSTRY: IDENTIFY AND DESCRIBE THE IMPACT OF SCIENTIFIC KNOWLEDGE OF THE HYDROSPHERE ON THE QUALITY OF HUMAN, ENVIRONMENTAL, AND SOCIO-ECONOMIC DEVELOPMENT

Subject outcome

Subject outcome 7.1: Identify and describe the impact of scientific knowledge of the hydrosphere on the quality of human, environmental, and socio-economic development.

Learning outcomes

- Describe the water cycle, its physical changes and energy transfers.
- Identify and describe the macroscopic properties of the three phases of water related to their microscopic properties.
- Define the term water pollution and give examples (also refer to industrial, agricultural, and human pollution).
- Classify water in terms of hardness and explain water hardness and describe its effects.
- Describe the types of impurity found in water and the reason for purification (human and industrial).
- Define water treatment and softening and give examples.

Unit 1 outcomes

By the end of this unit you will be able to:

- Describe the water cycle.
- Understand the physical changes of state within the water cycle.
- Understand the energy transfers within the water cycle.
- Understand the macroscopic properties of water, ice and water vapour in relation to their particle structure.

Unit 2 outcomes

By the end of this unit you will be able to:

- Understand what water pollution is.
- Identify the main causes:
  - industry, including mining
  - agriculture
  - human activities.

Unit 3 outcomes

By the end of this unit you will be able to:

- Classify water in terms of hardness.
- Explain water hardness and describe its effects.
- Describe the types of impurities found in water.
- Explain why water used by people and industries is purified.
- Define the water treatment and softening processes and give examples of them.

Unit 1: The hydrosphere

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Describe the water cycle.
- Understand the physical changes of state within the water cycle.
- Understand the energy transfers within the water cycle.
- Understand the macroscopic properties of water, ice and water vapour in relation to their particle structure.

What you should know

Before you start this unit, make sure you can:

- Identify and describe the phases of matter (physical property of matter), as covered in Subject outcome 5.1, Unit 1.
- Distinguish between the phases of matter in terms of energy, shape, and volume, as covered in Subject outcome 5.1, Unit 1.
- Describe heat and heat transfer (see thermal conductors), as covered in Subject outcome 6.1, Unit 3.
- Define and calculate heat capacity and specific heat, as covered in Subject outcome 6.1, Unit 3.

Introduction

As far as we know, the Earth we live on is the only planet that can support life. The Earth is just the right distance from the sun to have temperatures that are suitable for life to exist. Also, the Earth's atmosphere has exactly the right types of gases in the right amounts for life to survive. Our planet also has water on its surface, which is something unique. In fact, Earth is often called the "Blue Planet" because most of it is covered in water. This water is made up of freshwater in rivers and lakes, the saltwater of the oceans and estuaries, groundwater, and water vapour. Together, all these water bodies are called the hydrosphere.

The hydrosphere

A hydrosphere is the total amount of water on a planet. The hydrosphere includes water that is on the surface of the planet, underground, and in the air. A planet's hydrosphere can be liquid, vapour, or ice.

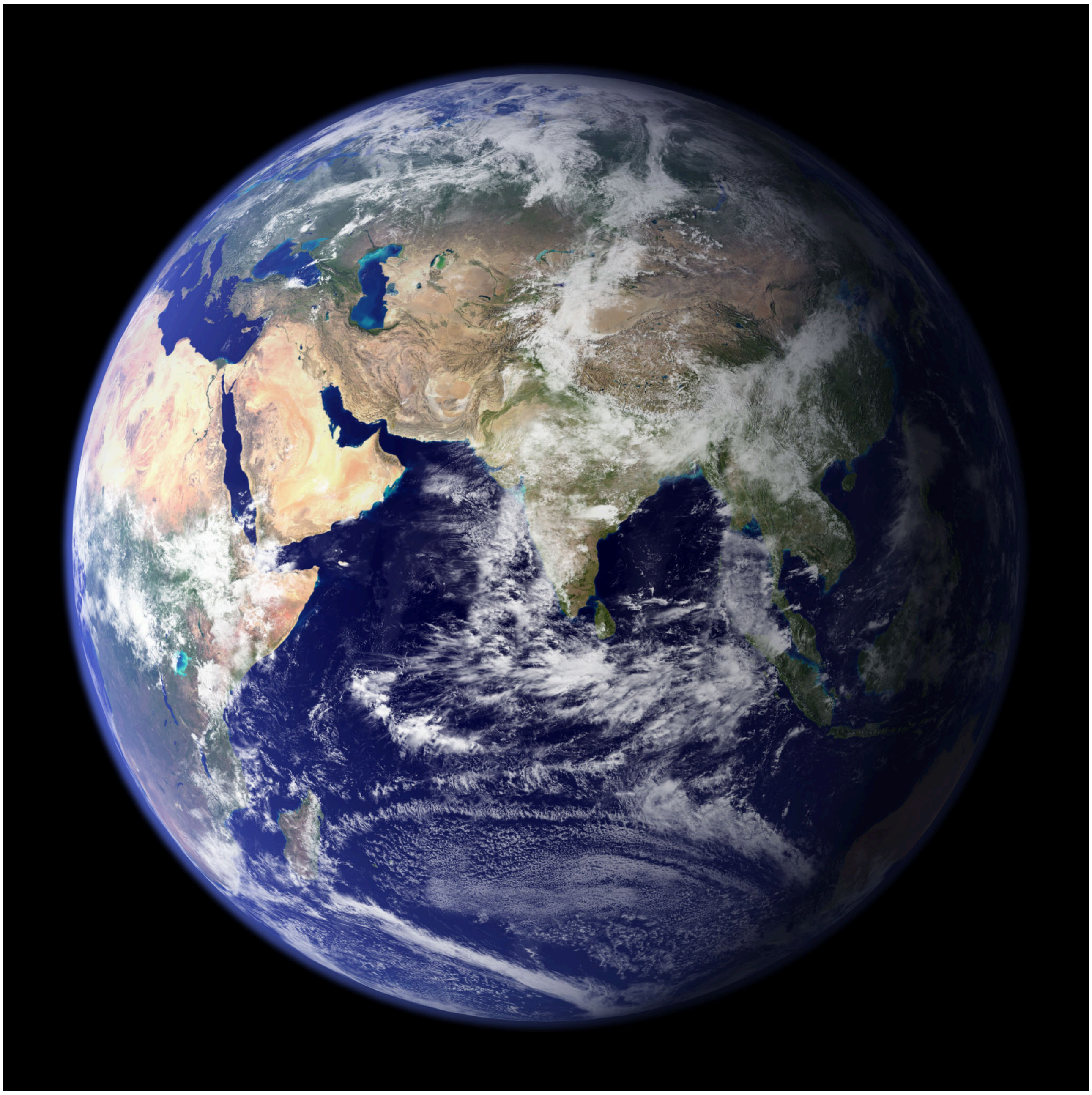


Figure 1: The Earth from space

On Earth, liquid water exists on the surface in the form of oceans, lakes, and rivers. It also exists below ground; as groundwater in wells and aquifers. Water vapour is most visible as clouds and fog. The frozen part of Earth's hydrosphere is made of ice: glaciers, ice caps and icebergs. The frozen part of the hydrosphere has its own name, the cryosphere.

The total amount of water on Earth is about 1386 million cubic kilometres, and the hydrosphere's composition in terms of percentage of water is as follows:

Oceans	97.6%
Saline lakes and inland seas	0.008%
Glaciers and ice caps	1.9%
Groundwater	0.5%
Soil moisture	0.01%
Lakes	0.009%
Freshwater rivers	0.0001%
Atmosphere	0.0009%

About 68.7% of all freshwater exists in the form of permanent snow. This exists in the Arctic and Antarctic regions, as well as other mountain glaciers. The amount of water on the Earth's surface does not change over time so the amount of water available on the Earth today is the same as it was when dinosaurs were roaming the Earth hundreds of millions of years ago.

Water moves through the hydrosphere in a cycle. Water collects in clouds, then falls to Earth in the form of rain or snow. This water collects in rivers, lakes, and oceans. Then it evaporates into the atmosphere to start the cycle all over again. This is called the water cycle.

It is important to realise that the hydrosphere is not an isolated system, it rather interacts with other global systems, including the atmosphere, lithosphere, and biosphere. These interactions are sometimes known collectively as the water cycle.

The atmosphere

The atmosphere is a collection of gases and consists of 78% nitrogen, 21% oxygen, 1% water vapour, and tiny amounts of other trace gases such as argon, and carbon monoxide. All these gases combine to absorb ultra-violet radiation from the sun and warm the planet's surface through heat retention.

The cycle of water moving through the atmosphere and the energy changes that accompany it, is what drives weather patterns on Earth.

The lithosphere

In the lithosphere (the ocean and continental crust at the Earth's surface), water is an important weathering agent, which means that it helps to break rock down into rock fragments and then soil. These fragments may then be transported by water to another place, where they are deposited. These two processes (weathering and the transporting of fragments) are collectively called erosion. Erosion helps to shape the Earth's surface. For example, you can see this in rivers. In the upper streams, rocks are eroded, and sediments are transported down the river and deposited on the wide flood plains lower down.

The biosphere

In the biosphere, land plants absorb water through their roots and then transport this through their vascular (transport) system to stems and leaves. This water is needed in photosynthesis, the food production process in plants. Transpiration (evaporation of water from the leaf surface) then returns water back to the atmosphere.

Note

For a further explanation on the hydrosphere, watch this video called Earth's Interconnected Cycles by Lincoln Learning Solutions (Duration: 4.12).

The importance of the hydrosphere

The hydrosphere does not only include the collected amount of water on Earth, it also enables a huge variety of organisms to survive on the Earth.

1. **A component of living cells:** Each cell in a living organism is composed of at least 75% water. This supports the normal functioning of the cell. Most of the chemical reactions that occur in living organisms involve materials that are dissolved in water. No cell would survive or be able to carry out its normal functions without water.
2. **Habitat for many life forms:** The hydrosphere provides an important place for a wide range of plants and animals to live. Many nutrients such as nitrate, nitrite, and ammonium ions, as well as gases such as carbon dioxide and oxygen are dissolved in water. These compounds play an integral role in the existence of life in water.
3. **Climate regulation:** One of water's exceptional features is its high specific heat. Namely, water takes not only a long time to heat up but also a long time to cool down. It plays a significant role in regulating temperatures on Earth, ensuring temperatures remain within a range that is suitable for the existence of life. Ocean currents also play a critical role in heat dispersion.
4. **Existence of our atmosphere:** The hydrosphere significantly contributes to the existence of our atmosphere in its present form. When the Earth was formed it had only a very thin atmosphere. This atmosphere was packed with helium and hydrogen. The gases helium and hydrogen were later ejected from the atmosphere, and the gases and water vapour produced as the Earth cooled formed our current atmosphere. Volcanoes also released other gases and water vapour, which entered the atmosphere. This process is estimated to have occurred about 400 million years ago.
5. **Human needs:** Humans benefit from the hydrosphere in numerous ways. Besides for drinking, water is used for domestic purposes like cooking and cleaning. Water can also be used for transportation, agriculture, and to generate electricity through hydropower.

Figure 2: The Limpopo river valley

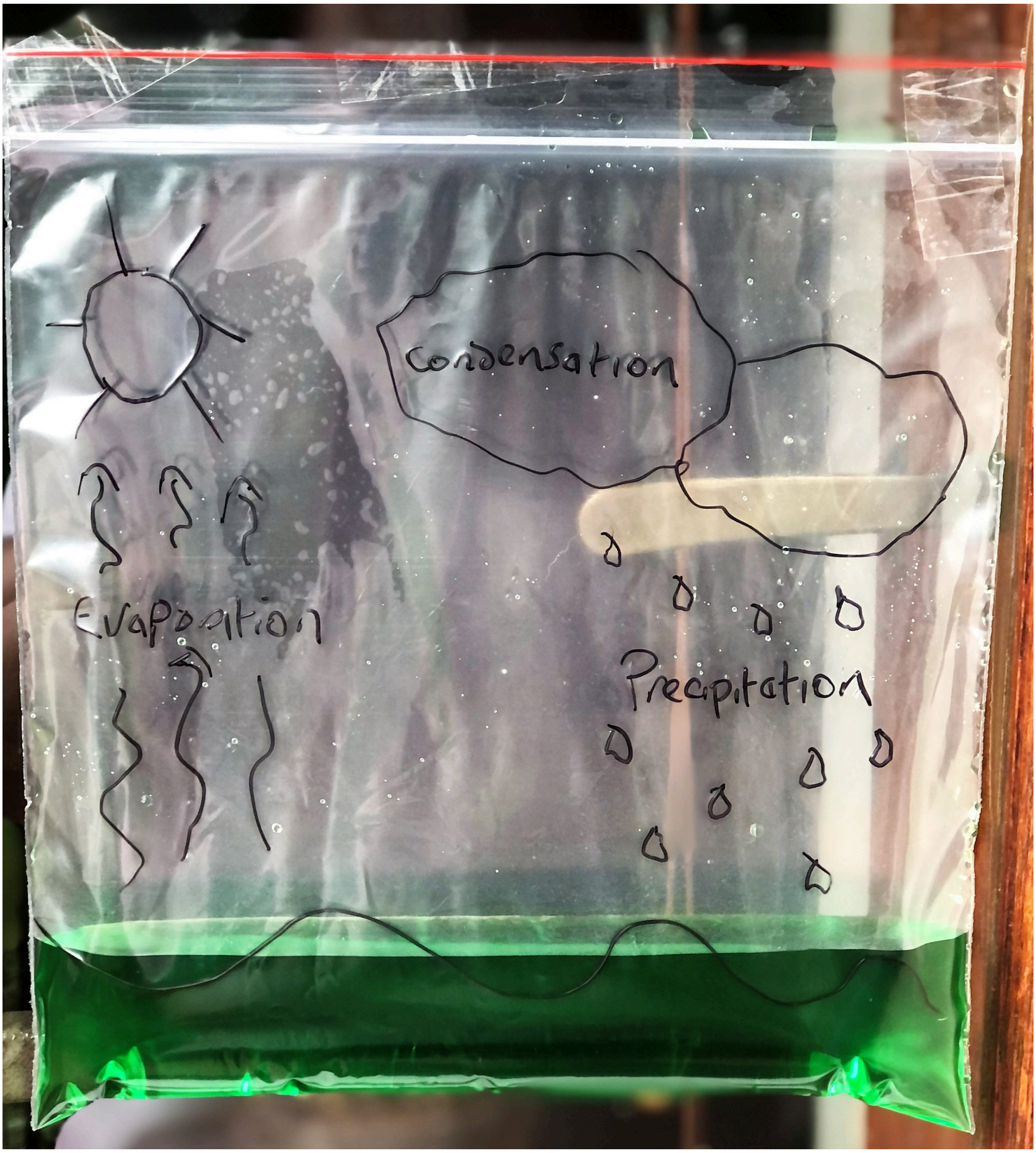
On a bigger scale, river valleys in mountains have been carved out by the action of water, and cliffs and caves on rocky beach coastlines are also the result of weathering and erosion by water. The processes of weathering and erosion also increase the content of dissolved minerals in the water. These dissolved minerals are important for the plants and animals that live in the water.

Activity 1: Make your own water cycle

Time required: 15 minutes

What you need:

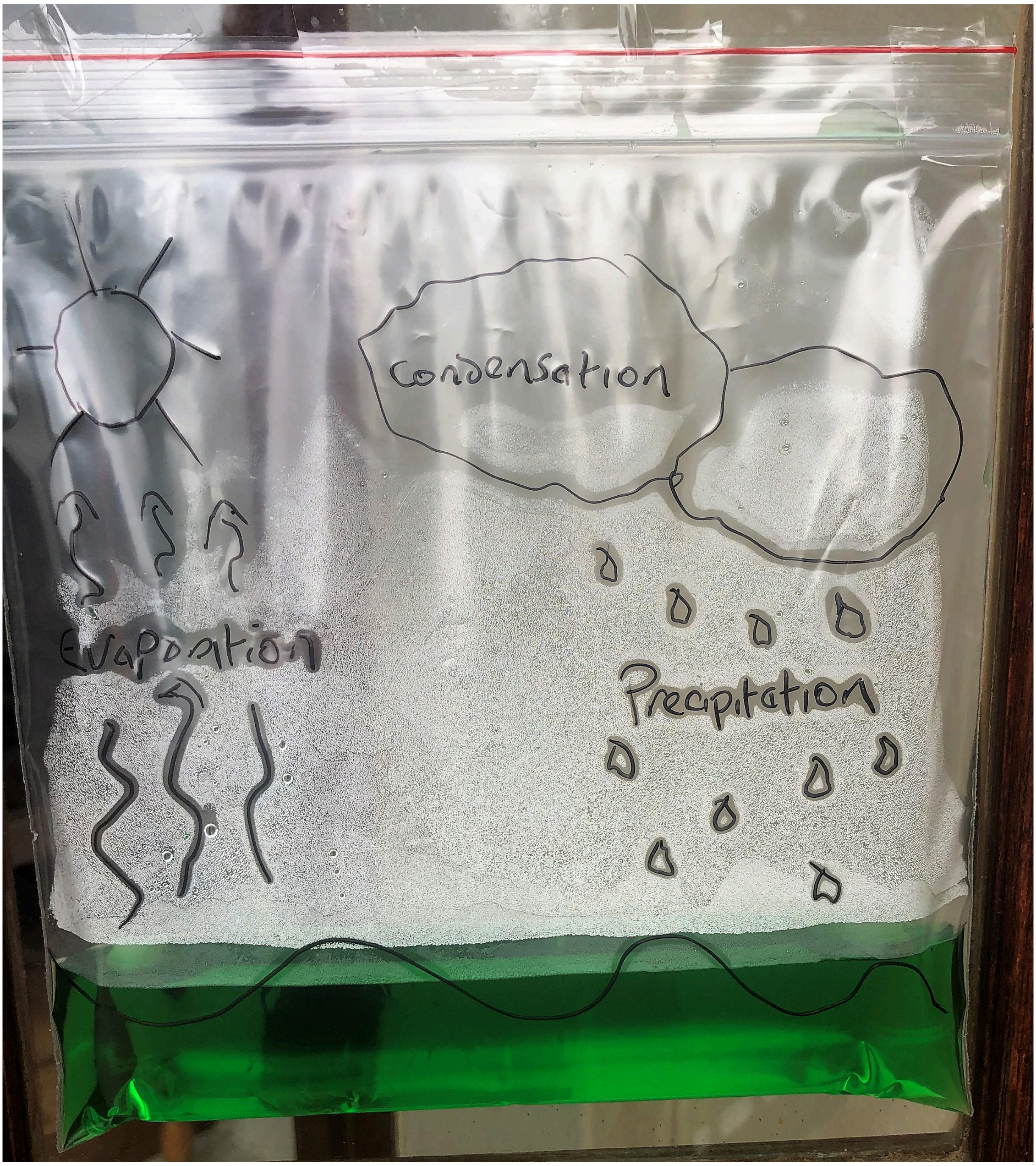
- a sealable, transparent sandwich bag or a sealable transparent jar
- food colouring (optional)
- a permanent marker
- sticky tape
- water
- a teaspoon



What to do:

1. Put some water in a container and add a teaspoon of blue food colouring. Stir well.
2. Take the sealable sandwich bag and draw a sun, some clouds, and rain. Label the areas where condensation, precipitation, evaporation, will occur.
3. Now, pour the blue water into the bag and seal it.
4. Attach the bag to a sunny window with the help of the tape.
5. Leave the bag on the window for a while and examine what changes occur when the sun begins to heat up the water.

What did you find:



The water in the bag is warmed up in the sun. That water transforms into a gas through the process of evaporation. In nature, evaporated water vapour goes into the atmosphere, but in our bag, it has nowhere to go, so it ends up settling on the sides of the bag, and rolling back into a liquid as condensation. That evaporated water then slides back into the pool of water below as "rain".

The water cycle

The hydrosphere interacts with the atmosphere and the lithosphere primarily through the water cycle. The water cycle or hydrologic cycle is driven by the energy from the sun. The water cycle goes through four main steps: evaporation, condensation, precipitation, and infiltration/percolation.

Plants release water vapour into the atmosphere in two ways. One way they release water vapour into the atmosphere is through respiration. The other way is through transpiration.

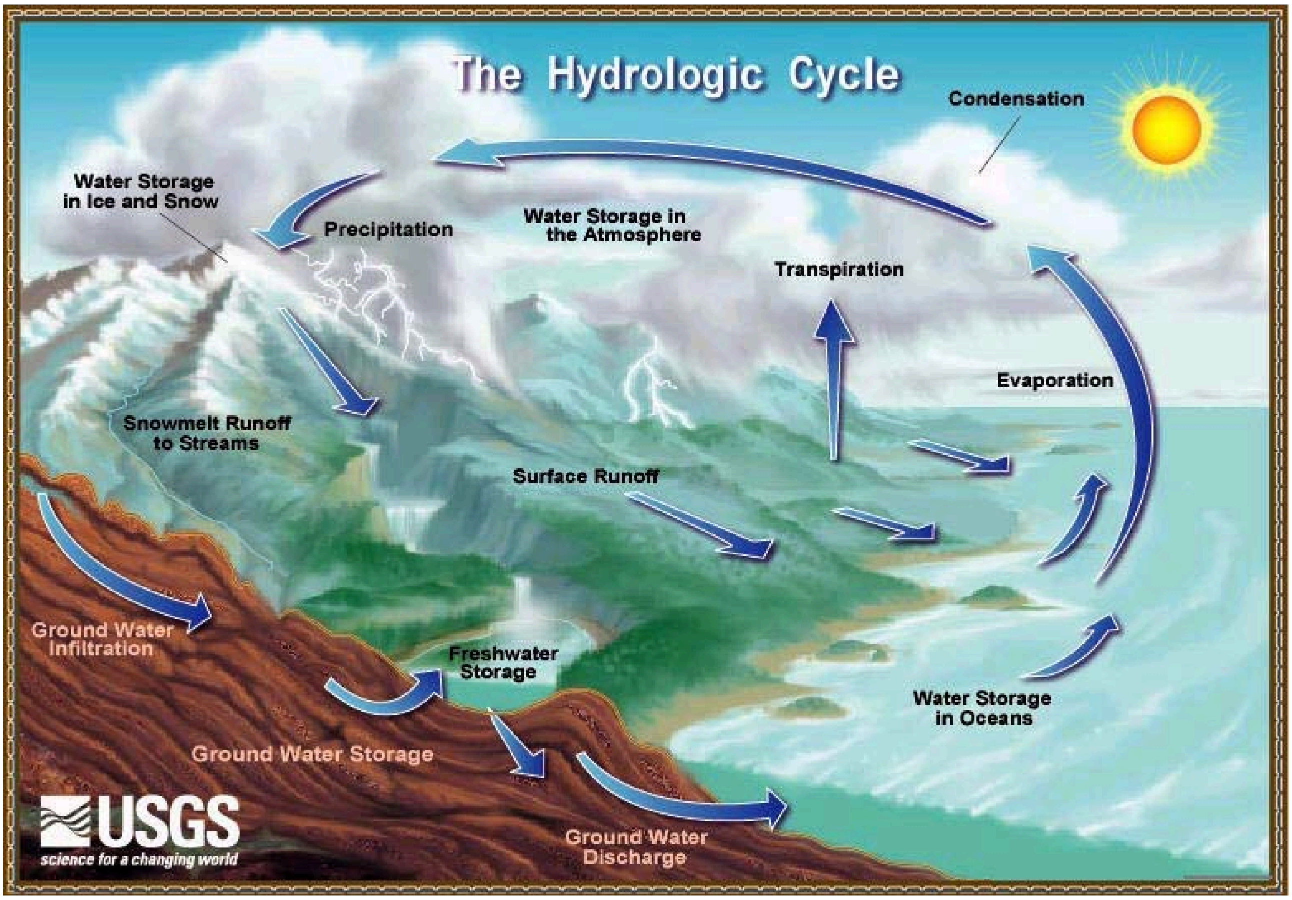


Figure 5: The water cycle

Water on the Earth's surface changes from liquid to vapour (gas) through evaporation as it absorbs energy from the sun.

When it gets to the atmosphere, the water vapour cools as it loses energy, and accumulates into water droplets, which become clouds. The process is called condensation.

Eventually, the water in the clouds falls back to Earth in the form of precipitation, which includes rain, hail, sleet, and snow. Some of that water infiltrates or sinks into the land and becomes ground water, the rest runs off the land into rivers, lakes and/or the sea.

Note

For a further explanation on the water cycle, watch this video called [The Water Cycle] by the National Science Foundation (Duration: 6.46).

Summary

In this unit you have learnt the following:

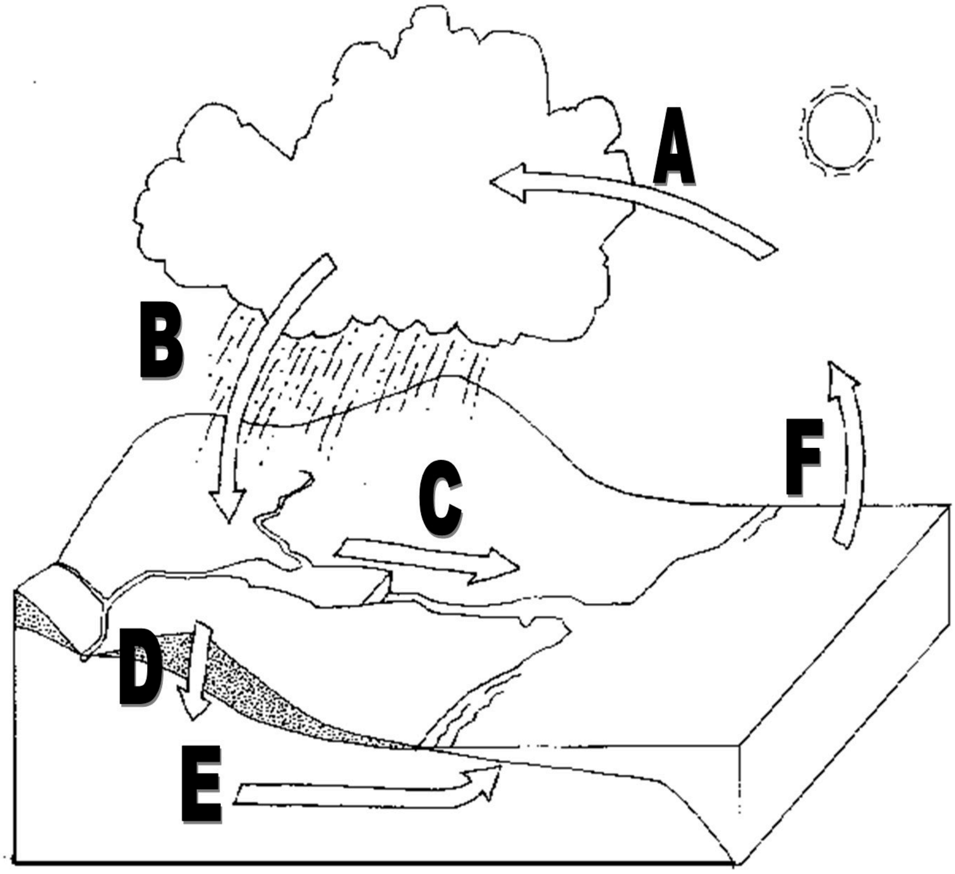
- The hydrosphere includes all the water that is on Earth. Sources of water include freshwater (e.g. rivers, lakes), saltwater (e.g. oceans), groundwater (e.g. boreholes) and water vapour. Ice (e.g. glaciers) is also part of the hydrosphere.
- The hydrosphere interacts with other global systems, including the atmosphere, lithosphere and biosphere.
- The hydrosphere has a number of important functions. Water is a part of all living cells, it provides a habitat for many living organisms, it helps to regulate climate and it is used by humans for domestic, industrial and other uses.

Unit 1: Assessment

1. How much of the Earth's water is freshwater?
   a. 50 %
   b. 3 %
   c. 97 %
   d. 93 %
2. Which best describes most of Earth's water?
   a. Freshwater
   b. Saltwater
   c. Drinking water
3. What follows evaporation during the water cycle?
   a. Water evaporates into water vapour.
   b. Water vapour condenses and forms a cloud.
   c. Water precipitates to the ground.
   d. Water runs down into the hydrosphere.
4. The clouds are formed because of:
   a. surface water
   b. evaporation
   c. condensation

d. precipitation

5. What is the hydrosphere? How does it interact with other global systems?
6. Using the diagram below, complete the table by adding the name of the process next to the correct letter.



A	
B	
C	
D	
E	
F	

7. With reference to the changes of state which occur in the water cycle, state whether energy is released or absorbed during the following changes:

Physical change	**Energy released or absorbed?**
Evaporation	
Condensation	

The full solutions are at the end of the unit.

Unit 1: Solutions

Unit 1: Assessment

1. b
2. b
3. b
4. c
5. The hydrosphere is all the water on the Earth's surface. All four systems, the atmosphere, biosphere, lithosphere, and the hydrosphere interact to form the living conditions need for organisms to survive on the Earth.
6.

A	Condensation
B	Precipitation
C	Run off
D	Infiltration/Percolation
E	Ground water discharge
F	Evaporation

7.

Physical change	**Energy released or absorbed?**
Evaporation	absorbed
Condensation	released

Back to Unit 1: Assessment

Media Attributions

Unit 2: Water pollution

EMMA HARRAGE

Unit outcomes

By the end of this unit you will be able to:

- Understand what water pollution is.
- Identify the main causes:
    - industry, including mining
    - agriculture
    - human activities.

What you should know

Before you start this unit, make sure you can:

- Understand the importance of the hydrosphere, as covered in Subject outcome 7.1, Unit 1.

Note

Before you begin this unit, please watch the video by Netflix called World's Water Crisis (Duration: 18.42).

Introduction

It should be clear by now that the hydrosphere plays an extremely important role in the survival of life on Earth and that the unique properties of water allow various important chemical processes to take place which would otherwise not be possible. Unfortunately for us however, there are many factors that threaten our hydrosphere and most of these threats are from human activities.

Water pollution occurs when water is contaminated with substances which negatively affect the ecosystem within the body of water or contaminate a source of drinking water. Only 1% of the water found on Earth is available and suitable for drinking, so it is very precious. Farming, mining, and industries commonly pollute our water supplies.

Threats to the hydrosphere

When we think of water pollution, we sometimes only think of things like plastic, bottles, oil and so on. But any chemical that is present in the hydrosphere in an amount that is not what it should be is a pollutant. Animals and plants that live in the Earth's water bodies are specially adapted to surviving within a certain range of conditions. If these conditions are changed (e.g. through pollution), these organisms may not be able to survive. Pollution then, can affect entire aquatic ecosystems. The most common forms of pollution in the hydrosphere are waste products from humans and from industries like mining and agriculture. Two common ingredients in fertilisers are nitrates and phosphates which are soluble in water and can runoff the land which causes eutrophication. Mining for precious metals can release toxic trace elements such as aluminium, mercury and copper into water systems. Acidic water, called acid mine drainage, can also enter water systems.

Water pollution is not limited to chemicals. Many industrial processes generate heat and use large amounts of water for cooling, which may be taken from the nearest river or lake. It is then returned to its source, possibly at a higher temperature if it has been insufficiently cooled beforehand. This artificial warming may have a damaging effect on local ecosystems because aquatic organisms do not usually adapt well to rapid temperature changes. Oxygen solubility decreases with rising temperatures, putting species requiring high oxygen levels at risk.

Pollution in a water system not only affects drinking water but also affects organisms that live in the water and can affect human food sources.

Humans continue to use more and more water to the point where water consumption is fast approaching the amount of water that is available. The situation is a serious one, particularly in countries like South Africa which are naturally dry and where water resources are limited. It is estimated that between 2020 and 2040, water supplies in South Africa will no longer be able to meet the growing demand for water in this country. This is partly due to population growth, and climate change, but also because of the increasing needs of industries as they expand and develop.

More than 80 percent of the world's wastewater flows back into the environment without being treated or reused, according to the United Nations. In some least-developed countries, the figure tops 95 percent.

Human sewage

Used water is wastewater. It comes from our sinks, showers, and toilets as sewage.

Untreated human sewage leaks into water systems through broken pipes, inadequate sanitation systems or by the sewage system becoming flooded with storm water. Human sewage teems with bacteria which can cause diseases including hepatitis, cholera and diarrheal diseases caused by E.Coli and salmonella bacteria and viruses called rotaviruses which cause acute diarrhoea in children. In 2017, 5.4 million children died from diarrheal disease. Diarrheal diseases are the third leading cause of child mortality globally.

Agricultural pollution

Agricultural pollution refers to the by-products of farming practices that result in contamination or degradation of the environment and surrounding ecosystems. Management practices play a crucial role in the amount and impact of these pollutants. There are several sources of agricultural pollutants which can cause water pollution, but pesticides, fertilisers and animal manure are the three main contributors. Most agricultural pollutants enter water sources by runoff or leaching.

Fertilisers

Fertilisers are used to provide crops with additional sources of nutrients, such as nitrates and phosphates to promote plant growth and increase crop yields. While they are beneficial for plant growth, they can also pose risks to human and ecological health.

The number of plants, algae, and microbes in a lake, pond or other water body will increase with an increased supply of nutrients and the increase in growth is not healthy for water resources.

Eutrophication is when a water body becomes abundant in aquatic plants resulting in low oxygen content.

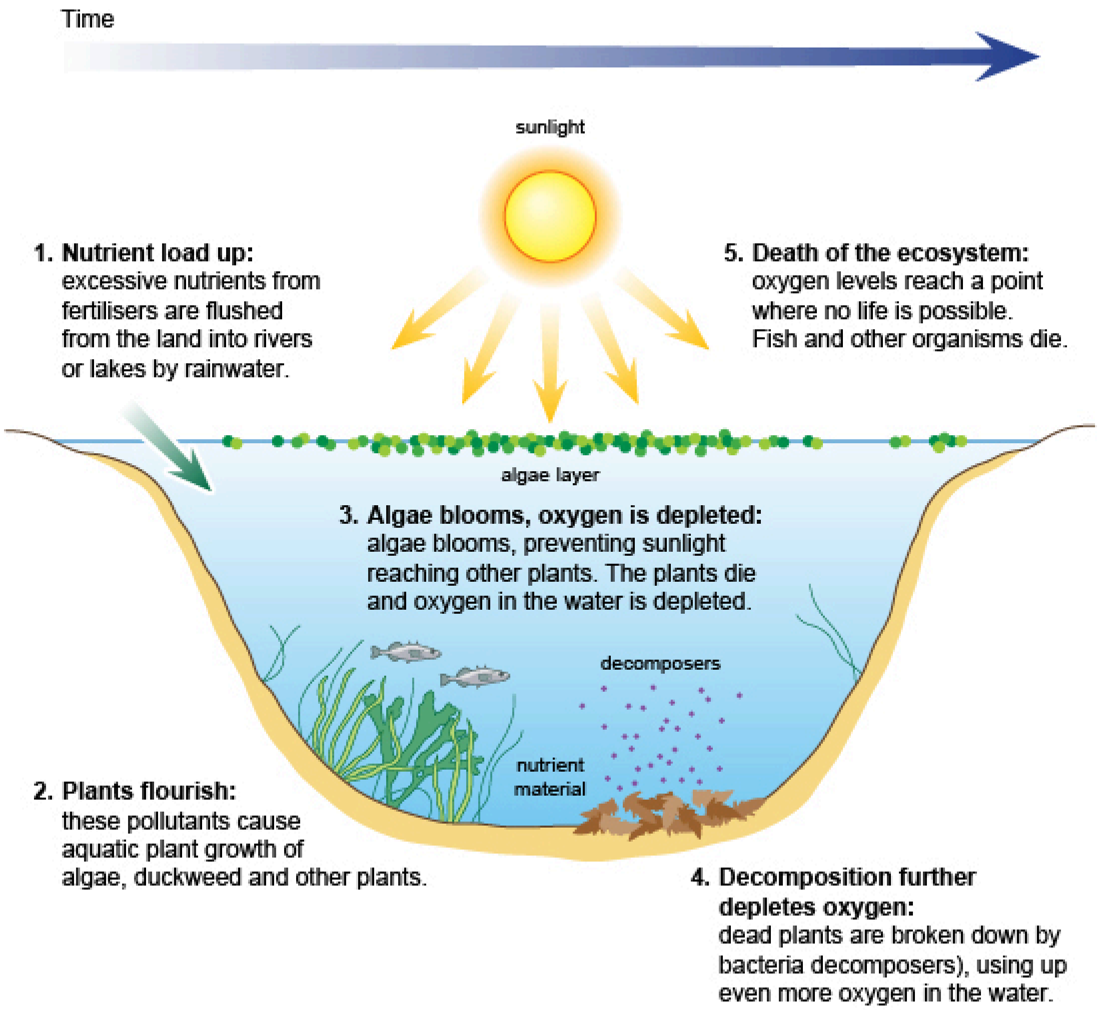


Figure 1: The process of eutrophication in a water body

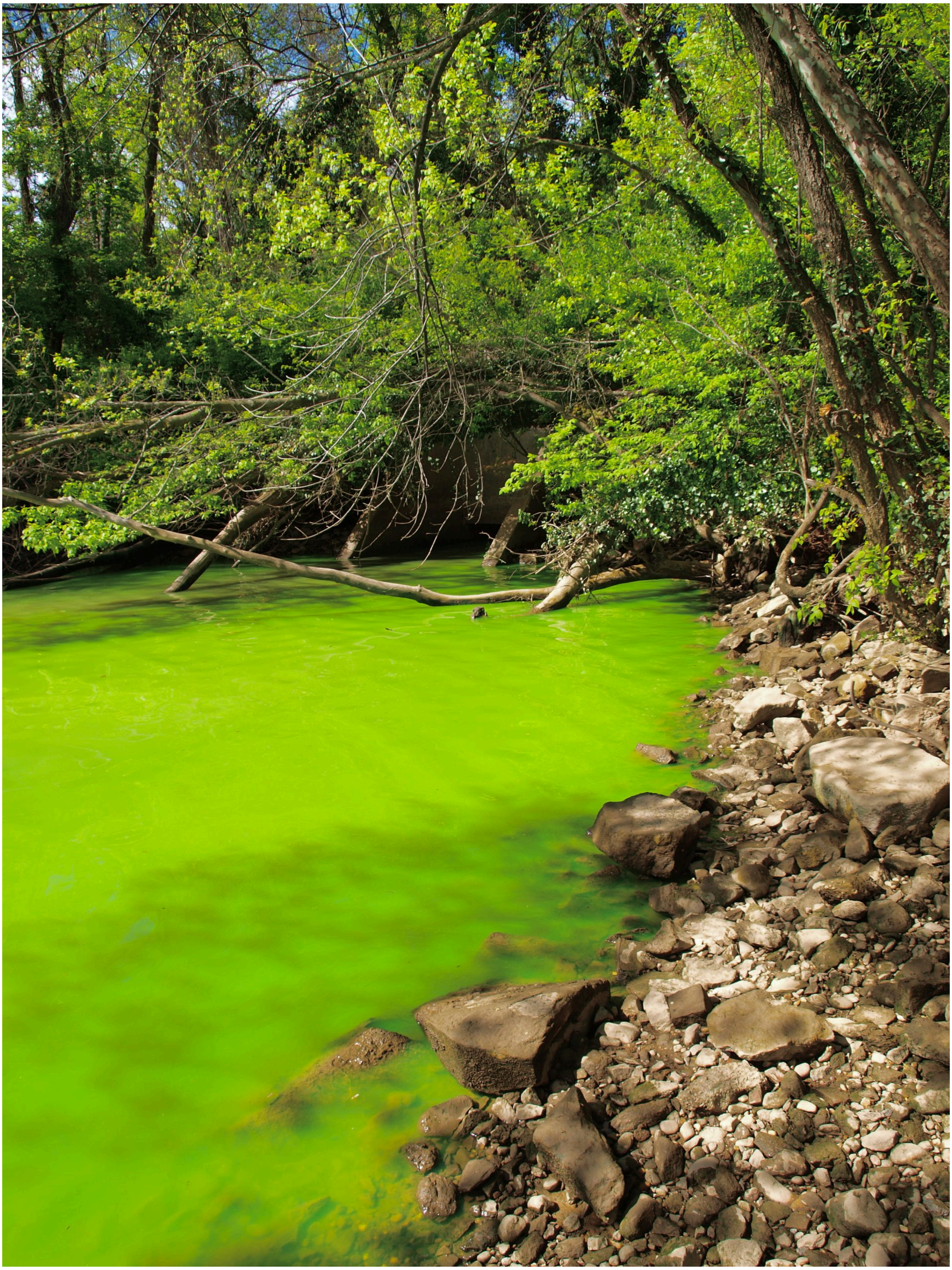


Figure 2: An algae bloom in a body of water

As the aquatic plants die, microbes use the organic matter as a food source. Once again, the microbes respire and reproduce, using up the oxygen in the water. Any increase in the amount of aquatic plant growth will result in a reduced dissolved oxygen content of the water body, eventually suffocating fish and other aquatic species. The resulting dead fish and other aquatic species degrade the water quality and cause unpleasant odours.

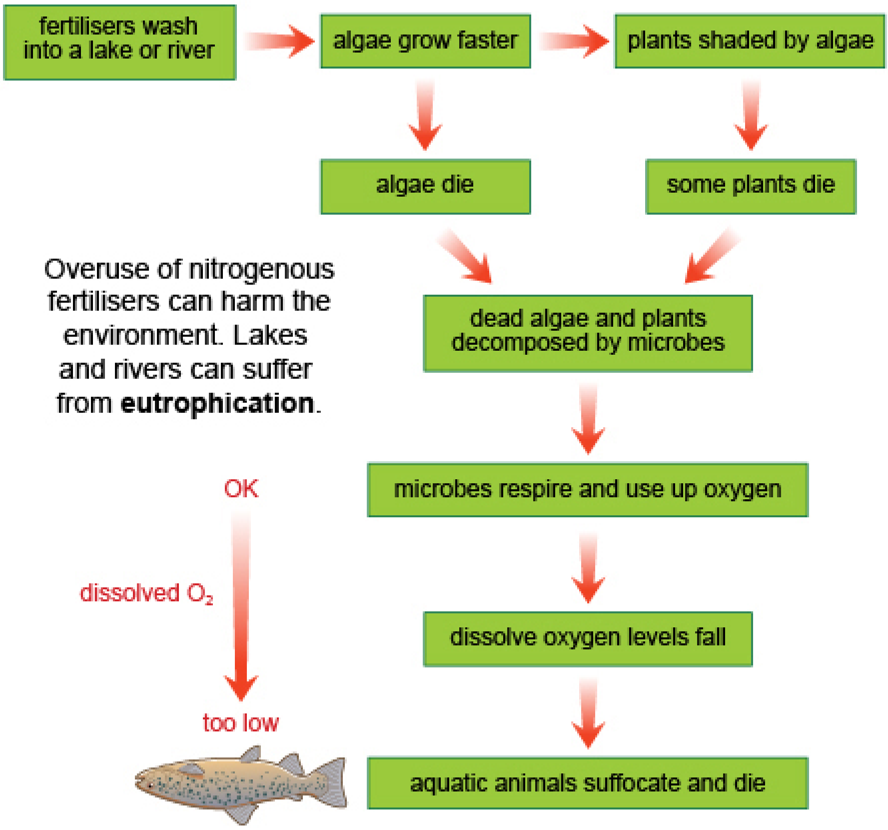


Figure 3: A flow diagram showing how an increase in nutrients which enter a body of water will cause eutrophication

Note

To learn more about this, watch the video called [What is Eutrophication] by Fuse Schools (Duration: 1.54).

Figure 4: Dead fish as a result of water pollution

Pesticides

Pesticides are used in farming to kill pests, weeds and insects which cause damage to crops. Pesticides can accumulate in the soil and depending on the amount of rainfall and/or irrigation, these pesticides leach into ground water sources and pollute the water.

Animal manure

Animal manure contains various toxins that pollute water. These are:

- nitrates which are toxic to both humans and animals. If these are in high concentration in drinking water, they cause a disease called methemoglobinemia which interferes with oxygen uptake in the circulatory system.
- ammonia-contaminated runoff, which is toxic to aquatic life. Fish are relatively sensitive to ammonia in water and high levels of ammonia will kill them. Ammonia toxicity also affects the diversity of the species, like water striders, that can live on the surface of the water.
- bacteria, viruses, parasites, and fungi from manure. These enter water systems and some of these organisms can cause diseases in both humans and animals.

Industrial pollution

There are various industries that cause pollution, for example the mining and metallurgical industries, power generating plants, manufacturing factories and processing industries.

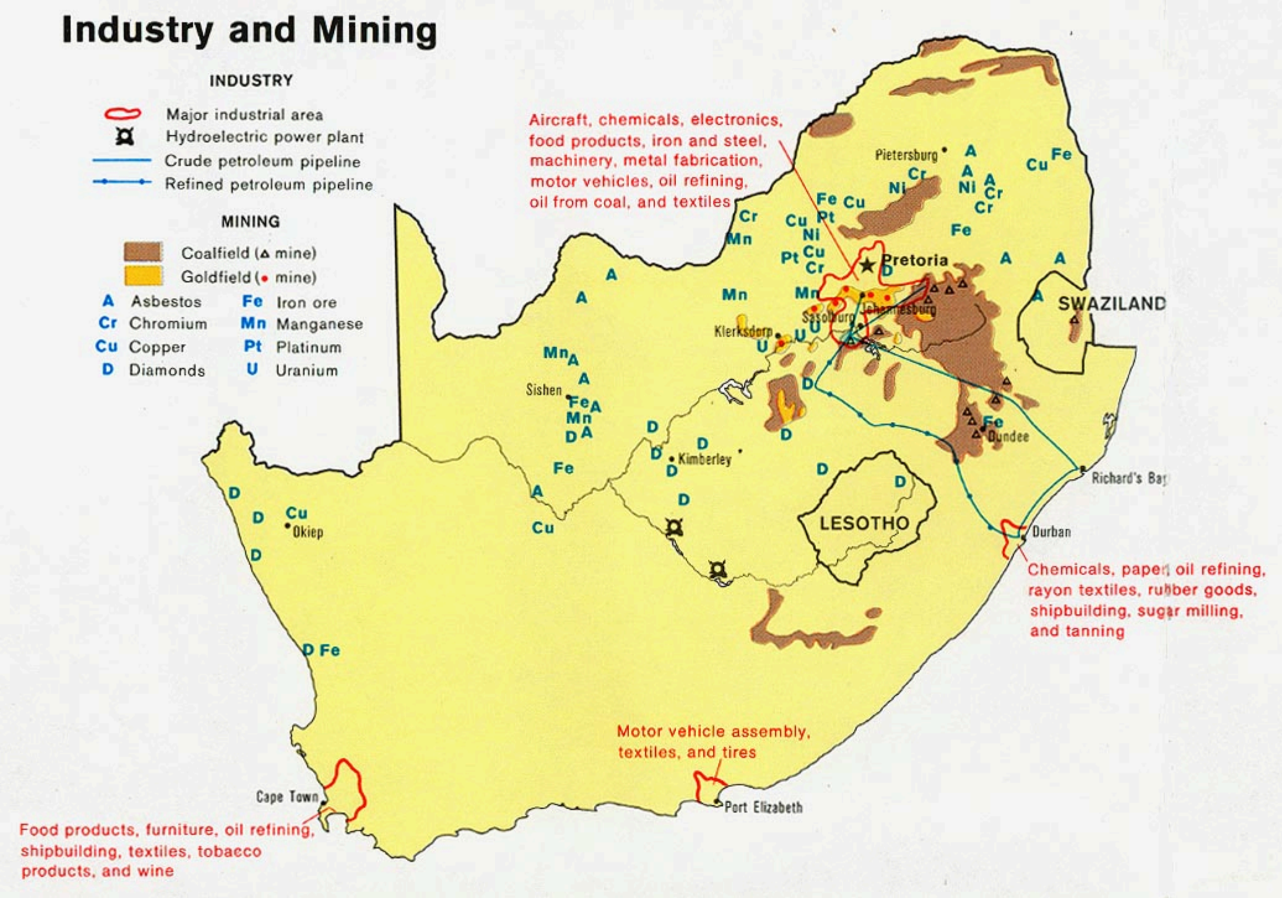


Figure 5: The different types of industries and mines found in South Africa

There are also different types of industrial pollution.

- Wastewater is water that has been used in processing or for cleaning equipment and has thereby become contaminated with pollutants. This water is then put back into water sources without being treated. Some by-products of industrial processes are polluting, such as the toxic compounds like Butanoic acid ($C_4H_4O_2$) produced in the manufacture of certain herbicides, or the acidic sulfur dioxide (SO_2) produced by burning coal which is released from the cleaning of power station chimneys.
- Many paper and pulp industries use chlorine as a bleaching agent. The chlorine combines with organic compounds in the wood to make several hazardous compounds.
- The chemical industry has produced thousands of synthetic compounds like High-Density Polyethylene (HDPE), polyethylene Terephthalate (PET or PETE or Polyester) which is used to make plastic bottles, and polystyrene which is used to make take away food containers. These compounds are xenobiotics, which means they do not occur in nature and may take a long time to break down in the environment by microbial action. When they break down, toxins can leach out and pollute water systems.

  Paper products, however, are made from cellulose, a natural material, and are therefore biodegradable If we compare the rate of decay of a paper bag and a plastic bag, the paper bag will take two to five months to rot away, but the plastic bag will take 50 years to breakdown into tiny pieces of plastic. Other everyday items that contain xenobiotics and take years to break down include:

  Foamed plastic cup: 50 years
  Cigarette filter: 10 years
  Disposable nappy: 450 years
  Plastic bottle: 450 years
  Fishing line: 600 years.

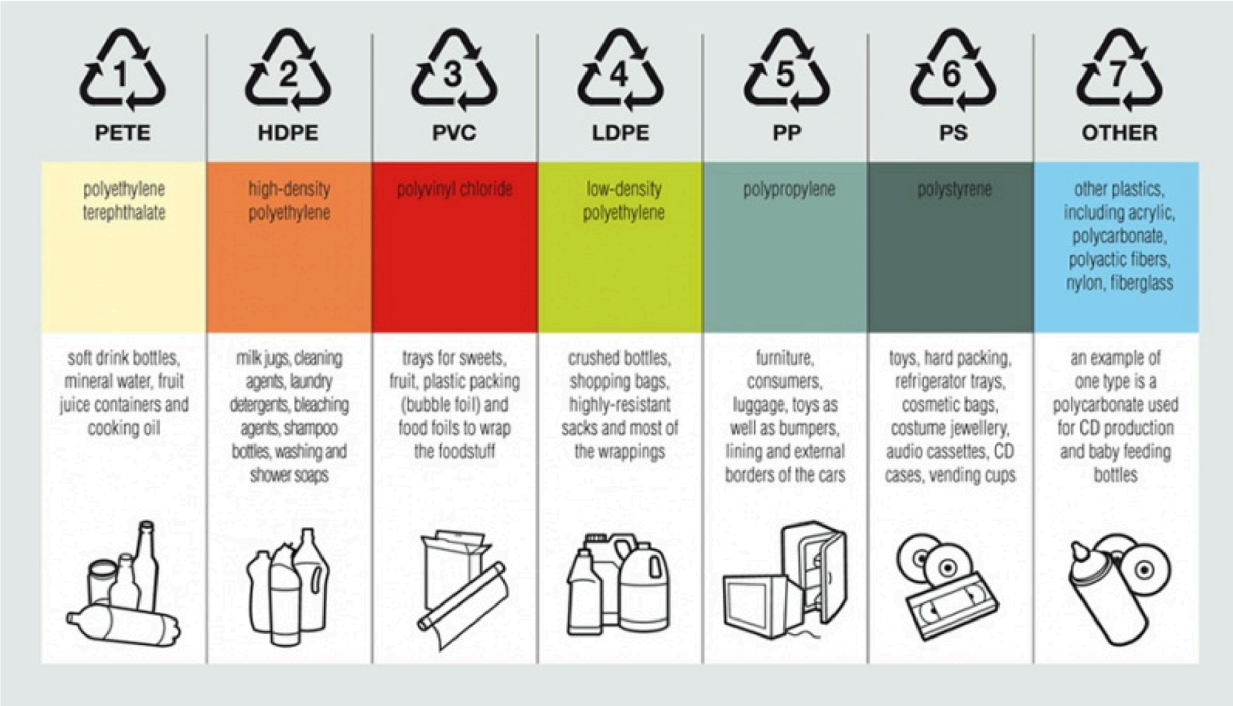


Figure 6: Types of plastics and their uses

- Mining is a significant contributor to water pollution, especially here in South Africa as we have a wealth of minerals. Water-pollution problems caused by mining include acid mine drainage (AMD), metal contamination, and increased sediment levels in streams. Sources can include active or abandoned surface and underground mines, processing plants, waste-disposal areas, haulage roads, or tailings ponds. Sediments, typically from increased soil erosion, cause the smothering of streambeds. This siltation affects fisheries, swimming, domestic water supply, irrigation, and other uses of streams.

Note

South Africa is the world's largest producers of chromium, manganese, platinum, vanadium and andalusite; and the second largest producer of ilmenite, palladium, rutile, and zirconium. We are the third largest coal exporter, fifth largest diamond producer and seventh largest iron ore producer. We are currently fifth on the list of gold producers.

Metal contamination from mining

For every gram of gold produced, gold mines release about two grams of mercury into the environment. Together, gold mines release about 1000 tons of mercury into the environment each year, or 35 percent of man-made mercury pollution. Mercury is extremely harmful to human health. The amount of mercury vapour released by mining activities has been proven to damage the kidneys, liver, brain, heart, lungs, colon, and immune system. Chronic exposure to mercury may result in fatigue, weight loss, tremors, and changes in behaviour. In children and developing foetuses, mercury can impair neurological development.

Unfortunately, mercury can bioaccumulate in aquatic food chains. Mercury is absorbed by plant plankton and then bioaccumulates up the food chain in increasing concentrations. People who eat contaminated fish may get mercury poisoning.

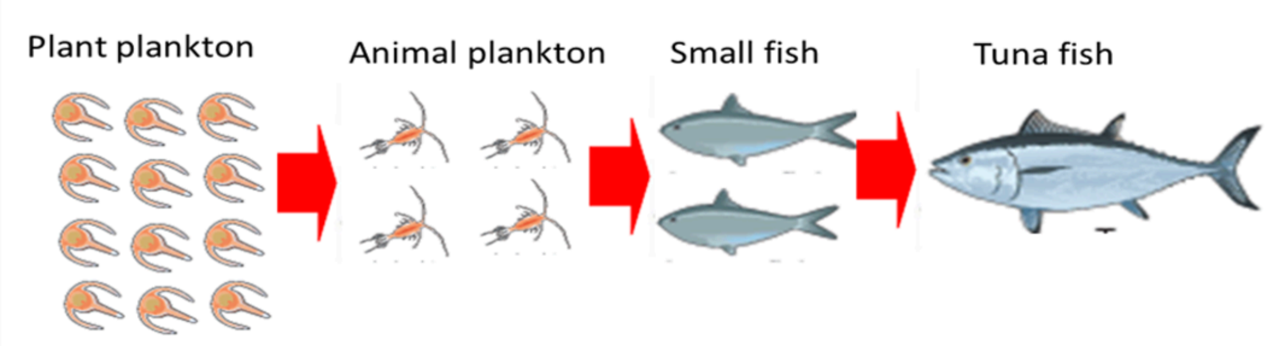


Figure 7: Mercury poisoning increases as you move up the food chain (mercury is represented here by the red dots)

Animal plankton will eat lots of plant plankton and absorb the mercury from the plants. A small fish will eat lots of animal plankton and absorb the mercury from the animal plankton. The tuna will eat many small fish and absorb lots of mercury. A person eats lots of tuna and will become ill because of all the mercury he or she has consumed from the tuna.

Mercury damages the reproductive and nervous systems of mammals – including humans!

Note

To consolidate your understanding of water pollution, you can watch this video called [What is water pollution?](#) by Fuse Schools (Duration: 5.29).

Acid mine drainage from mining

When mineral deposits that contain sulfides are mined, they have the potential to produce acid mine drainage (AMD). This includes the mining of coal, copper, gold, silver, zinc, lead, and uranium. Acid mine drainage impacts stream and river ecosystems through acidity, ferric ion (Fe^{3+}) precipitation, oxygen depletion, and the release of heavy metals associated with coal and metal mining, such as aluminium, zinc, and manganese. The mineral pyrite, more commonly known as "fool's gold", is iron disulfide (FeS_2). Pyrite is one of the most important sulfides found in the waste rock of mines. When exposed to water and oxygen, it can react to form sulfuric acid (H_2SO_4). The reaction is summarised below:

$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$
Pyrite + Oxygen + Water → Ferrous Sulfate + Sulfuric Acid

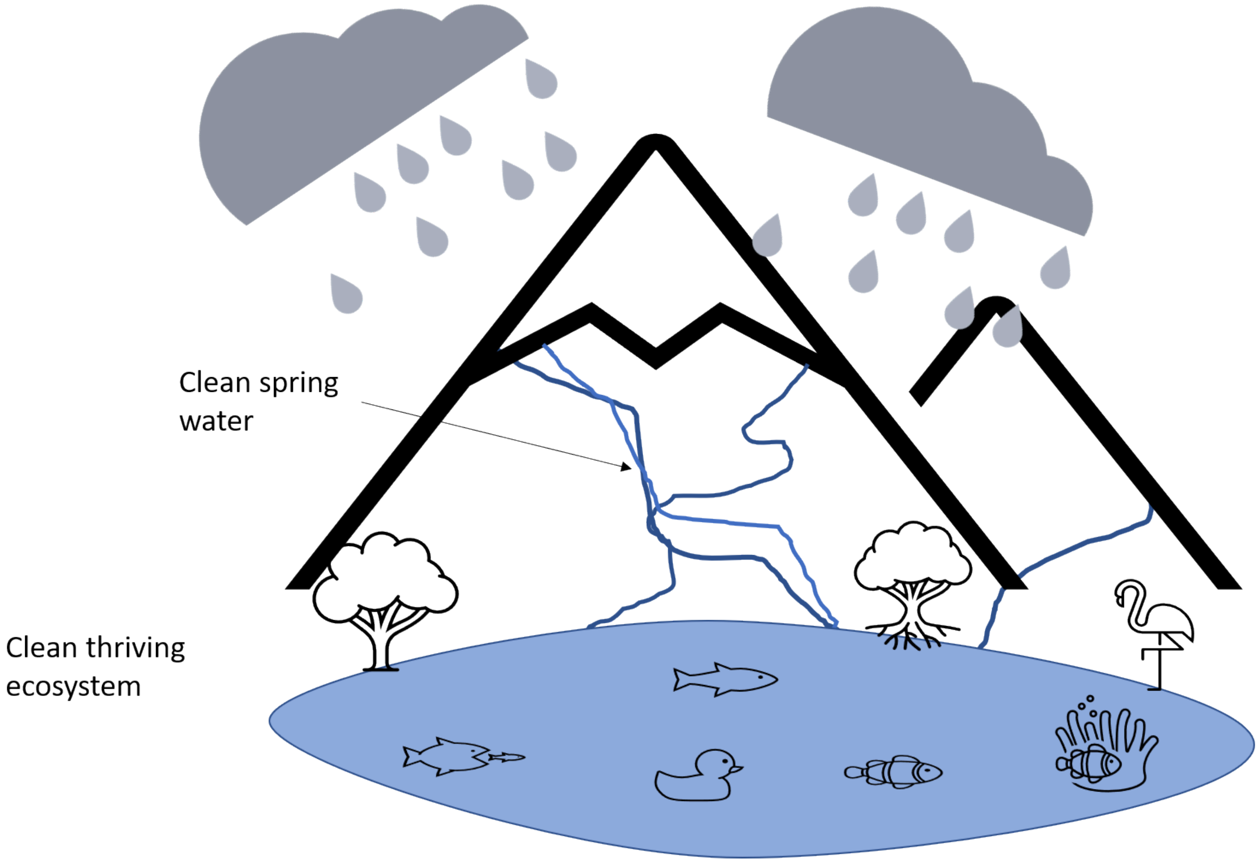


Figure 8: Prior to mining, snowmelt and rain seep through and down the mountains, eventually emerging as a freshwater spring

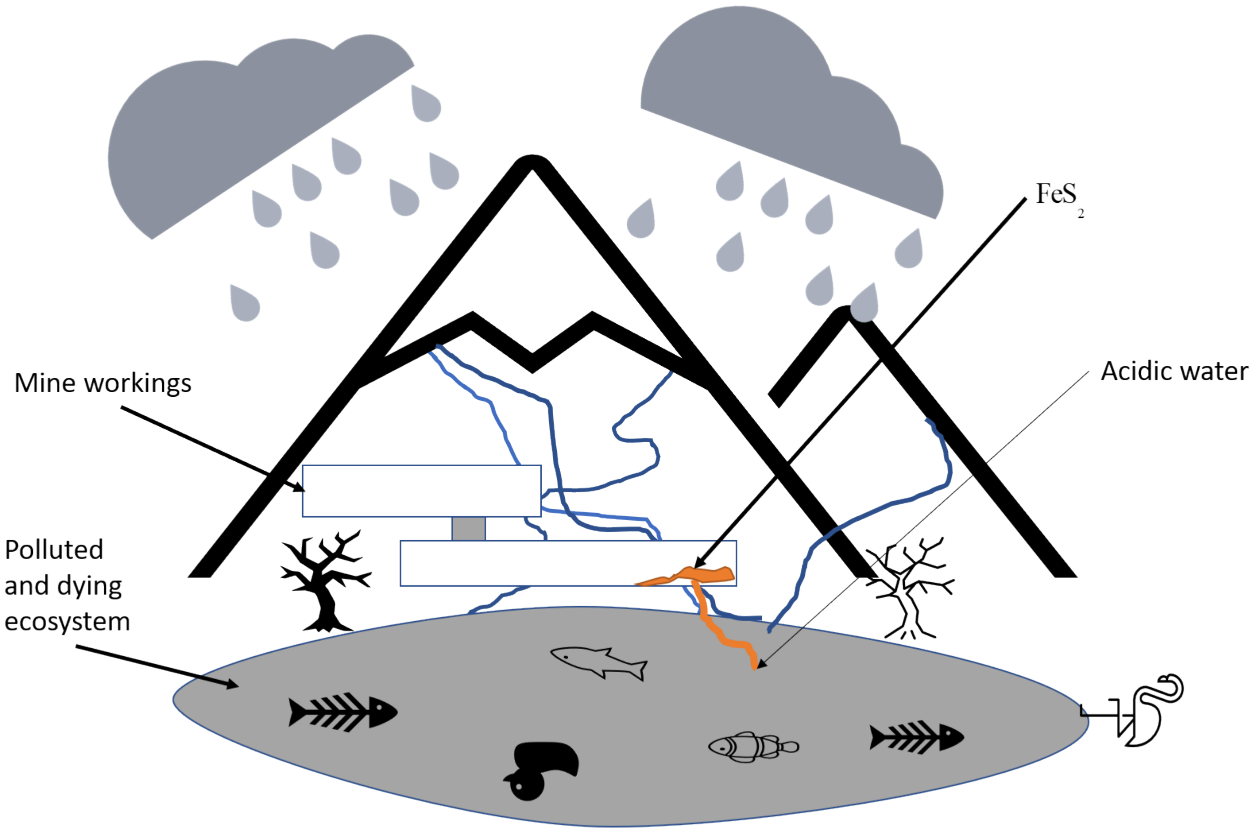


Figure 9: Mine tunnels intercept groundwater and expose it to pyrite and oxygen, setting up a chemical reaction that produces acid mine drainage

The dangers increase when this acidic water runs over rocks and strips out other embedded heavy metals. Rivers and streams can become contaminated with metals such as cadmium, arsenic, lead, and iron. Cadmium has been linked to liver disease, while arsenic can cause skin cancer and tumours. Lead poisoning can cause learning disabilities and impaired development in children.

Production of AMD can occur long after mines have been abandoned if piles of waste rock are in contact with air and water. The red colour often seen in streams receiving acid mine drainage is a stain on the rocks called ferrous hydroxide $\mathrm{Fe(OH)_3}$.

Figure 10: Acid mine drainage (AMD) in a stream

The precipitate forms as the AMD becomes neutralised. At low pH values, the metal ions remain soluble. When the pH rises, the iron oxidises and precipitates out. The precipitates can be harmful to aquatic life. The clumps reduce the amount of light that can penetrate the water, affecting photosynthesis and visibility for animal life. Furthermore, when the precipitate settles, it blankets the stream bed, smothering the bottom-dwellers and their food resources.

Note

Follow this link to view photographs taken of the effects of acidic rivers in South Africa.

A neutral pH has a value of 7. Any sample that reads below a pH of 7 is characterised as being acidic. Anything greater than 7 is described as being basic. The more acidic the water is, the better it is at eroding mining slag, rocks, and other materials. The water then transports the contaminated mine materials to nearby rivers before eventually depositing the materials downstream. Some mine drainage has been seen to have pH in the 2.5-4 range.

In Gauteng, around Carletonville, Krugersdorp, Johannesburg, and Ekurhuleni there are large gold mine dumps, which look like yellow mountains. The dumps are excavated rock and soil from when gold was mined in those areas. These mine dumps contain traces of gold, iron, lead, arsenic and mercury, all of which leach out of the dumps into the surrounding water systems.

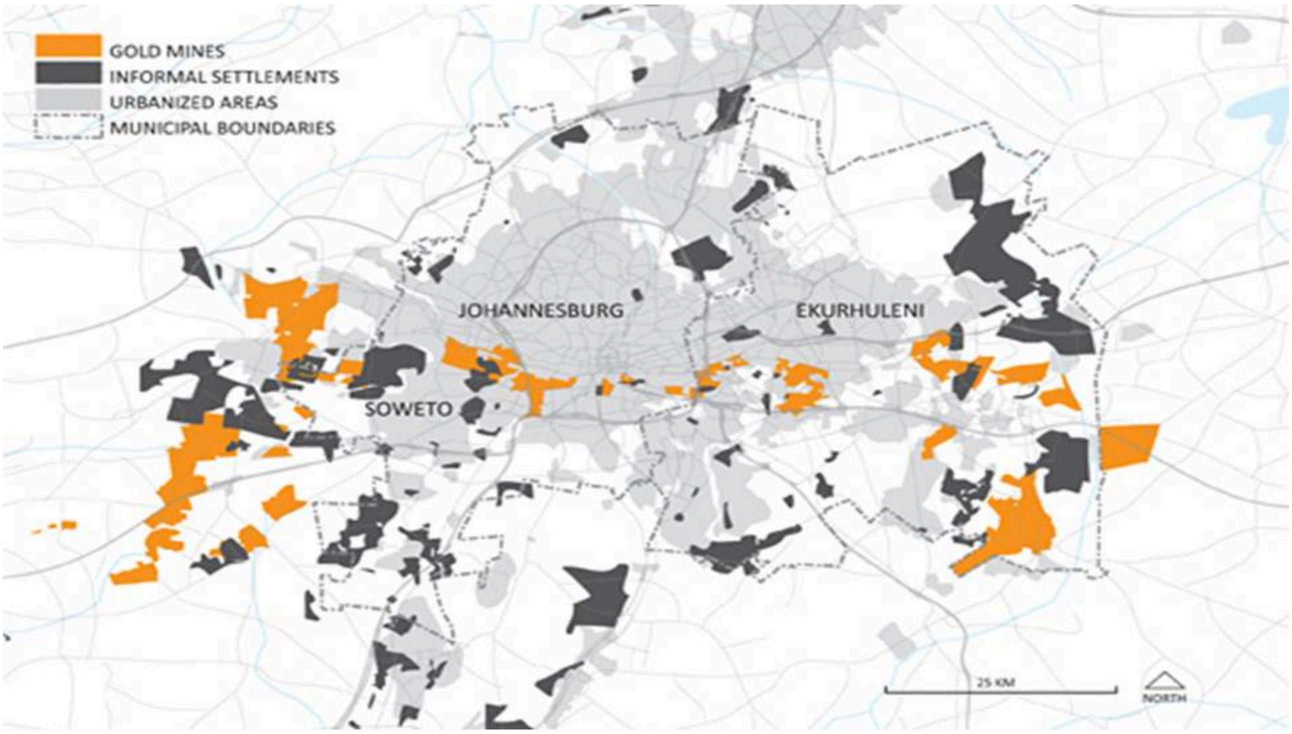


Figure 11: The areas in Gauteng where gold was mined

Figure 12: A gold tailings dump in Gauteng

Possibly more worrying, and more dangerous, is the fact that these dumps have a high concentration of uranium. This uranium is radioactive and is blown by wind with the dust off the dumps, and when inhaled it causes a variety of respitory problems including cancer and asthma. Uranium occurs naturally alongside gold reefs, and for every tonne of gold mined in the Witwatersrand gold fields, it is estimated that 10 tonnes of uranium were also mined. For most of the gold mines, uranium was merely a waste product and therefore dumped without being recovered.

Without the proper precautions in place, ore-bearing uranium leaches from the tailings and enters surrounding streams and wetlands as run-off. A similar process occurs in abandoned mines underground, with polluted water seeping through porous rock as the mines flood.

As well as cancer, high radioactive levels are linked to other health risks such as Parkinson's disease, Alzheimer's, neurotoxic syndromes, and growth deficiencies.

Acidic water and water which is polluted with heavy metals and uranium is not suitable as drinking water, nor can it be used to irrigate crops.

Note

You can find out more about acid mine drainage in South Africa by reading this case study: Africa Groundwater Atlas. 2019. [Case study: Acid mine drainage in South Africa]. British Geological Survey.

Summary

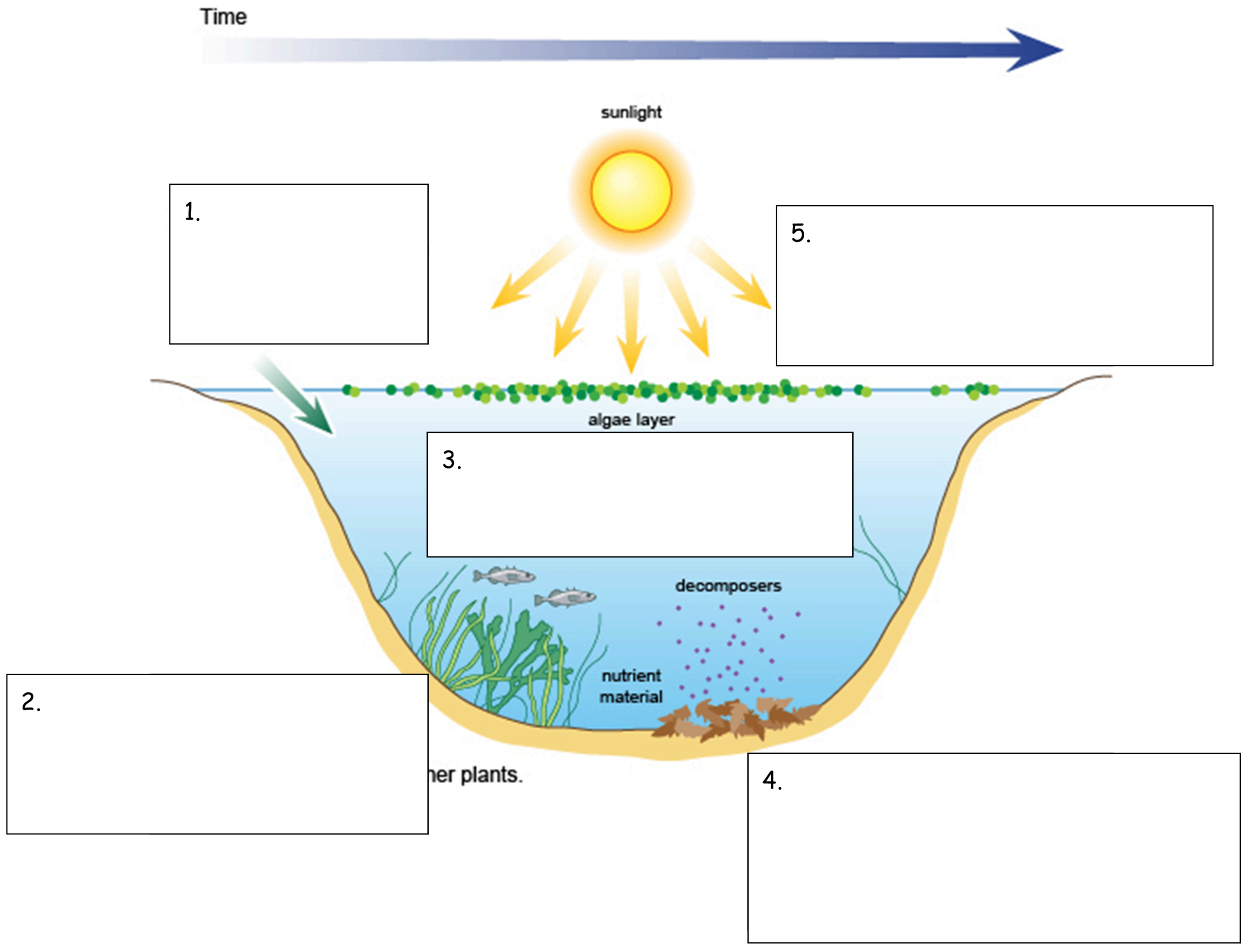
In this unit you have learnt the following:

- Water is a precious resource, and only 1% of the water available on Earth is fresh water. Despite the importance of the hydrosphere, a number of factors threaten it. These include overuse of water, and pollution.
- Water resources need protecting from pollution.
- Water is not pure, but has many substances dissolved in it.
- Human sewage, mining, agriculture, and industry are the main sources of water pollution.
- Mining can cause acid mine drainage, which acidifies water. This can cause metals to leach into water sources which cause serious health problems.
- Agriculture practices include the use of fertilisers, pesticides and herbicides which can pollute water sources.
- Industrial practices can pollute water sources with dissolved chemicals, with insoluble solids including plastics, as well as heat.

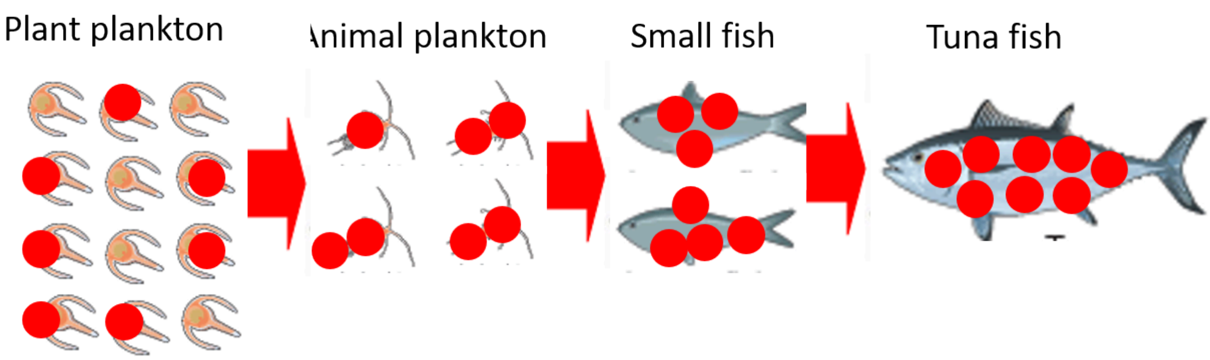
Unit 2: Assessment

Suggested time to complete: 30 minutes

1. Which of the following are the primary causes of water pollution?
    a. Plants
    b. Animals
    c. Human activities
    d. None of these
2. What is the main cause of eutrophication?
    a. Fertilisers
    b. Flooding
    c. Boat traffic
    d. Photosynthesis
3. Eutrophication is less likely to occur in areas that:
    a. are surrounded by fertilised land.
    b. are not surrounded by fertilised land.
    c. have lots of fish.
    d. already have algal blooms.
4. Local farmers have expanded the grazing area of their cattle. How will this impact the river that runs along with their lands?
    a. Animal waste will run into the river with every rainfall.
    b. This will not impact the river significantly.
    c. Animal waste will decompose and add important nutrients to the river.
    d. Cattle will pollute the river by using it as a source of water.
5.
    a. What constitutes water pollution?
    b. List the major categories of water pollutants.
6.
    a. Give a definition for the following:
        i. fertiliser
        ii. herbicide
        iii. pesticide
    b. In what industries are the chemicals above used, and briefly explain how they can pollute a water system.
7. Using the diagram below, write a sentence to describe each stage of eutrophication.



8. Describe how mercury bioaccumulates in the aquatic food chain and explain what impact this has on people who eat tuna fish.



9. It was reported in a newspaper article in 2015 that Johannesburg pumps most of its drinking water from Lesotho despite having large ground water reserves.

Write a short paragraph to explain why this would be the case.

The full solutions are at the end of the unit.

Unit 2: Solutions

Unit 2: Assessment

1. c
2. a
3. b
4. a
5.
    a. Water pollution occurs when any water source becomes contaminated.
    b. The major categories of water pollution include:
        - Sewage
        - Agricultural pollution
        - Mining pollution
        - Chemical pollution
6.
    a.
        i. a chemical compound added to crops to increase growth
        ii. a chemical compound used to kill weeds
        iii. a chemical compound used to kill insects
    b. Fertilisers are used in agriculture. They can run off into water systems and cause eutrophication. Herbicides and pesticides are also used in agriculture and if they run off into water systems they cause water pollution.
7.
    1. Excessive nutrients from fertilisers wash into a water system.
    2. Plants including algae grow rapidly.
    3. The algae bloom, which blocks sunlight from reaching plants which then die, depleting the water of oxygen.
    4. Decomposition of the dead plants by microbes uses up more oxygen.
    5. The ecosystem in the water body dies because of a lack of oxygen.
8. Mercury accumulates up the food chain, because it accumulates in organisms. Larger organisms need to eat many smaller organisms so they will consume more mercury.

    Mercury will be present in the water, and this will be absorbed by the plant plankton.

    Animal plankton will eat lots of plant plankton and absorb the mercury from the plants.

    A small fish will eat lots of animal plankton and absorb the mercury from the animal plankton.

    The tuna will eat many small fish and absorb even more mercury.

A person eats lots of tuna and will become ill because of all the mercury he or she has consumed from the tuna.

9. Johannesburg needs to use water pumped from Lesotho because of water contamination and pollution. This pollution is from mines around Johannesburg. The water is contaminated with heavy metals such as lead and cadmium and chemicals such as arsenic and mercury. All these cause health problems. Uranium also leaches into the streams and rivers. Acid mine drainage, which causes the water to become more acidic than vinegar, is also caused by the production of iron sulfide due to reactions with the by-products of mining. This turns water systems orange and destroys the ecosystem.

Back to Exercise Unit 2: Assessment

Media Attributions

Unit 3: Treatment and purification of potable water

EMMA HARRAGE

Unit 3 outcomes

By the end of this unit you will be able to:

- Classify water in terms of hardness.
- Explain water hardness and describe its effects.
- Describe the types of impurities found in water.
- Explain why water used by people and industries is purified.
- Define the water treatment and softening processes and give examples of them.

What you should know.

Before you start this unit, make sure you can:

- Recall the process of separating solids from liquids, as covered in Subject outcome 6.2, Unit 2.
- Understand that some compounds are soluble in water, as covered in Subject outcome 6.3, Unit 1.
- Understand the importance of the hydrosphere, as covered in Subject outcome 7.1, Unit 1.
- Understand that water becomes polluted with substances, as covered in Subject outcome 7.1, Unit 2.

Introduction

Before water is pumped to houses it goes through a treatment process which removes insoluble and some insoluble substances. Treating and purifying water is necessary for good health. Depending on the concentration of calcium and magnesium in the water, water can either be hard or soft. The hardness of water determines how much soap you will need when you are cleaning, and hard water causes a build-up of scale and scum which can affect the working of appliances.

Treatment and purification of potable water

When you drink a glass of water you are not just drinking water, but many other substances that are dissolved in the water. Some of these come from the process of making the water safe for humans to drink, while others come from the environment. Even if you took water from a mountain stream (which is often considered pure and bottled for people to consume), the water would still have impurities in it. Water pollution increases the amount of impurities in the water and sometimes makes the water unsafe for drinking. In this unit we will look at a few of the substances that make water impure and how we can make pure water. We will also look at the pH of water.

In Subject outcome 6.3 Unit 1: Principles of chemical reactions we saw how compounds can dissolve in water. Most of these compounds (e.g.Na^{+}, Cl^{-}, Ca^{2+}, Mg^{2+} etc.) are safe for humans to consume in the small amounts and are naturally present in water. It is only when the amounts of these ions rise above the safe levels that water is considered to be polluted.

You may have noticed sometimes that when you fill a glass with water straight from the tap, it has a sharp smell. This smell is the same smell that you notice around swimming pools and is from chlorine in the water. Chlorine is the most common compound added to water to make it safe for humans to use. Chlorine helps to remove bacteria and other biological contaminants in water. Other methods to purify water include filtration and flocculation; a process of adding chemicals to water to help remove small particles.

The pH of water is also important. Water that is too basic (has a pH greater than 7) or too acidic (has a pH less than 7) may present problems when humans consume it. If you have ever noticed after swimming that your eyes are red or your skin is itchy, then the pH of the swimming pool was probably too basic or too acidic. This shows you just how sensitive we are to the smallest changes in our environment. The pH of water depends on what ions are dissolved in the water. Adding chlorine to water often lowers the pH.

Why and how water is purified

When water arrives at a purification plant or station it may contain both soluble and insoluble substances which may be harmful to human health. So before water comes out of our taps it goes through several processes:

1. Screening: When raw water arrives at a purification station it passes through metal screens. These trap large living organisms (fish, crabs, floating plants, etc.), sticks, leaves and litter, but allow the water to pass through them.
2. Coagulation: The raw water enters the middle of a spiral flocculator where slaked lime (calcium hydroxide) is added. This is thoroughly mixed in the rapidly moving water. The slaked lime attracts sand, silt and clay particles, some small living organisms, germs and all the ‘bad guys’ (pesticides, lead, mercury, arsenic, etc.) to form ‘clumps’.
3. Flocculation: As the water begins to slow down in the outer section of the flocculator, the ‘clumps’ join to form ‘floc’.
4. Sedimentation: The water then flows slowly into large sedimentation tanks. The ‘floc’ then settles to the bottom of the tank to form ‘sludge’. This is called sedimentation. The ‘sludge’ is sucked up by desludging bridges and sent to a sludge deposit site. The water in the top part of the tank is now cleaner. It flows over the side of the sedimentation tank into the carbonation tank.
5. Carbonation: When water leaves the sedimentation tank it has a pH of about 10.5, from the slaked lime that was added. This high pH (alkaline) makes the water feel and taste soapy. In order to make the water less alkaline (have a lower pH), carbon dioxide is bubbled through the water. The pH of the water is now between 8.0 and 8.4. This makes the water taste and feel much better. At this pH level, calcium carbonate is deposited in the distribution pipes. This protects them from rusting.
6. Filtration: The pH of the water has now been corrected through carbonation, but it still contains some small living organisms and germs. It flows into closed filter houses where it passes through sand filters. These are big, flat beds made up of different sized particles of sand and stone. As the water flows slowly through these filters all the small living organisms and some germs are trapped by the sand. The water now enters underground pipes.
7. Chlorination: Even after the water has been filtered it still contains some germs. To kill these germs, chlorine gas (a disinfectant) is mixed with the water.

This clean water is pumped through underground pipes to booster pumping stations. The chlorine is only effective for 6 to 8 hours, so it is necessary to add chloramine (chlorine and ammonia) to prevent any other germs, which may get into the water, from growing or multiplying. From the booster pumping stations, the water is pumped into reservoirs. The water company then sells it to various local authorities that supply homes, schools, businesses, and factories with clean water.

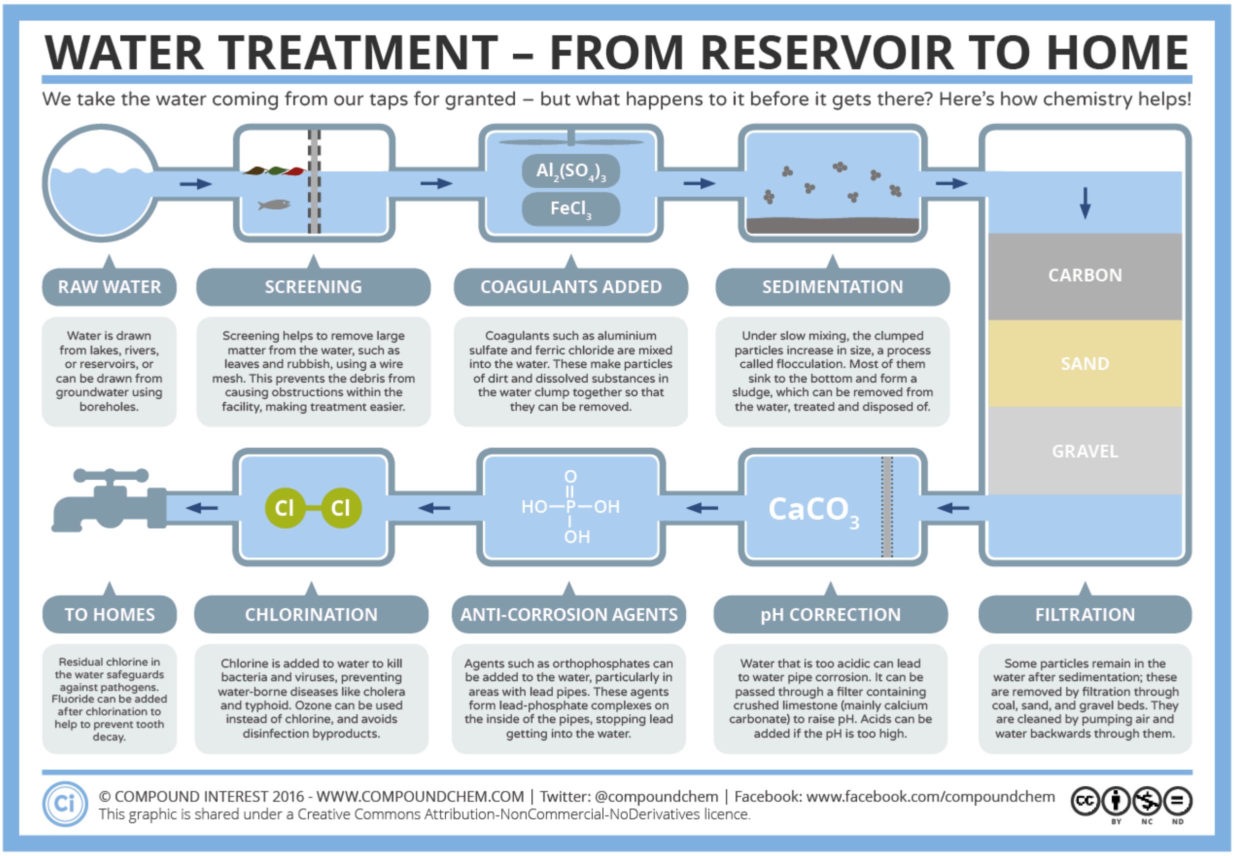


Figure 1: A flow diagram showing the water treatment process

Note

For a further explanation of water treatment, you can watch this edited video by Concerning Reality, [How do water treatment plants work?](#) (Duration: 8.01).

Water hardness

Water is classified as either soft or hard. Soft water contains relatively few minerals and lathers easily. Hard water is rich in minerals such as calcium and magnesium ions, which is the cause of "scale" in kettles. Water hardness is usually expressed as the number of parts per million (ppm) of calcium carbonate present in the water.

Type of water	Hardness (ppm)
Soft water	$10 - 50$
Slightly hard water	$50 - 100$
Hard water	$100 - 200$
Very hard water	Over 200

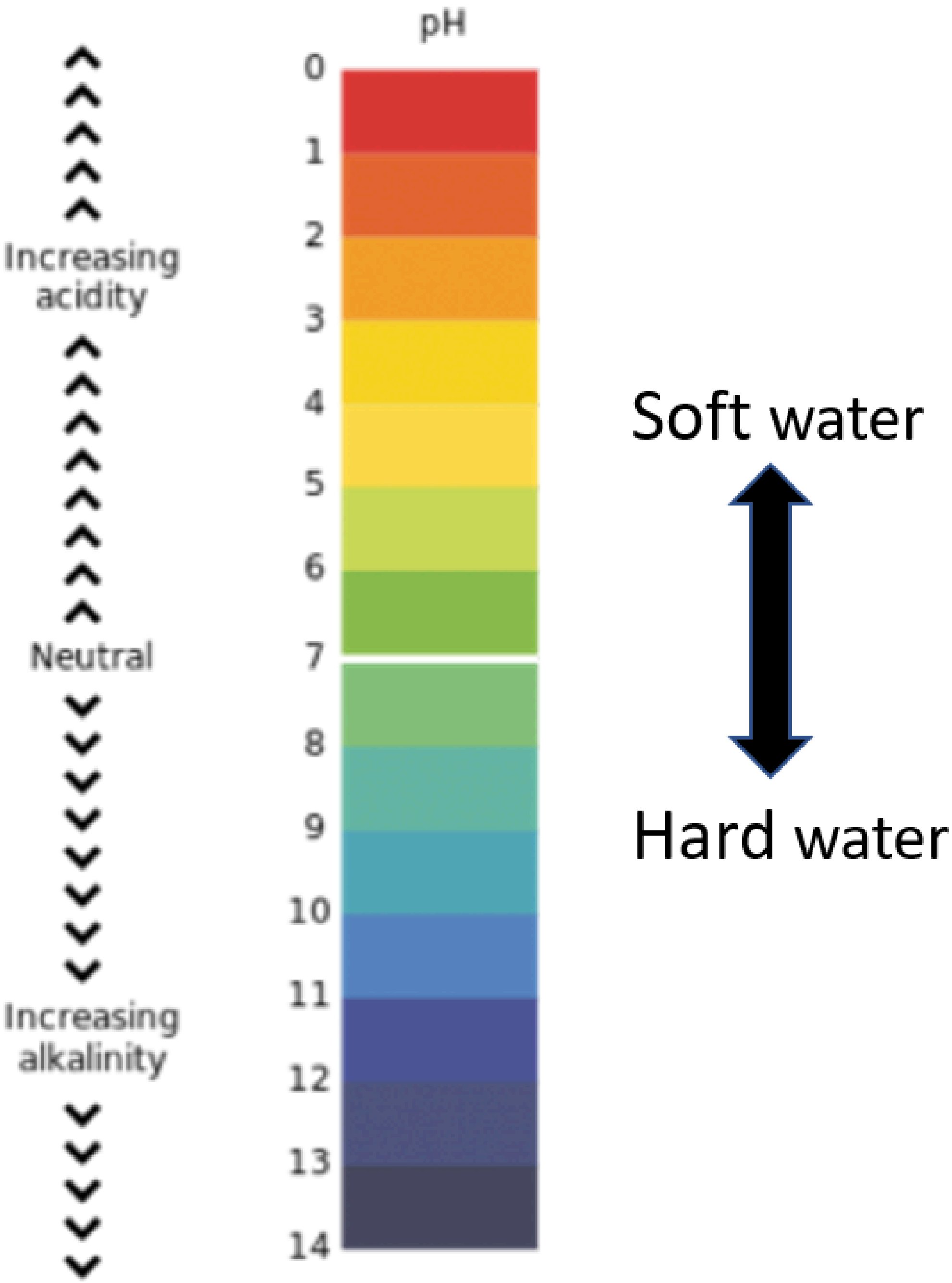


Figure 2: Hard water is more alkaline and soft water is more acidic

In general terms, areas with rainy climates have acidic water. Rain leaches out much of the mineral ions in the soil, replacing them with hydrogen ions. The result is that the water is rich in hydrogen ions and thus acidic (*soft water*). The reverse is the case in dry regions, where moisture evaporates, leaving the minerals intact. The result is water rich in minerals and thus alkaline (*hard water*).

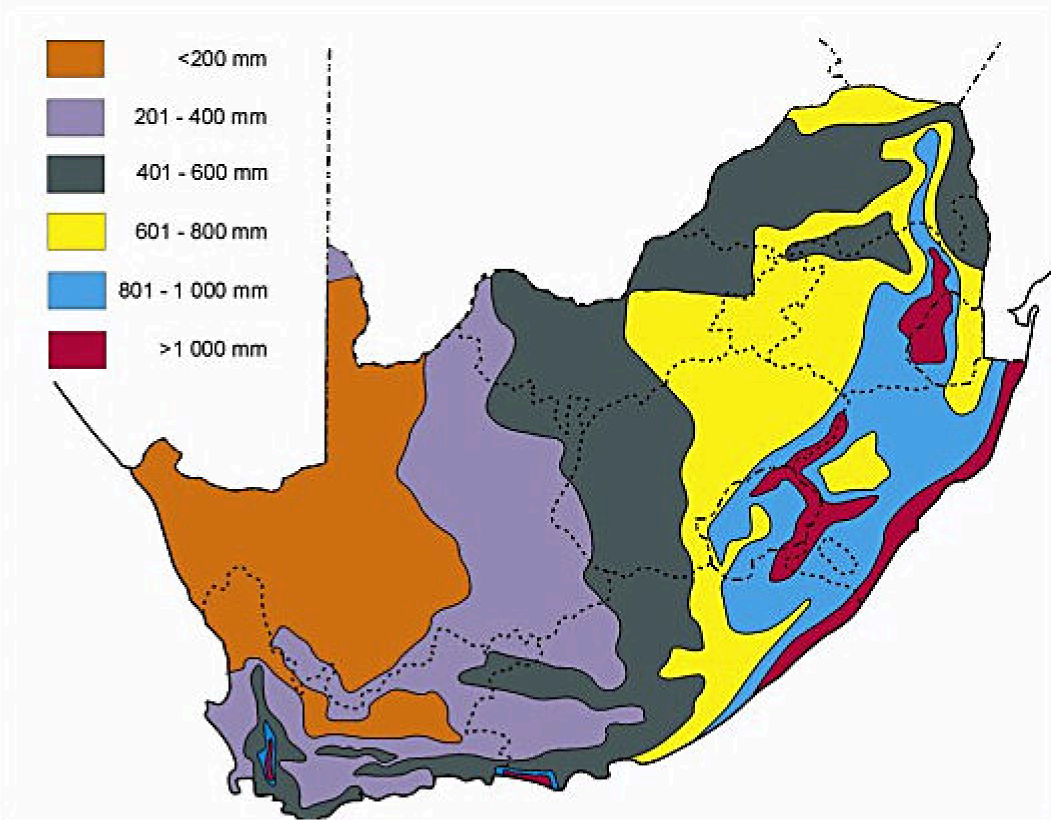


Figure 3: A map of the rainfall in South Africa

Hard water has high mineral content because it is formed when water percolates through the deposits of chalk and limestone which are made up of magnesium and calcium carbonates. It does not lather with soap, so it is not suitable for laundry purposes.

Kinds of hard water

There are three kinds of hard water:

- Temporary hardness: Temporary hardness is caused by soluble calcium bicarbonate $(Ca(HCO_2)_2)$ and/or magnesium bicarbonate $(Mg(HCO_3)_2)$ present in groundwater. Temporary hardness can be removed by boiling the water.
- Permanent hardness: When temporary hard water, caused by chlorides and sulphates of calcium and magnesium is heated, it forms calcium carbonate and/or magnesium carbonate $(MgCO_3)$ which precipitates out as scale or lime. Permanent hardness cannot be removed by boiling.
- Total hardness: Total hardness is the sum of all hardness constituents in water and is expressed as the equivalent concentration of calcium carbonate. It is primarily caused by calcium and magnesium but may include small amounts of metal ions such as iron.

Water in Gauteng in Rand Water's area of supply ranges from $60 \text{ to } 110 \text{ mg/l} CaCO_3$, so Johannesburg has moderately soft to slightly hard water as does the rest of Gauteng. In Kwazulu-Natal and the Western Cape around Cape Town, which receives a large amount of rain, the water is generally soft.

Determining how hard the water is

Total water hardness (calcium and magnesium included) is expressed in parts per million (ppm) or milligram per litre (mg/l) of $CaCO_3$ (calcium carbonate). Water hardness tests usually measure the total concentration of Ca and Mg, the dominant divalent metal ions. In certain regions iron, aluminium and manganese can also be present in high concentrations. Water hardness can be determined by using test strips or hardness test kits, and more accurately by titration or ion specific photometers.

The hardness of water is harmful to geysers and kettles as the deposition of salts occurs, which reduces the efficiency of the boiler. Hard water is safe to drink but using it for cleaning over a long period can lead to many problems. Hard water can cause linen and clothes to look dull and feel rough, it can cause ugly stains on white porcelain, scale build-up on taps, lower water pressure in showers due to clogged pipes, chalky or white residue or spots on dishes, and stains appearing in the shower. Under these circumstances water appliances have to work harder resulting in higher electricity bills.

Note

For a further explanation on the hardness of water you can watch this video by Fuse Schools: Hard & soft water (Duration: 4.21).

Softening water

Water hardness can be temporarily or permanently removed using various chemical or non-chemical methods.

The following are temporary chemical methods:

- Boiling: Temporary Hardness is due to bicarbonate ions, HCO_3^-, being present in the water. This type of hardness can be removed by boiling the water to remove theCO_2. Soluble bicarbonates are converted into insoluble carbonates which are removed by filtration.

  $Ca(HCO_3)_2 \rightarrow CaCO_3 + H_2O + CO_2$

  $Mg(HCO_3)_2 \rightarrow MgCO_3 + H_2O + CO_2$
- Clark's method: Clark's method is a process for the large-scale removal of temporary hardness from water. Clark's method involves adding a controlled quantity of slaked lime (calcium hydroxide). It removes the hardness of water by converting bicarbonates into carbonates. Slaked lime is itself a source of calcium ions (and hence hardness) so care must be taken to avoid adding too much.

  $Ca(OH)_2 + Ca(HCO_3)_2 \rightarrow 2CaCO_3 + 2H_2O$

  $Mg(HCO_3)_2 + Ca(OH)_2 \rightarrow CaCO_3 + MgCO_3 + 2H_2O$

The following are permanent chemical methods:

- Washing soda method: In this method, water is treated with a calculated amount of washing soda, Na_2CO_3, which converts the chlorides and sulphates of calcium and magnesium into their respective carbonates, which get precipitated.

  $CaCl_2 + Na_2CO_3 \rightarrow CaCO_3 + 2NaCl$

  $MgSO_4 + Na_2CO_3 \rightarrow MgCO_3 + Na_2SO_4$
- Ion exchange resin method: In this method, the permanent hardness of water is removed by using resins. Ca^{2+} and Mg^{2+} ions are exchanged with Cl^- and SO_4^{2-} ions.
- Calgon's process: In this method, sodium-hexa-meta-phosphate known as Calgon is used. The hardness in water is removed by the adsorption of Ca^{2+} and Mg^{2+} ions.

The following are the two most widely used non-chemical methods of permanent water softening.

- Distillation: Ca^{2+} and Mg^{2+} can be removed by distilling water. Distillation is, however, very expensive in most cases. Rainwater is soft because it is naturally distilled during the water cycle of evaporation, condensation, and precipitation.
- Reverse osmosis: this method uses an applied pressure gradient across a semipermeable membrane to overcome osmotic pressure and remove water molecules from the solution with hardness ions. The membrane has pores large enough to let water molecules through, but the ions Ca^{2+} and Mg^{2+} will not fit through the pores. These membranes are a type of water filter and need to be cleaned or replaced regularly.

Summary

In this unit you have learnt the following:

- Water is treated to remove insoluble and soluble substances which may have polluted the water.
- The treatment process involves several stages including the addition of chlorine to kill any bacteria which may be in the water.
- Water can be classified as hard or soft depending on the concentration of calcium and/or magnesium ions present.
- Hard water needs to be treated to remove these ions. Hard water can cause a scale build up in appliances and soap to not lather.

Unit 3: Assessment

Suggested time to complete: 20 minutes

1. What is the purpose of chlorine?
   a. make water smell clean
   b. disinfect
   c. create floc
   d. make water clear
2. The cleaning process of putting water through several screens is called:
   a. coagulation
   b. sedimentation

   c. filtration
   d. aeration
3. Water supplied to homes is treated by local councils in water treatment plants. Which one of the following is NOT one of the stages of this water treatment?
   a. settling
   b. boiling
   c. disinfection
   d. screening
4. One of the treatments of water for domestic use is to add a flocculent such as aluminium sulphate to the water stored in large tanks. This helps small particles fall to the bottom of the tanks. This stage of the treatment is called:
   a. screening
   b. fluoridation
   c. settling
   d. filtration
5. Hardness of water is due mainly to the presence of salts of:
   a. Potassium
   b. Chlorine
   c. Magnesium
   d. Boron
6. Calcium hydroxide is also called:
   a. slaked lime
   b. quicklime
   c. hydrated lime
   d. dehydrated lime
7. Coagulation is a slow stirring process that causes the gathering together of small particles into larger, settleable particles.
   a. True
   b. False
8. What is the purpose of coagulation and flocculation?
   a. to control corrosion
   b. to filter out suspended particles
   c. to remove particulate impurities, especially non-settleable solids, and colour from the water being treated
   d. to settle out larger suspended particles
9. What is the purpose of a water treatment plant?
   a. to modify source water
   b. to produce safe and pleasant drinking water
   c. to provide work experience for operators
   d. to treat drinking water
10. What is the purpose of filtration?
   a. to control corrosion
   b. to filter out suspended particles
   c. to gather together fine, light particles to form larger particles (floc) to aid the sedimentation and

filtration processes
d. to settle out larger suspended particles

11. Sedimentation is a physical process used in wastewater treatment to:
    a. remove particles that are less dense than water.
    b. remove particles that are denser than water.
    c. remove material from the water.
    d. none of the above
12. Which of the following chemicals is sometimes added in the process of coagulation and flocculation?
    a. aluminium sulphate
    b. aluminium oxide
    c. calcium chloride
    d. none of these
13. Why are calcium and magnesium ions undesirable in water?
    a. They can be removed economically, and the mineral recovered.
    b. They cause hard water.
    c. They can cause undesirable colour in water.
    d. They can promote the growth of iron bacteria, which can cause bad tastes and odours.
14. Water hardness is mainly as a result of:
    a. calcium ions
    b. magnesium ions
    c. multivalent cations
    d. a and b
15. Water hardness cations attract and bind up with:
    a. natural skin oils.
    b. phosphate ions.
    c. soaps and detergents.
    d. all of the above
16. When temporary hard water is boiled, one of the substances formed is:
    a. calcium bicarbonate
    b. calcium sulfate
    c. hydrogen chloride
    d. carbon dioxide
17. Reverse osmosis is a process used to remove molecules through a:
    a. permeable membrane.
    b. non-permeable membrane.
    c. semipermeable membrane.
    d. The process does not use a membrane.
18. Calgon is used for the removal of:
    a. sodium carbonate.
    b. permanent hardness of water.
    c. potassium carbonate.
    d. none of these

The full solutions are at the end of the unit.

Unit 3: Solutions

Unit 3: Assessment

1. b
2. c
3. b
4. c
5. c
6. a
7. a
8. d
9. b
10. b
11. b
12. a
13. b
14. d
15. c
16. d
17. c
18. b

Back to Unit 3: Assessment

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