



FHSST Authors

**The Free High School Science Texts:  
Textbooks for High School Students  
Studying the Sciences  
Physical Science  
Grade 10**

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# Chapter 1

## Units

### 1.1 Introduction

Imagine you had to make curtains and needed to buy fabric. The shop assistant would need to know how much fabric you needed. Telling her you need fabric 2 wide and 6 long would be insufficient — you have to specify the **unit** (i.e. 2 *metres* wide and 6 *metres* long). Without the unit the information is incomplete and the shop assistant would have to guess. If you were making curtains for a doll's house the dimensions might be 2 centimetres wide and 6 centimetres long!

It is not just lengths that have units, all physical quantities have units (e.g. time, temperature, distance, etc.).

**Definition: Physical Quantity**

A physical quantity is anything that you can measure. For example, length, temperature, distance and time are physical quantities.

### 1.2 Unit Systems

#### 1.2.1 SI Units

We will be using the SI units in this course. SI units are the internationally agreed upon units. Historically these units are based on the metric system which was developed in France at the time of the French Revolution.

**Definition: SI Units**

The name *SI units* comes from the French *Système International d'Unités*, which means *international system of units*.

There are seven base SI units. These are listed in Table 10.1. All physical quantities have units which can be built from these seven base units. These seven units were defined to be the base units. So, it is possible to create a different set of units by defining a different set of base units.

These seven units are called base units because none of them can be expressed as combinations of the other six. This is identical to bricks and concrete being the base units of a building. You can build different things using different combinations of bricks and concrete. The 26 letters of the alphabet are the base units for a language like English. Many different words can be formed by using these letters.

Base quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 1.1: SI Base Units

## 1.2.2 The Other Systems of Units

The SI Units are not the only units available, but they are most widely used. In Science there are three other sets of units that can also be used. These are mentioned here for interest only.

### c.g.s Units

In the c.g.s. system, the metre is replaced by the centimetre and the kilogram is replaced by the gram. This is a simple change but it means that all units derived from these two are changed. For example, the units of force and work are different. These units are used most often in astrophysics and atomic physics.

### Imperial Units

Imperial units arose when kings and queens decided the measures that were to be used in the land. All the imperial base units, except for the measure of time, are different to those of SI units. This is the unit system you are most likely to encounter if SI units are not used. Examples of imperial units are pounds, miles, gallons and yards. These units are used by the Americans and British. As you can imagine, having different units in use from place to place makes scientific communication very difficult. This was the motivation for adopting a set of internationally agreed upon units.

### Natural Units

This is the most sophisticated choice of units. Here the most fundamental discovered quantities (such as the speed of light) are set equal to 1. The argument for this choice is that all other quantities should be built from these fundamental units. This system of units is used in high energy physics and quantum mechanics.

## 1.3 Writing Units as Words or Symbols

Unit names are always written with a lowercase first letter, for example, we write metre and litre. The symbols or abbreviations of units are also written with lowercase initials, for example  $m$  for metre and  $\ell$  for litre. The exception to this rule is if the unit is named after a person, then the symbol is a capital letter. For example, the kelvin was named after Lord Kelvin and its symbol is K. If the abbreviation of the unit that is named after a person has two letters, the second letter is lowercase, for example Hz for hertz.



### Exercise: Naming of Units

For the following symbols of units that you will come across later in this book, write whether you think the unit is named after a person or not.

- |                   |                |
|-------------------|----------------|
| 1. J (joule)      | 5. C (coulomb) |
| 2. $\ell$ (litre) | 6. lm (lumen)  |
| 3. N (newton)     | 7. m (metre)   |
| 4. mol (mole)     | 8. bar (bar)   |

---

## 1.4 Combinations of SI Base Units

To make working with units easier, some combinations of the base units are given special names, but it is always correct to reduce everything to the base units. Table 10.2 lists some examples of combinations of SI base units that are assigned special names. Do not be concerned if the formulae look unfamiliar at this stage - we will deal with each in detail in the chapters ahead (as well as many others)!

It is very important that you are able to recognise the units correctly. For instance, the **newton** (N) is another name for force, which is defined as **kilogram metre per second squared** ( $\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$ ), while work is measured in **kilogram metre squared per second squared** ( $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$ ) and is called the **joule** (J).

Quantity	Formula	Unit Expressed in Base Units	Name of Combination
Force	$ma$	$\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$	N (newton)
Frequency	$\frac{1}{T}$	$\text{s}^{-1}$	Hz (hertz)
Work	$F\cdot s$	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$	J (joule)

Table 1.2: Some examples of combinations of SI base units assigned special names



**Important:** When writing combinations of base SI units, place a dot ( $\cdot$ ) between the units to indicate that different base units are used. For example, the symbol for metres per second is correctly written as  $\text{m}\cdot\text{s}^{-1}$ , and not as  $\text{ms}^{-1}$  or  $\text{m/s}$ .

## 1.5 Rounding, Scientific Notation and Significant Figures

### 1.5.1 Rounding Off

Certain numbers may take an infinite amount of paper and ink to write out. Not only is that impossible, but writing numbers out to a high accuracy (many decimal places) is very inconvenient and rarely gives better answers. For this reason we often estimate the number to a certain number of decimal places. Rounding off or approximating a decimal number to a given number of decimal places is the quickest way to approximate a number. For example, if you wanted to round-off 2,6525272 to three decimal places then you would first count three places after the decimal.

$$2,652|5272$$

All numbers to the right of  $|$  are ignored after you determine whether the number in the third decimal place must be rounded up or rounded down. You *round up* the final digit (make the digit one more) if the first digit after the  $|$  was greater or equal to 5 and *round down* (leave the digit alone) otherwise. So, since the first digit after the  $|$  is a 5, we must round up the digit in the third decimal place to a 3 and the final answer of 2,6525272 rounded to three decimal places is 2,653.



#### Worked Example 1: Rounding-off

**Question:** Round-off  $\pi = 3,141592654\dots$  to 4 decimal places.

**Answer**

**Step 1 :** Determine the last digit that is kept and mark the cut-off with  $|$ .

$$\pi = 3,1415|92654\dots$$

**Step 2 :** Determine whether the last digit is rounded up or down.

The last digit of  $\pi = 3,1415|92654\dots$  must be rounded up because there is a 9 after the  $|$ .



**Step 3 : Write the final answer.**

$\pi = 3,1416$  rounded to 4 decimal places.

**Worked Example 2: Rounding-off****Question:** Round-off 9,191919... to 2 decimal places**Answer****Step 1 :** Determine the last digit that is kept and mark the cut-off with |.

9,19|1919...

**Step 2 :** Determine whether the last digit is rounded up or down.

The last digit of 9,19|1919... must be rounded down because there is a 1 after the |.

**Step 3 :** Write the final answer.

Answer = 9,19 rounded to 2 decimal places.

**1.5.2 Error Margins**

In a calculation that has many steps, it is best to leave the rounding off right until the end. For example, Jack and Jill walk to school. They walk 0,9 kilometers to get to school and it takes them 17 minutes. We can calculate their speed in the following two ways.

Method 1	Method 2
Change 17 minutes to hours: time = $\frac{17}{60}$ = 0,28333333 km	Change 17 minutes to hours: time = $\frac{17}{60}$ = 0,28 km
Speed = $\frac{\text{Distance}}{\text{Time}}$ = $\frac{0,9}{0,28333333}$ = 3,176470588 3,18 km·hr <sup>-1</sup>	Speed = $\frac{\text{Distance}}{\text{Time}}$ = $\frac{0,9}{0,28}$ = 3,214285714 3,21 km·hr <sup>-1</sup>

Table 1.3: Rounding numbers

You will see that we get two different answers. In Method 1 no rounding was done, but in Method 2, the time was rounded to 2 decimal places. This made a big difference to the answer. The answer in Method 1 is more accurate because rounded numbers were not used in the calculation. Always round off only your final answer.

**1.5.3 Scientific Notation**

In Science one often needs to work with very large or very small numbers. These can be written more easily in scientific notation, in the general form

$$d \times 10^e$$

where  $d$  is a decimal number between 0 and 10 that is rounded off to a few decimal places.  $e$  is known as the *exponent* and is an integer. If  $e > 0$  it represents how many times the decimal place in  $d$  should be moved to the right. If  $e < 0$ , then it represents how many times the decimal place in  $d$  should be moved to the left. For example  $3,24 \times 10^3$  represents 3240 (the decimal moved three places to the right) and  $3,24 \times 10^{-3}$  represents 0,00324 (the decimal moved three places to the left).

If a number must be converted into scientific notation, we need to work out how many times the number must be multiplied or divided by 10 to make it into a number between 1 and 10 (i.e. the value of  $e$ ) and what this number between 1 and 10 is (the value of  $d$ ). We do this by counting the number of decimal places the decimal comma must move.

For example, write the speed of light in scientific notation, to two decimal places. The speed of light is 299 792 458 m·s<sup>-1</sup>. First, find where the decimal comma must go for two decimal places (to find  $d$ ) and then count how many places there are after the decimal comma to determine  $e$ .

In this example, the decimal comma must go after the first 2, but since the number after the second 9 is 7,  $d = 3,00$ .  $e = 8$  because there are 8 digits left after the decimal comma. So the speed of light in scientific notation, to two decimal places is  $3,00 \times 10^8 \text{ m}\cdot\text{s}^{-1}$ .

### 1.5.4 Significant Figures

In a number, each non-zero digit is a significant figure. Zeroes are only counted if they are between two non-zero digits or are at the end of the decimal part. For example, the number 2000 has 1 significant figure (the 2), but 2000,0 has 5 significant figures. You estimate a number like this by removing significant figures from the number (starting from the right) until you have the desired number of significant figures, rounding as you go. For example 6,827 has 4 significant figures, but if you wish to write it to 3 significant figures it would mean removing the 7 and rounding up, so it would be 6,83.



#### Exercise: Using Significant Figures

1. Round the following numbers:
  - (a) 123,517  $\ell$  to 2 decimal places
  - (b) 14,328  $\text{km}\cdot\text{h}^{-1}$  to one decimal place
  - (c) 0,00954 m to 3 decimal places
2. Write the following quantities in scientific notation:
  - (a) 10130 Pa to 2 decimal places
  - (b) 978,15  $\text{m}\cdot\text{s}^{-2}$  to one decimal place
  - (c) 0,000001256 A to 3 decimal places
3. Count how many significant figures each of the quantities below has:
  - (a) 2,590 km
  - (b) 12,305  $\text{m}\ell$
  - (c) 7800 kg

## 1.6 Prefixes of Base Units

Now that you know how to write numbers in scientific notation, another important aspect of units is the prefixes that are used with the units.



#### Definition: Prefix

A prefix is a group of letters that are placed in front of a word. The effect of the prefix is to change meaning of the word. For example, the prefix *un* is often added to a word to mean *not*, as in *unnecessary* which means *not necessary*.

In the case of units, the prefixes have a special use. The kilogram (kg) is a simple example. 1 kg is equal to 1 000 g or  $1 \times 10^3$  g. Grouping the  $10^3$  and the g together we can replace the  $10^3$  with the prefix k (kilo). Therefore the k takes the place of the  $10^3$ . The kilogram is unique in that it is the only SI base unit containing a prefix.

In Science, all the prefixes used with units are some power of 10. Table 10.4 lists some of these prefixes. You will not use most of these prefixes, but those prefixes listed in **bold** should be learnt. The case of the prefix symbol is very important. Where a letter features twice in the table, it is written in uppercase for exponents bigger than one and in lowercase for exponents less than one. For example M means mega ( $10^6$ ) and m means milli ( $10^{-3}$ ).

Prefix	Symbol	Exponent	Prefix	Symbol	Exponent
yotta	Y	$10^{24}$	yocto	y	$10^{-24}$
zetta	Z	$10^{21}$	zepto	z	$10^{-21}$
exa	E	$10^{18}$	atto	a	$10^{-18}$
peta	P	$10^{15}$	femto	f	$10^{-15}$
tera	T	$10^{12}$	pico	p	$10^{-12}$
<b>giga</b>	G	$10^9$	<b>nano</b>	n	$10^{-9}$
<b>mega</b>	M	$10^6$	<b>micro</b>	$\mu$	$10^{-6}$
<b>kilo</b>	k	$10^3$	<b>milli</b>	m	$10^{-3}$
<b>hecto</b>	h	$10^2$	<b>centi</b>	c	$10^{-2}$
<b>deca</b>	da	$10^1$	<b>deci</b>	d	$10^{-1}$

Table 1.4: Unit Prefixes



**Important:** There is no space and no dot between the prefix and the symbol for the unit.

Here are some examples of the use of prefixes:

- 40000 m can be written as 40 km (kilometre)
- 0,001 g is the same as  $1 \times 10^{-3}$  g and can be written as 1 mg (milligram)
- $2,5 \times 10^6$  N can be written as 2,5 MN (meganewton)
- 250000 A can be written as 250 kA (kiloampere) or 0,250 MA (megaampere)
- 0,000000075 s can be written as 75 ns (nanoseconds)
- $3 \times 10^{-7}$  mol can be rewritten as  $0,3 \times 10^{-6}$  mol, which is the same as  $0,3 \mu\text{mol}$  (micromol)



### Exercise: Using Scientific Notation

- Write the following in scientific notation using Table 10.4 as a reference.
  - 0,511 MV
  - 10 cℓ
  - $0,5 \mu\text{m}$
  - 250 nm
  - 0,00035 hg
- Write the following using the prefixes in Table 10.4.
  - $1,602 \times 10^{-19}$  C
  - $1,992 \times 10^6$  J
  - $5,98 \times 10^4$  N
  - $25 \times 10^{-4}$  A
  - $0,0075 \times 10^6$  m

## 1.7 The Importance of Units

Without units much of our work as scientists would be meaningless. We need to express our thoughts clearly and units give meaning to the numbers we measure and calculate. Depending on which units we use, the numbers are different. For example if you have 12 water, it means nothing. You could have 12 ml of water, 12 litres of water, or even 12 bottles of water. Units are an essential part of the language we use. Units must be specified when expressing physical quantities. Imagine that you are baking a cake, but the units, like grams and millilitres, for the flour, milk, sugar and baking powder are not specified!

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### Activity :: Investigation : Importance of Units

Work in groups of 5 to discuss other possible situations where using the incorrect set of units can be to your disadvantage or even dangerous. Look for examples at home, at school, at a hospital, when travelling and in a shop.

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### Activity :: Case Study : The importance of units

Read the following extract from CNN News 30 September 1999 and answer the questions below.

#### NASA: Human error caused loss of Mars orbiter November 10, 1999

Failure to convert English measures to metric values caused the loss of the Mars Climate Orbiter, a spacecraft that smashed into the planet instead of reaching a safe orbit, a NASA investigation concluded Wednesday.

The Mars Climate Orbiter, a key craft in the space agency's exploration of the red planet, vanished on 23 September after a 10 month journey. It is believed that the craft came dangerously close to the atmosphere of Mars, where it presumably burned and broke into pieces.

An investigation board concluded that NASA engineers failed to convert English measures of rocket thrusts to newton, a metric system measuring rocket force. One English pound of force equals 4,45 newtons. A small difference between the two values caused the spacecraft to approach Mars at too low an altitude and the craft is thought to have smashed into the planet's atmosphere and was destroyed.

The spacecraft was to be a key part of the exploration of the planet. From its station about the red planet, the Mars Climate Orbiter was to relay signals from the Mars Polar Lander, which is scheduled to touch down on Mars next month.

"The root cause of the loss of the spacecraft was a failed translation of English units into metric units and a segment of ground-based, navigation-related mission software," said Arthus Stephenson, chairman of the investigation board.

#### Questions:

1. Why did the Mars Climate Orbiter crash? Answer in your own words.
  2. How could this have been avoided?
  3. Why was the Mars Orbiter sent to Mars?
  4. Do you think space exploration is important? Explain your answer.
- 

## 1.8 How to Change Units

It is very important that you are aware that different systems of units exist. Furthermore, you must be able to convert between units. Being able to change between units (for example, converting from millimetres to metres) is a useful skill in Science.

The following conversion diagrams will help you change from one unit to another.

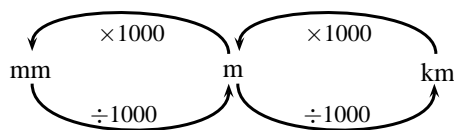


Figure 1.1: The distance conversion table

If you want to change millimetre to metre, you divide by 1000 (follow the arrow from mm to m); or if you want to change kilometre to millimetre, you multiply by  $1000 \times 1000$ .

The same method can be used to change millilitre to litre or kilolitre. Use figure 10.2 to change volumes:

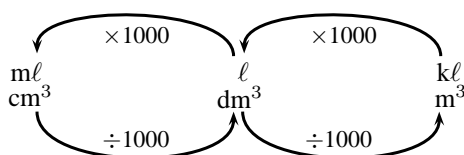


Figure 1.2: The volume conversion table



### Worked Example 3: Conversion 1

**Question:** Express 3 800 mm in metres.

**Answer**

**Step 1 : Find the two units on the conversion diagram.**

Use Figure 10.1 . Millimetre is on the left and metre in the middle.

**Step 2 : Decide whether you are moving to the left or to the right.**

You need to go from mm to m, so you are moving from left to right.

**Step 3 : Read from the diagram what you must do and find the answer.**

$$3\,800\text{ mm} \div 1000 = 3,8\text{ m}$$



### Worked Example 4: Conversion 2

**Question:** Convert 4,56 kg to g.

**Answer**

**Step 1 : Find the two units on the conversion diagram.**

Use Figure 10.1. Kilogram is the same as kilometre and gram the same as metre.

**Step 2 : Decide whether you are moving to the left or to the right.**

You need to go from kg to g, so it is from right to left.

**Step 3 : Read from the diagram what you must do and find the answer.**

$$4,56\text{ kg} \times 1000 = 4560\text{ g}$$

### 1.8.1 Two other useful conversions

Very often in Science you need to convert speed and temperature. The following two rules will help you do this:

#### Converting speed

When converting  $\text{km}\cdot\text{h}^{-1}$  to  $\text{m}\cdot\text{s}^{-1}$  you divide by 3,6. For example  $72 \text{ km}\cdot\text{h}^{-1} \div 3,6 = 20 \text{ m}\cdot\text{s}^{-1}$ .

When converting  $\text{m}\cdot\text{s}^{-1}$  to  $\text{km}\cdot\text{h}^{-1}$ , you multiply by 3,6. For example  $30 \text{ m}\cdot\text{s}^{-1} \times 3,6 = 108 \text{ km}\cdot\text{h}^{-1}$ .

#### Converting temperature

Converting between the kelvin and celsius temperature scales is easy. To convert from celsius to kelvin add 273. To convert from kelvin to celsius subtract 273. Representing the kelvin temperature by  $T_K$  and the celsius temperature by  $T_{\circ C}$ ,

$$T_K = T_{\circ C} + 273$$

## 1.9 A sanity test

A sanity test is a method of checking whether an answer makes sense. All we have to do is to take a careful look at our answer and ask the question *Does the answer make sense?*

Imagine you were calculating the number of people in a classroom. If the answer you got was 1 000 000 people you would know it was wrong — it is not possible to have that many people in a classroom. That is all a sanity test is — is your answer insane or not?

It is useful to have an idea of some numbers before we start. For example, let us consider masses. An average person has a mass around 70 kg, while the heaviest person in medical history had a mass of 635 kg. If you ever have to calculate a person's mass and you get 7 000 kg, this should fail your sanity check — your answer is insane and you must have made a mistake somewhere. In the same way an answer of 0.01 kg should fail your sanity test.

The only problem with a sanity check is that you must know what typical values for things are. For example, finding the number of learners in a classroom you need to know that there are usually 20–50 people in a classroom. If you get an answer of 2500, you should realise that it is wrong.

---

**Activity :: The scale of the matter... : Try to get an idea of the typical values for the following physical quantities and write your answers into the table:**

Category	Quantity	Minimum	Maximum
People	mass		
	height		
Transport	speed of cars on freeways		
	speed of trains		
	speed of aeroplanes		
	distance between home and school		
General	thickness of a sheet of paper		
	height of a doorway		

---

## 1.10 Summary

1. You need to know the seven base SI Units as listed in table 10.1. Combinations of SI Units can have different names.



- 
2. Unit names and abbreviations are written with lowercase letter unless it is named after a person.
  3. Rounding numbers and using scientific notation is important.
  4. Table 10.4 summarises the prefixes used in Science.
  5. Use figures 10.1 and 10.2 to convert between units.

## 1.11 End of Chapter Exercises

1. Write down the SI unit for the each of the following quantities:
  - (a) length
  - (b) time
  - (c) mass
  - (d) quantity of matter

(4)
2. For each of the following units, write down the symbol and what power of 10 it represents:
  - (a) millimetre
  - (b) centimetre
  - (c) metre
  - (d) kilometre

(4)
3. For each of the following symbols, write out the unit in full and write what power of 10 it represents:
  - (a)  $\mu\text{g}$
  - (b)  $\text{mg}$
  - (c)  $\text{kg}$
  - (d)  $\text{Mg}$

(4)
4. Write each of the following in scientific notation, correct to 2 decimal places:
  - (a) 0,00000123 N
  - (b) 417 000 000 kg
  - (c) 246800 A
  - (d) 0,00088 mm

(4)
5. Rewrite each of the following, using the correct prefix using 2 decimal places where applicable:
  - (a) 0,00000123 N
  - (b) 417 000 000 kg
  - (c) 246800 A
  - (d) 0,00088 mm

(4)
6. For each of the following, write the measurement using the correct symbol for the prefix and the base unit:
  - (a) 1,01 microseconds
  - (b) 1 000 milligrams
  - (c) 7,2 megameters
  - (d) 11 nanolitre

(4)
7. The Concorde is a type of aeroplane that flies very fast. The top speed of the Concorde is  $844 \text{ km}\cdot\text{hr}^{-1}$ . Convert the Concorde's top speed to  $\text{m}\cdot\text{s}^{-1}$ .

(3)
8. The boiling point of water is  $100^\circ\text{C}$ . What is the boiling point of water in kelvin?

(3)

Total = 30

**Part I**

**Chemistry**



## Chapter 2

# Classification of Matter - Grade 10

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 own human bodies are made of matter!

Different objects can be made of different types of matter, or **materials**. For example, a cupboard (an *object*) is made of wood, nails and hinges (the *materials*). The **properties** of the materials will affect the properties of the object. In the example of the cupboard, the strength of the wood and metals make the cupboard strong and durable. In the same way, the raincoats that you wear during bad weather, are made of a material that is waterproof. The electrical wires in your home are made of metal because metals are a type of material that is able to conduct electricity. It is very important to understand the properties of materials, so that we can use them in our homes, in industry and in other applications. In this chapter, we will be looking at different types of materials and their properties.

The diagram below shows one way in which matter can be classified (grouped) according to its different properties. As you read further in this chapter, you will see that there are also other ways of classifying materials, for example according to whether they are good electrical conductors.

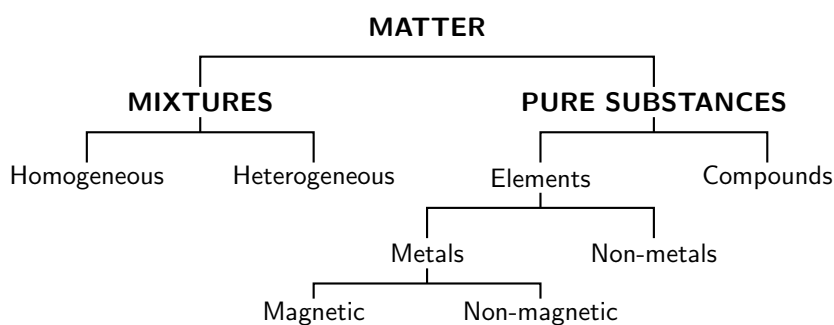


Figure 2.1: The classification of matter

## 2.1 Mixtures

We see mixtures all the time in our everyday lives. A stew, for example, is a mixture of different foods such as meat and vegetables; sea water is a mixture of water, salt and other substances, and air is a mixture of gases such as carbon dioxide, oxygen and nitrogen.

**Definition: Mixture**

A **mixture** is a combination of more than one substance, where these substances are not bonded to each other.

In a mixture, the substances that make up the mixture:

- *are not in a fixed ratio*

Imagine, for example, that you have a 250 ml beaker of water. It doesn't 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 the sand and water, neither of these substances has changed in any way when they are mixed together. Even though the sand is in water, it still has the same properties as when it was out of the water.

- *can be separated by mechanical means*

To separate something by 'mechanical 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*.

Some other examples of mixtures include blood (a mixture of blood cells, platelets and plasma), steel (a mixture of iron and other materials) and the gold that is used to make jewellery. The gold in jewellery is not pure gold but is a mixture of metals. The *carat* of the gold gives an idea of how much gold is in the item.

We can group mixtures further by dividing them into those that are heterogeneous and those that are homogeneous.

### 2.1.1 Heterogeneous mixtures

A **heterogeneous** mixture does not have a definite composition. Think of a pizza, that is a mixture of cheese, tomato, mushrooms and peppers. Each slice will probably be slightly different from the next because the toppings like the mushrooms and peppers are not evenly distributed. Another example would be granite, a type of rock. Granite is made up of lots of different mineral substances including quartz and feldspar. But these minerals are not spread evenly through the rock and so some parts of the rock may have more quartz than others. Another example is a mixture of oil and water. 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.

**Definition: Heterogeneous mixture**

A heterogeneous mixture is one that is non-uniform, and where the different components of the mixture can be seen.

### 2.1.2 Homogeneous mixtures

A **homogeneous** mixture has a definite composition, and specific properties. In a homogeneous mixture, the different parts cannot be seen. A solution of salt dissolved in water is an example of a homogeneous mixture. When the salt dissolves, it will 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. Think also of a powdered drink that you mix with water. Provided you give the container a good shake after you have added the powder to the water, the drink will have the same sweet taste for anyone who drinks it, it won't matter whether they take a sip from the top

or from the bottom. The air we breathe is another example of a homogeneous mixture since it is made up of different gases which are in a constant ratio, and which can't be distinguished from each other.

**Definition: Homogeneous mixture**

A homogeneous mixture is one that is uniform, and where the different components of the mixture cannot be seen.

An **alloy** is a homogeneous mixture of two or more elements, at least one of which is a metal, where the resulting material has metallic properties. Alloys are usually made to improve on the properties of the elements that make them up. Steel for example, is much stronger than iron, which is its main component.

### 2.1.3 Separating mixtures

Sometimes it is important to be able to separate a mixture. There are lots of different ways to do this. These are some examples:

- *Filtration*

A piece of filter paper in a funnel can be used to separate a mixture of sand and water.

- *Heating / evaporation*

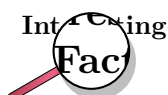
Sometimes, heating a solution causes the water to evaporate, leaving the other part of the mixture behind. You can try this using a salt solution.

- *Centrifugation*

This is a laboratory process which uses the centrifugal force of spinning objects to separate out the heavier substances from a mixture. This process is used to separate the cells and plasma in blood. When the test tubes that hold the blood are spun round in the machine, the heavier cells sink to the bottom of the test tube. Can you think of a reason why it might be important to have a way of separating blood in this way?

- *Dialysis*

This is an interesting way of separating a mixture because it can be used in some important applications. Dialysis works using a process called *diffusion*. Diffusion takes place when one substance in a mixture moves from an area where it has a high concentration to an area where its concentration is lower. When this movement takes place across a semi-permeable membrane it is called osmosis. A semi-permeable membrane is a barrier that lets some things move across it, but not others. This process is very important for people whose kidneys are not functioning properly, an illness called *renal failure*.



Normally, healthy kidneys remove waste products from the blood. When a person has renal failure, their kidneys cannot do this any more, and this can be life-threatening. Using dialysis, the blood of the patient flows on one side of a semi-permeable membrane. On the other side there will be a fluid that has no waste products but lots of other important substances such as potassium ions ( $K^+$ ) that the person will need. Waste products from the blood diffuse from where their concentration is high (i.e. in the person's blood) into the 'clean' fluid on the other side of the membrane. The potassium ions will move in the opposite direction from the fluid into the blood. Through this process, waste products are taken out of the blood so that the person stays healthy.

**Activity :: Investigation : The separation of a salt solution****Aim:**

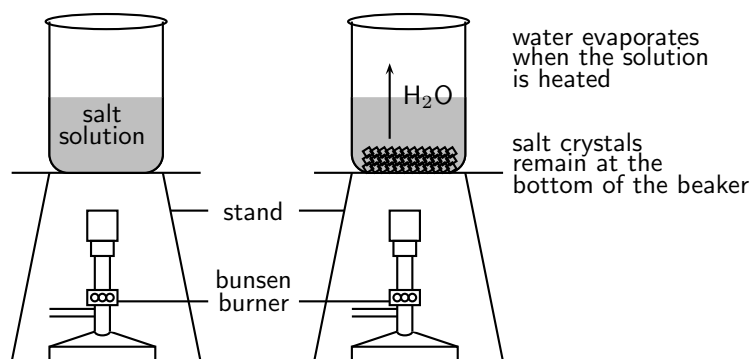
To demonstrate that a homogeneous salt solution can be separated using physical methods.

**Apparatus:**

glass beaker, salt, water, retort stand, bunsen burner.

**Method:**

1. Pour a small amount of water (about 20 ml) into a beaker.
2. Measure a teaspoon of salt and pour this into the water.
3. Stir until the salt dissolves completely. This is now called a *salt solution*. This salt solution is a homogeneous mixture.
4. Place the beaker on a retort stand over a bunsen burner and heat gently. You should increase the heat until the water almost boils.
5. Watch the beaker until all the water has evaporated. What do you see in the beaker?

**Results:**

The water evaporates from the beaker and tiny grains of salt remain at the bottom.

**Conclusion:**

The sodium chloride solution, which was a homogeneous mixture of salt and water, has been separated using heating and evaporation.

**Activity :: Discussion : Separating mixtures**

Work in groups of 3-4

Imagine that you have been given a container which holds a mixture of sand, iron filings (small pieces of iron metal), salt and small stones of different sizes. Is this a homogeneous or a heterogeneous mixture? In your group, discuss how you would go about separating this mixture into the four materials that it contains.



**Exercise: Mixtures**

- Which of the following substances are *mixtures*?
    - tap water
    - brass (an alloy of copper and zinc)
    - concrete
    - aluminium
    - Coca cola
    - distilled water
  - In each of the examples above, say whether the mixture is homogeneous or heterogeneous
- 

## 2.2 Pure Substances: Elements and Compounds

Any material that is not a mixture, is called a **pure substance**. Pure substances include **elements** and **compounds**. It is much more difficult to break down pure substances into their parts, and complex chemical methods are needed to do this.

### 2.2.1 Elements

An **element** is a chemical substance that can't be divided or changed into other chemical substances by any ordinary chemical means. The smallest unit of an element is the **atom**.

**Definition: Element**

An element is a substance that cannot be broken down into other substances through chemical means.

There are 112 officially named elements and about 117 known elements. Most of these are natural, but some are man-made. The elements we know are represented in the **Periodic Table of the Elements**, where each element is abbreviated to a **chemical symbol**. Examples of elements are magnesium (Mg), hydrogen (H), oxygen (O) and carbon (C). On the Periodic Table you will notice that some of the abbreviations do not seem to match the elements they represent. The element iron, for example, has the chemical formula Fe. This is because the elements were originally given Latin names. Iron has the abbreviation Fe because its Latin name is 'ferrum'. In the same way, sodium's Latin name is 'natrium' (Na) and gold's is 'aurum' (Au).

### 2.2.2 Compounds

A **compound** is a chemical substance that forms when two or more elements combine in a fixed ratio. Water (H<sub>2</sub>O), for example, is a compound that is made up of two hydrogen atoms for every one oxygen atom. Sodium chloride (NaCl) is a compound made up of one sodium atom for every chlorine atom. 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.

**Definition: Compound**

A substance made up of two or more elements that are joined together in a fixed ratio.

Diagram 2.2 might help you to understand the difference between the terms *element*, *mixture* and *compound*. Iron (Fe) and sulfur (S) are two elements. When they are added together, they

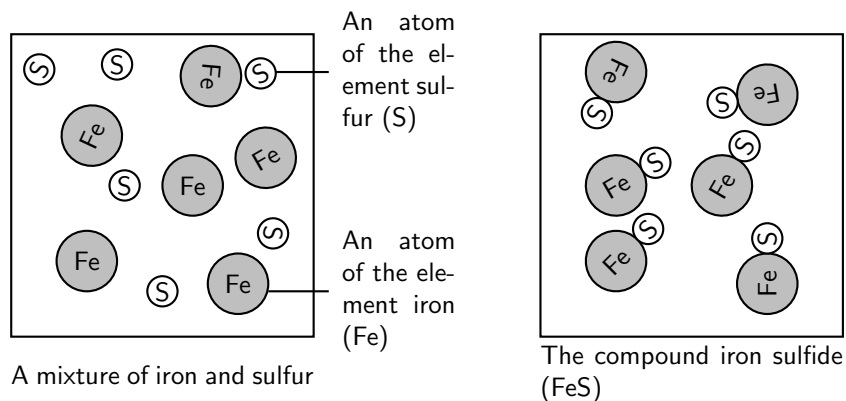


Figure 2.2: Understanding the difference between a mixture and a compound

form a *mixture* of iron and sulfur. The iron and sulfur are not joined together. However, if the mixture is heated, a new *compound* is formed, which is called iron sulfide (FeS). In this compound, the iron and sulfur are joined to each other in a ratio of 1:1. In other words, one atom of iron is joined to one atom of sulfur in the compound iron sulfide.



### Exercise: Elements, mixtures and compounds

- In the following table, tick whether each of the substances listed is a *mixture* or a *pure substance*. If it is a mixture, also say whether it is a homogeneous or heterogeneous mixture.

Substance	Mixture or pure	Homogeneous or heterogeneous mixture
fizzy cold drink		
steel		
oxygen		
iron filings		
smoke		
limestone ( $CaCO_3$ )		

- In each of the following cases, say whether the substance is an element, a mixture or a compound.
  - Cu
  - iron and sulfur
  - Al
  - $H_2SO_4$
  - $SO_3$

## 2.3 Giving names and formulae to substances

It is easy to describe elements and mixtures. But how are compounds named? In the example of iron sulfide that was used earlier, which element is named first, and which 'ending' is given to the compound name (in this case, the ending is -ide)?

The following are some guidelines for naming compounds:

- 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)
- 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 7 on the right of the table. Sodium therefore comes first in the compound name. The same is true for FeS and KBr.
- The **symbols** of the elements can be used to represent compounds e.g. FeS, NaCl and KBr. These are called **chemical formulae**. In these three examples, the ratio of the elements in each compound is 1:1. So, for FeS, there is one atom of iron for every atom of sulfur in the compound.
- A compound may contain **compound ions**. An ion is an atom that has lost (positive ion) or gained (negative ion) electrons. Some of the more common compound ions and their names are shown below.

Name of compound ion	formula
Carbonate	$\text{CO}_3^{2-}$
Sulfate	$\text{SO}_4^{2-}$
Hydroxide	$\text{OH}^-$
Ammonium	$\text{NH}_4^+$
Nitrate	$\text{NO}_3^-$
Hydrogen carbonate	$\text{HCO}_3^-$
Phosphate	$\text{PO}_4^{3-}$
Chlorate	$\text{ClO}_3^-$
Cyanide	$\text{CN}^-$
Chromate	$\text{CrO}_4^{2-}$
Permanganate	$\text{MnO}_4^-$

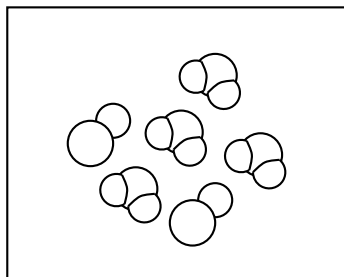
- When there are only two elements in the compound, the compound is often given a **suffix** (ending) of -ide. You would have seen this in some of the examples we have used so far. For compound ions, when a non-metal is combined with oxygen to form a negative ion (anion) which then combines with a positive ion (cation) from hydrogen or a metal, then the suffix of the name will be ...ate or ...ite.  $\text{NO}_3^-$  for example, is a negative ion, which may combine with a cation such as hydrogen ( $\text{HNO}_3$ ) or a metal like potassium ( $\text{KNO}_3$ ). The  $\text{NO}_3^-$  anion has the name **nitrate**.  $\text{SO}_3^{2-}$  in a formula is **sulphite**, e.g. sodium sulfite ( $\text{Na}_2\text{SO}_3$ ).  $\text{SO}_4^{2-}$  is **sulfate** and  $\text{PO}_4^{3-}$  is **phosphate**.
- Prefixes** can be used to describe the ratio of the elements that are in the compound. You should know the following prefixes: 'mono' (one), 'di' (two) and 'tri' (three).
  - $\text{CO}$  (carbon monoxide) - There is one atom of oxygen for every one atom of carbon
  - $\text{NO}_2$  (nitrogen dioxide) - There are two atoms of oxygen for every one atom of nitrogen
  - $\text{SO}_3$  (sulfur trioxide) - There are three atoms of oxygen for every one atom of sulfur

### Important:

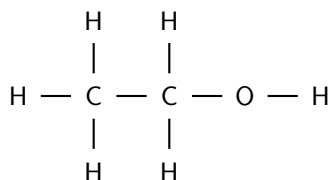
When numbers are written as 'subscripts' in compounds (i.e. they are written below the element symbol), this tells us how many atoms of that element there are in relation to other elements in the compound. For example in nitrogen dioxide ( $\text{NO}_2$ ) there are two oxygen atoms for every one atom of nitrogen. In sulfur trioxide ( $\text{SO}_3$ ), there are three oxygen atoms for every one atom of sulfur in the compound. Later, when we start looking at chemical equations, you will notice that sometimes there are numbers *before* the compound name. For example,  $2\text{H}_2\text{O}$  means that there are two molecules of water, and that in each molecule there are two hydrogen atoms for every one oxygen atom.

**Exercise: Naming compounds**

- The formula for calcium carbonate is  $\text{CaCO}_3$ .
  - Is calcium carbonate a mixture or a compound? Give a reason for your answer.
  - What is the ratio of Ca:C:O atoms in the formula?
- Give the name of each of the following substances.
  - KBr
  - HCl
  - $\text{KMnO}_4$
  - $\text{NO}_2$
  - $\text{NH}_4\text{OH}$
  - $\text{Na}_2\text{SO}_4$
- Give the chemical formula for each of the following compounds.
  - potassium nitrate
  - sodium iodide
  - barium sulfate
  - nitrogen dioxide
  - sodium monosulfate
- Refer to the diagram below, showing sodium chloride and water, and then answer the questions that follow.



- What is the chemical formula for water?
  - What is the chemical formula for sodium chloride?
  - Label the water and sodium chloride in the diagram.
  - Which of the following statements most accurately describes the picture?
    - The picture shows a mixture of an element and a compound
    - The picture shows a mixture of two compounds
    - The picture shows two compounds that have been chemically bonded to each other
5. What is the formula of this molecule?



- $\text{C}_6\text{H}_2\text{O}$
- $\text{C}_2\text{H}_6\text{O}$
- $2\text{C}_6\text{H}_2\text{O}$
- $2\text{CH}_6\text{O}$

## 2.4 Metals, Semi-metals and Non-metals

The elements in the Periodic Table can also be divided according to whether they are **metals**, **semi-metals** or **non-metals**. On the right hand side of the Periodic Table is a dark 'zigzag' line. This line separates all the elements that are metals from those that are non-metals. Metals are found on the left of the line, and non-metals are those on the right. Metals, semi-metals and non-metals all have their own specific properties.

### 2.4.1 Metals

Examples of metals include copper (Cu), zinc (Zn), gold (Au) and silver (Ag). On the Periodic Table, the metals are on the left of the zig-zag line. There are a large number of elements that are metals. The following are some of the properties of metals:

- *Thermal conductors*

Metals are good conductors of heat and are therefore used in cooking utensils such as pots and pans.

- *Electrical conductors*

Metals are good conductors of electricity, and are therefore used in electrical conducting wires.

- *Shiny metallic lustre*

Metals have a characteristic shiny appearance and are often used to make jewellery.

- *Malleable*

This means that they can be bent into shape without breaking.

- *Ductile*

Metals (such as copper) can stretched into thin wires, which can then be used to conduct electricity.

- *Melting point*

Metals usually have a high melting point and can therefore be used to make cooking pots and other equipment that needs to become very hot, without being damaged.

You can see how the properties of metals make them very useful in certain applications.

---

#### Activity :: Group Work : Looking at metals

1. Collect a number of metal items from your home or school. Some examples are listed below:
    - hammer
    - wire
    - cooking pots
    - jewellery
    - burglar bars
    - coins
  2. In groups of 3-4, combine your collection of metal objects.
  3. What is the function of each of these objects?
  4. Discuss why you think metal was used to make each object. You should consider the properties of metals when you answer this question.
-

### 2.4.2 Non-metals

In contrast to metals, non-metals are poor thermal conductors, good electrical insulators (meaning that they do *not* conduct electrical charge) and are neither malleable nor ductile. The non-metals are found on the right hand side of the Periodic Table, and include elements such as sulfur (S), phosphorus (P), nitrogen (N) and oxygen (O).

### 2.4.3 Semi-metals

Semi-metals 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. The semi-metals include elements such as silicon (Si) and germanium (Ge). Notice where these elements are positioned in the Periodic Table.

## 2.5 Electrical conductors, semi-conductors and insulators

An **electrical conductor** is a substance that allows an electrical current to pass through it. Many electrical conductors are metals, but non-metals can also be good conductors. *Copper* is one of the best electrical conductors, and this is why it is used to make conducting wire. In reality, *silver* actually has an even higher electrical conductivity than copper, but because silver is so expensive, it is not practical to use it for electrical wiring because such large amounts are needed. In the overhead power lines that we see above us, *aluminium* is used. The aluminium usually surrounds a steel core which adds tensile strength to the metal so that it doesn't break when it is stretched across distances. Occasionally gold is used to make wire, not because it is a particularly good conductor, but because it is very resistant to surface corrosion. *Corrosion* is when a material starts to deteriorate at the surface because of its reactions with the surroundings, for example oxygen and water in the air.

An **insulator** is a non-conducting material that does not carry any charge. Examples of insulators would be plastic and wood. Do you understand now why electrical wires are normally covered with plastic insulation? **Semi-conductors** behave like insulators when they are cold, and like conductors when they are hot. The elements silicon and germanium are examples of semi-conductors.

**Definition: Conductors and insulators**

A conductor allows the easy movement or flow of something such as heat or electrical charge through it. Insulators are the opposite to conductors because they *inhibit* or *reduce* the flow of heat, electrical charge, sound etc through them.

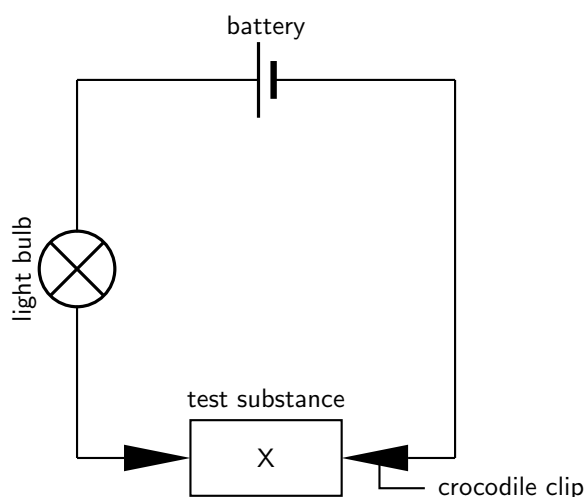
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**Activity :: Experiment : Electrical conductivity****Aim:**

To investigate the electrical conductivity of a number of substances

**Apparatus:**

- two or three cells
- light bulb
- crocodile clips
- wire leads
- a selection of test substances (e.g. a piece of plastic, aluminium can, metal pencil sharpener, metal magnet, wood, chalk).

**Method:**

1. Set up the circuit as shown above, so that the test substance is held between the two crocodile clips. The wire leads should be connected to the cells and the light bulb should also be connected into the circuit.
2. Place the test substances one by one between the crocodile clips and see what happens to the light bulb.

**Results:**

Record your results in the table below:

Test substance	Metal/non-metal	Does bulb glow?	Conductor or insulator

**Conclusions:**

In the substances that were tested, the metals were able to conduct electricity and the non-metals were not. Metals are good electrical conductors and non-metals are not.

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## 2.6 Thermal Conductors and Insulators

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. An easy way to understand this concept is through a simple demonstration.

---

**Activity :: Demonstration : Thermal conductivity****Aim:**

To demonstrate the ability of different substances to conduct heat.

**Apparatus:**

You will need two cups (made from the same material e.g. plastic); a metal spoon and a plastic spoon.

**Method:**

- Pour boiling water into the two cups so that they are about half full.
- At the same time, place a metal spoon into one cup and a plastic spoon in the other.
- Note which spoon heats up more quickly

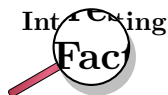
**Results:**

The metal spoon heats up more quickly than the plastic spoon. In other words, the metal conducts heat well, but the plastic does not.

**Conclusion:**

Metal is a good thermal conductor, while plastic is a poor thermal conductor. This explains why cooking pots are metal, but their handles are often plastic or wooden. The pot itself must be metal so that heat from the cooking surface can heat up the pot to cook the food inside it, but the handle is made from a poor thermal conductor so that the heat does not burn the hand of the person who is cooking.

An **insulator** is a material that does not allow a transfer of electricity or energy. Materials that are poor thermal conductors can also be described as being good insulators.



Water is a better thermal conductor than air and conducts heat away from the body about 20 times more efficiently than air. A person who is not wearing a wetsuit, will lose heat very quickly to the water around them and can be vulnerable to hypothermia. Wetsuits help to preserve body heat by trapping a layer of water against the skin. This water is then warmed by body heat and acts as an insulator. Wetsuits are made out of closed-cell, foam neoprene. Neoprene is a synthetic rubber that contains small bubbles of nitrogen gas when made for use as wetsuit material. Nitrogen gas has very low thermal conductivity, so it does not allow heat from the body (or the water trapped between the body and the wetsuit) to be lost to the water outside of the wetsuit. In this way a person in a wetsuit is able to keep their body temperature much higher than they would otherwise.

**Activity :: Investigation : A closer look at thermal conductivity**

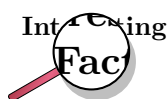
Look at the table below, which shows the thermal conductivity of a number of different materials, and then answer the questions that follow. The higher the number in the second column, the better the material is at conducting heat (i.e. it is a good thermal conductor). Remember that a material that conducts heat efficiently, will also lose heat more quickly than an insulating material.



Material	Thermal Conductivity (W/m/K)
Silver	429
Stainless steel	16
Standard glass	1.05
Concrete	0.9 - 2
Red brick	0.69
Water	0.58
Snow	0.25 - 0.5
Wood	0.04 - 0.12
Polystyrene	0.03
Air	0.024

Use this information to answer the following questions:

1. Name two materials that are good thermal conductors.
2. Name two materials that are good insulators.
3. Explain why:
  - (a) cooler boxes are often made of polystyrene
  - (b) homes that are made from wood need less internal heating during the winter months.
  - (c) igloos (homes made from snow) are so good at maintaining warm temperatures, even in freezing conditions.



It is a known fact that well-insulated buildings need less energy for heating than do buildings that have no insulation. Two building materials that are being used more and more worldwide, are **mineral wool** and **polystyrene**. Mineral wool is a good insulator because it holds air still in the matrix of the wool so that heat is not lost. Since air is a poor conductor and a good insulator, this helps to keep energy within the building. Polystyrene is also a good insulator and is able to keep cool things cool and hot things hot! It has the added advantage of being resistant to moisture, mould and mildew.

Remember that concepts such as conductivity and insulation are not only relevant in the building, industrial and home environments. Think for example of the layer of blubber or fat that we find in animals. In very cold environments, fat and blubber not only provide protection, but also act as an insulator to help the animal to keep its body temperature at the right level. This is known as *thermoregulation*.

## 2.7 Magnetic and Non-magnetic Materials

We have now looked at a number of ways in which matter can be grouped, such as into metals, semi-metals and non-metals; electrical conductors and insulators, and thermal conductors and insulators. One way in which we can further group metals, is to divide them into those that are **magnetic** and those that are **non-magnetic**.



### Definition: Magnetism

Magnetism is one of the phenomena by which materials exert attractive or repulsive forces on other materials.

A metal is said to be **ferromagnetic** if it can be magnetised (i.e. made into a magnet). If you hold a magnet very close to a metal object, it may happen that its own electrical field will be induced and the object becomes magnetic. Some metals keep their magnetism for longer than others. Look at iron and steel 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 the metals in a scrap yard, in compasses to find direction, in the magnetic strips of video tapes and ATM cards where information must be stored, in computers and TV's, as well as in generators and electric motors.

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#### Activity :: Investigation : Magnetism

You can test whether an object is magnetic or not by holding another magnet close to it. If the object is attracted to the magnet, then it too is magnetic.

Find some objects in your classroom or your home and test whether they are magnetic or not. Then complete the table below:

Object	Magnetic or non-magnetic

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#### Activity :: Group Discussion : Properties of materials

In groups of 4-5, discuss how our knowledge of the properties of materials has allowed society to:

- develop advanced computer technology
  - provide homes with electricity
  - find ways to conserve energy
- 

## 2.8 Summary

- 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 one or more substances that are not chemically bonded to each other. Examples of mixtures are air (a mixture of different gases) and blood (a mixture of cells, platelets and plasma).
- The main **characteristics** of mixtures are that the substances that make them up are not in a fixed ratio, they keep their individual properties and they can be separated from each other using mechanical means.

- A **heterogeneous mixture** is non-uniform and the different parts of the mixture can be seen. An example would be a mixture of sand and salt.
- A **homogeneous mixture** is uniform, and the different components of the mixture can't be seen. An example would be a salt solution. A salt solution is a mixture of salt and water. The salt dissolves in the water, meaning that you can't see the individual salt particles. They are interspersed between the water molecules. Another example is a metal **alloy** such as steel.
- Mixtures can be **separated** using a number of methods such as filtration, heating, evaporation, centrifugation and dialysis.
- Pure substances can be further divided into **elements** and **compounds**.
- An **element** is a substance that can't be broken down into simpler substances through chemical means.
- All the elements are recorded in the **Periodic Table of the Elements**. 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 that is made up of two or more elements that are chemically bonded to each other in a fixed ratio. Examples of compounds are sodium chloride (NaCl), iron sulfide (FeS), calcium carbonate (CaCO<sub>3</sub>) and water (H<sub>2</sub>O).
- 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. A number of rules can then be followed to name the compound.
- Another way of classifying matter is into **metals** (e.g. iron, gold, copper), **semi-metals** (e.g. silicon and germanium) and **non-metals** (e.g. sulfur, phosphorus and nitrogen).
- **Metals** are good electrical and thermal conductors, they have a shiny lustre, they are malleable and ductile, and they have a high melting point. These properties make metals very useful in electrical wires, cooking utensils, jewellery and many other applications.
- A further way of classifying matter is into **electrical conductors**, **semi-conductors** and **insulators**.
- An **electrical conductor** allows an electrical current to pass through it. Most metals are good electrical conductors.
- An **electrical insulator** is not able to carry an electrical current. Examples are plastic, wood, cotton material and ceramic.
- Materials may also be classified as **thermal conductors** or **thermal insulators** depending on whether or not they are able to conduct heat.
- Materials may also be either **magnetic** or **non-magnetic**.



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### Exercise: Summary

1. For each of the following **multiple choice** questions, choose *one* correct answer from the list provided.
  - A Which of the following can be classified as a mixture:
    - i. sugar
    - ii. table salt
    - iii. air
    - iv. iron
  - B An element can be defined as:

- i. A substance that cannot be separated into two or more substances by ordinary chemical (or physical) means
  - ii. A substance with constant composition
  - iii. A substance that contains two or more substances, in definite proportion by weight
  - iv. A uniform substance
2. Classify each of the following substances as an *element*, a *compound*, a *solution* (homogeneous mixture), or a *heterogeneous mixture*: salt, pure water, soil, salt water, pure air, carbon dioxide, gold and bronze
3. Look at the table below. In the first column (A) is a list of substances. In the second column (B) is a description of the group that each of these substances belongs in. Match up the *substance* in Column A with the *description* in Column B.

**Column A**

iron  
 $\text{H}_2\text{S}$   
sugar solution  
sand and stones  
steel

**Column B**

a compound containing 2 elements  
a heterogeneous mixture  
a metal alloy  
an element  
a homogeneous mixture

4. You are given a test tube that contains a mixture of iron filings and sulfur. 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 sulfur.
  - b What property of metals allows you to do this?
5. Given the following descriptions, write the chemical formula for each of the following substances:
- a silver metal
  - b a compound that contains only potassium and bromine
  - c a gas that contains the elements carbon and oxygen in a ratio of 1:2
6. Give the names of each of the following compounds:
- a  $\text{NaBr}$
  - b  $\text{BaSO}_4$
  - c  $\text{SO}_2$
7. For each of the following materials, say what properties of the material make it important in carrying out its particular function.
- a **tar** on roads
  - b **iron** burglar bars
  - c **plastic** furniture
  - d **metal** jewellery
  - e **clay** for building
  - f **cotton** clothing
-

## Chapter 3

# What are the objects around us made of? - Grade 10

### 3.1 Introduction: The atom as the building block of matter

We have now seen that different materials have different properties. Some materials are metals and some are non-metals; some are electrical or thermal conductors, while others are not. Depending on the properties of these materials, they can be used in lots of useful applications. But what is it exactly that makes up these materials? In other words, if we were to break down a material into the parts that make it up, what would we find? And how is it that a material's microscopic structure is able to give it all these different properties?

The answer lies in the smallest building block of matter: the **atom**. It is the *type* of atoms, and the way in which they are *arranged* in a material, that affects the properties of that substance.

It is not often that substances are found in atomic form. Normally, atoms are bonded to other atoms to form **compounds** or **molecules**. It is only in the *noble gases* (e.g. helium, neon and argon) that atoms are found individually and are not bonded to other atoms. We will look at the reasons for this in a later chapter.

### 3.2 Molecules



#### Definition: Molecule

A molecule is a group of two or more atoms that are attracted to each other by relatively strong forces or bonds

Almost everything around us is made up of molecules. *Water* is made up of molecules, each of which has two hydrogen atoms joined to one oxygen atom. *Oxygen* is a molecule that is made up of two oxygen atoms that are joined to one another. Even the food that we eat is made up of molecules that contain atoms of elements such as carbon, hydrogen and oxygen that are joined to one another in different ways. All of these are known as **small molecules** because there are only a few atoms in each molecule. **Giant molecules** are those where there may be millions of atoms per molecule. Examples of giant molecules are *diamonds*, which are made up of millions of carbon atoms bonded to each other, and *metals*, which are made up of millions of metal atoms bonded to each other.

#### 3.2.1 Representing molecules

The structure of a molecule can be shown in many different ways. Sometimes it is easiest to show what a molecule looks like by using different types of **diagrams**, but at other times, we may decide to simply represent a molecule using its **chemical formula** or its written name.

## 1. Using formulae to show the structure of a molecule

A **chemical formula** is an abbreviated (shortened) way of describing a molecule, or some other chemical substance. In chapter 2, we saw how chemical compounds can be represented using element symbols from the Periodic Table. A chemical formula can also tell us the *number* of atoms of each element that are in a molecule, and their *ratio* in that molecule.

For example, the chemical formula for a molecule of carbon dioxide is:

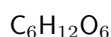


The formula above is called the **molecular formula** of that compound. The formula tells us that in one molecule of carbon dioxide, there is one atom of carbon and two atoms of oxygen. The ratio of carbon atoms to oxygen atoms is 1:2.

**Definition: Molecular formula**

A concise way of expressing information about the atoms that make up a particular chemical compound. The molecular formula gives the exact number of each type of atom in the molecule.

A molecule of glucose has the molecular formula:



In each glucose molecule, there are six carbon atoms, twelve hydrogen atoms and six oxygen atoms. The ratio of carbon:hydrogen:oxygen is 6:12:6. We can simplify this ratio to write 1:2:1, or if we were to use the element symbols, the formula would be written as  $\text{CH}_2\text{O}$ . This is called the **empirical formula** of the molecule.

**Definition: Empirical formula**

This is a way of expressing the *relative* number of each type of atom in a chemical compound. In most cases, the empirical formula does not show the exact number of atoms, but rather the simplest *ratio* of the atoms in the compound.

The empirical formula is useful when we want to write the formula for a *giant molecule*. Since giant molecules may consist of millions of atoms, it is impossible to say exactly how many atoms are in each molecule. It makes sense then to represent these molecules using their empirical formula. So, in the case of a metal such as copper, we would simply write Cu, or if we were to represent a molecule of sodium chloride, we would simply write NaCl.

Chemical formulae therefore tell us something about the *types* of atoms that are in a molecule and the *ratio* in which these atoms occur in the molecule, but they don't give us any idea of what the molecule actually looks like, in other words its *shape*. Another useful way of representing molecules is to use diagrams.

Another type of formula that can be used to describe a molecule is its **structural formula**. A structural formula uses a graphical representation to show a molecule's structure (figure 3.1).

## 2. Using diagrams to show the structure of a molecule

Diagrams of molecules are very useful because they give us an idea of the *space* that is occupied by the molecule, and they also help us to picture how the atoms are arranged in the molecule. There are two types of diagrams that are commonly used:

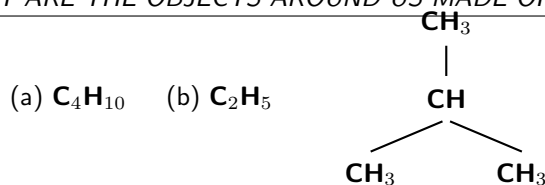


Figure 3.1: Diagram showing (a) the molecular, (b) the empirical and (c) the structural formula of isobutane

- *Ball and stick models*

This is a 3-dimensional molecular model that uses 'balls' to represent atoms and 'sticks' to represent the bonds between them. The centres of the atoms (the balls) are connected by straight lines which represent the bonds between them. A simplified example is shown in figure 3.2.

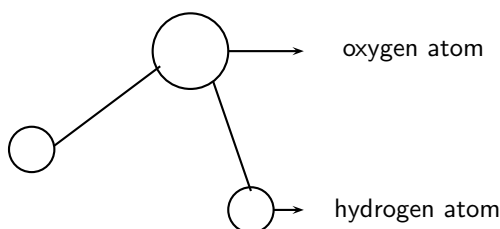


Figure 3.2: A ball and stick model of a water molecule

- *Space-filling model*

This is also a 3-dimensional molecular model. The atoms are represented by multi-coloured spheres. Space-filling models of water and ammonia are shown in figures 3.3 and 3.4.

Figures 3.3 and 3.4 are some examples of **simple molecules** that are represented in different ways.

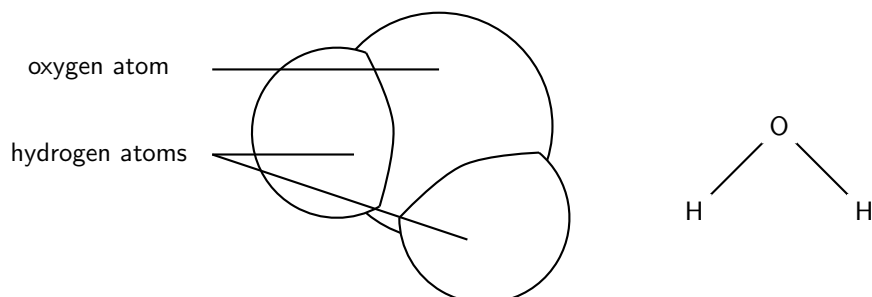


Figure 3.3: A space-filling model and structural formula of a water molecule. Each molecule is made up of two hydrogen atoms that are attached to one oxygen atom. This is a simple molecule.

Figure 3.5 shows the bonds between the carbon atoms in diamond, which is a **giant molecule**. Each carbon atom is joined to four others, and this pattern repeats itself until a complex *lattice* structure is formed. Each black ball in the diagram represents a carbon atom, and each line represents the bond between two carbon atoms.

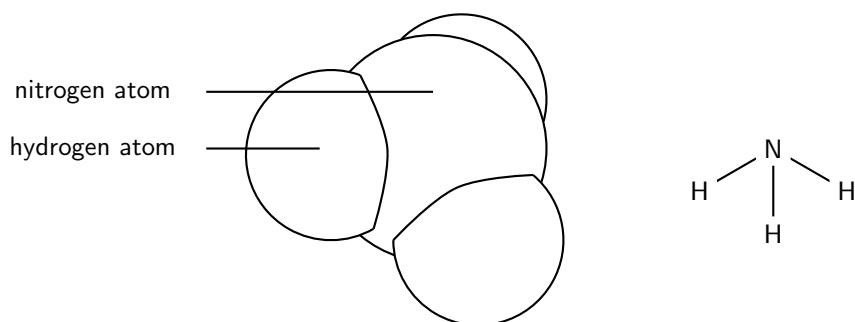


Figure 3.4: A space-filling model and structural formula of a molecule of ammonia. Each molecule is made up of one nitrogen atom and three hydrogen atoms. This is a simple molecule.

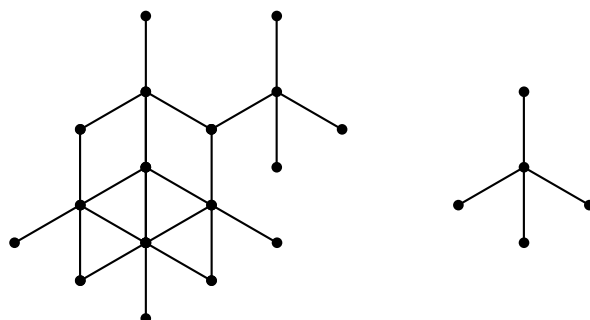


Figure 3.5: Diagrams showing the microscopic structure of diamond. The diagram on the left shows part of a diamond lattice, made up of numerous carbon atoms. The diagram on the right shows how each carbon atom in the lattice is joined to four others. This forms the basis of the lattice structure. Diamond is a giant molecule.

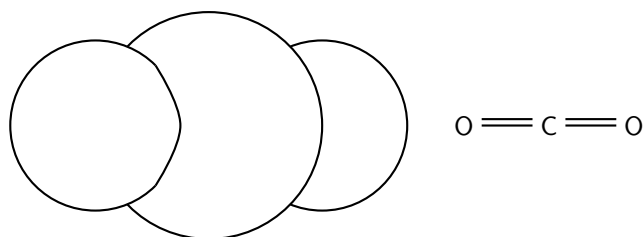
properties of diamonds are due to the strong covalent bonds between the carbon atoms in diamond. The most common uses for diamonds in industry are in cutting, drilling, grinding, and polishing.



### Exercise: Atoms and molecules

- In each of the following, say whether the chemical substance is made up of single atoms, simple molecules or giant molecules.
  - ammonia gas ( $\text{NH}_3$ )
  - zinc metal ( $\text{Zn}$ )
  - graphite ( $\text{C}$ )
  - nitric acid ( $\text{HNO}_3$ )
  - neon gas ( $\text{Ne}$ )
- Refer to the diagram below and then answer the questions that follow:





- (a) Identify the molecule.
  - (b) Write the molecular formula for the molecule.
  - (c) Is the molecule a simple or giant molecule?
3. Represent each of the following molecules using its *chemical formula*, *structural formula* and *ball and stick model*.
- (a)  $\text{H}_2$
  - (b)  $\text{NH}_3$
  - (c) sulfur dioxide
- 

### 3.3 Intramolecular and intermolecular forces

When atoms join to form molecules, they are held together by **chemical bonds**. The type of bond, and the strength of the bond, depends on the atoms that are involved. These bonds are called **intramolecular forces** because they are bonding forces *inside* a molecule ('intra' means 'within' or 'inside'). Sometimes we simply call these intramolecular forces chemical bonds.



**Definition: Intramolecular force**

The force between the atoms of a molecule, which holds them together.

Examples of the types of chemical bonds that can exist between atoms inside a molecule are shown below. These will be looked at in more detail in Grade 11.

- *Covalent bond*

Covalent bonds exist between non-metal atoms e.g. There are covalent bonds between the carbon and oxygen atoms in a molecule of carbon dioxide.

- *Ionic bond*

Ionic bonds occur between non-metal and metal atoms e.g. There are ionic bonds between the sodium and chlorine atoms in a molecule of sodium chloride.

- *Metallic bond*

Metallic bonds join metal atoms e.g. There are metallic bonds between copper atoms in a piece of copper metal.

**Intermolecular forces** are those bonds that hold *molecules* together. A glass of water for example, contains many molecules of water. These molecules are held together by intermolecular forces. The strength of the intermolecular forces is important because they affect properties such as *melting point* and *boiling point*. For example, the stronger the intermolecular forces, the higher the melting point and boiling point for that substance. The strength of the intermolecular forces increases as the size of the molecule increases.

**Definition: Intermolecular force**

A force between molecules, which holds them together.

Diagram 3.6 may help you to understand the difference between intramolecular forces and intermolecular forces.

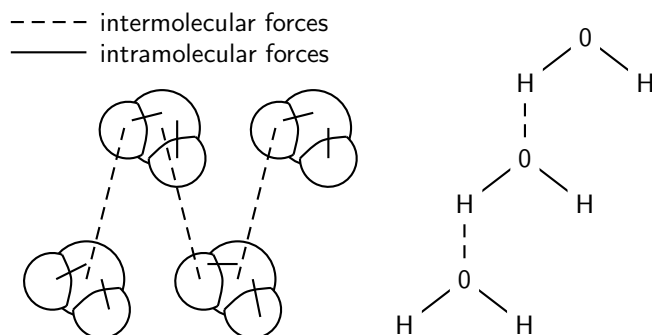


Figure 3.6: Two representations showing the intermolecular and intramolecular forces in water: space-filling model and structural formula.

It should be clearer now that there are two types of forces that hold matter together. In the case of water, there are intramolecular forces that hold the two hydrogen atoms to the oxygen atom *in each molecule of water*. There are also intermolecular forces *between each of these water molecules*. As mentioned earlier, these forces are very important because they affect many of the *properties of matter* such as boiling point, melting point and a number of other properties. Before we go on to look at some of these examples, it is important that we first take a look at the **Kinetic Theory of Matter**.

**Exercise: Intramolecular and intermolecular forces**

- Using ammonia gas as an example...
  - Explain what is meant by an *intramolecular* force or *chemical bond*.
  - Explain what is meant by an *intermolecular* force.
- Draw a diagram showing three molecules of carbon dioxide. On the diagram, show where the intramolecular and intermolecular forces are.
- Why is it important to understand the types of forces that exist between atoms and between molecules? Try to use some practical examples in your answer.

### 3.4 The Kinetic Theory of Matter

The **kinetic theory of matter** is used to explain why matter exists in different *phases* (i.e. solid, liquid and gas), and how matter can change from one phase to the next. The kinetic theory of matter also helps us to understand other properties of matter. It is important to realise that what we will go on to describe is only a *theory*. It cannot be proved beyond doubt, but the fact that it helps us to explain our observations of changes in phase, and other properties of matter, suggests that it probably is more than just a theory.

Broadly, the Kinetic Theory of Matter says that:

- Matter is made up of **particles** that are constantly moving.
- All particles have **energy**, but the energy varies depending on whether the substance is a solid, liquid or gas. Solid particles have the least energy and gas particles have the most amount of energy.
- The **temperature** of a substance is a measure of the *average kinetic energy* of the particles.
- A change in **phase** may occur when the energy of the particles is changed.
- There are **spaces** between the particles of matter.
- There are **attractive forces** between particles and these become stronger as the particles move closer together. These attractive forces will either be intramolecular forces (if the particles are atoms) or intermolecular forces (if the particles are molecules). When the particles are extremely close, repulsive forces start to act.

Table 3.1 summarises the characteristics of the particles that are in each phase of matter.

Table 3.1: Table summarising the general features of solids, liquids and gases.

Property of matter	Gas	Liquid	Solid
Particles	Atoms or molecules	Atoms or molecules	Atoms or molecules
Energy and movement of particles	Particles have high energy and are constantly moving	Particles have less energy than in the gas phase	Low energy - particles vibrate around a fixed point
Spaces between particles	Large spaces because of high energy	Smaller spaces than in gases	Very little space between particles. Particles are tightly packed together
Attractive forces between particles	Weak forces because of the large distance between particles	Stronger forces than in gas. Liquids can be poured.	Very strong forces. Solids have a fixed volume.
Changes in phase	In general a gas becomes a liquid or solid when it is cooled. Particles have less energy and therefore move closer together so that the attractive forces become stronger, and the gas becomes a liquid or a solid	A liquid becomes a gas if its temperature is increased. It becomes a solid if its temperature decreases.	Solids become liquids or gases if their temperature is increased.

Let's look at an example that involves the three phases of water: ice (solid), water (liquid) and water vapour (gas).

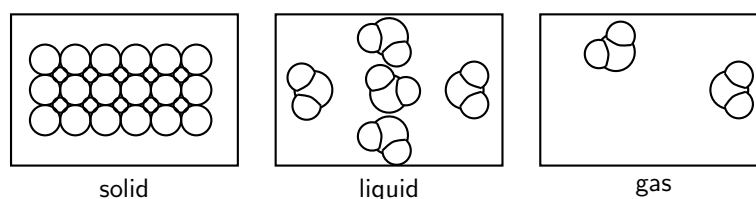


Figure 3.7: The three phases of matter

In a solid (e.g. ice), the water molecules have very little energy and can't move away from each other. The molecules are held closely together in a regular pattern called a *lattice*. If the ice is

heated, the energy of the molecules increases. This means that some of the water molecules are able to overcome the intermolecular forces that are holding them together, and the molecules move further apart to form *liquid water*. This is why liquid water is able to flow, because the molecules are more free to move than they were in the solid lattice. If the molecules are heated further, the liquid water will become water vapour, which is a gas. Gas particles have lots of energy and are far away from each other. That is why it is difficult to keep a gas in a specific area! The attractive forces between the particles are very weak and they are only loosely held together. Figure 3.8 shows the changes in phase that may occur in matter, and the names that describe these processes.

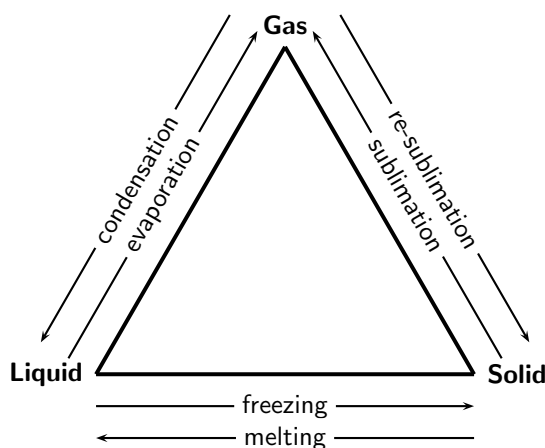


Figure 3.8: Changes in phase

## 3.5 The Properties of Matter

Let us now look at what we have learned about chemical bonds, intermolecular forces and the kinetic theory of matter, and see whether this can help us to understand some of the macroscopic properties of materials.

### 1. Melting point



#### Definition: Melting point

The temperature at which a *solid* changes its phase or state to become a *liquid*. The reverse process (change in phase from liquid to solid) is called **freezing**.

In order for a solid to melt, the energy of the particles must increase enough to overcome the bonds that are holding the particles together. It makes sense then that a solid which is held together by strong bonds will have a *higher* melting point than one where the bonds are weak, because more energy (heat) is needed to break the bonds. In the examples we have looked at, metals, ionic solids and some atomic lattices (e.g. diamond) have high melting points, whereas the melting points for molecular solids and other atomic lattices (e.g. graphite) are much lower. Generally, the intermolecular forces between molecular solids are *weaker* than those between ionic and metallic solids.

### 2. Boiling point



#### Definition: Boiling point

The temperature at which a *liquid* changes its phase to become a *gas*.

When the temperature of a liquid increases, the average kinetic energy of the particles also increases, and they are able to overcome the bonding forces that are holding them in the liquid. When boiling point is reached, *evaporation* takes place and some particles in the liquid become a gas. In other words, the energy of the particles is too great for them to be held in a liquid anymore. The stronger the bonds within a liquid, the higher the boiling point needs to be in order to break these bonds. Metallic and ionic compounds have high boiling points while the boiling point for molecular liquids is lower.

The data in table 3.2 below may help you to understand some of the concepts we have explained. Not all of the substances in the table are solids at room temperature, so for now, let's just focus on the *boiling points* for each of these substances. Of the substances listed, ethanol has the weakest intermolecular forces, and sodium chloride and mercury have the strongest. What do you notice?

Substance	Melting point ( $^{\circ}\text{C}$ )	Boiling point ( $^{\circ}\text{C}$ )
Ethanol ( $\text{C}_2\text{H}_6\text{O}$ )	-114,3	78,4
Water	0	100
Mercury	-38,83	356,73
Sodium chloride	801	1465

Table 3.2: The melting and boiling points for a number of substances

You will have seen that substances such as ethanol, with relatively weak intermolecular forces, have the lowest boiling point, while substances with stronger intermolecular forces such as sodium chloride and mercury, must be heated much more if the particles are to have enough energy to overcome the forces that are holding them together in the liquid.



### Exercise: Forces and boiling point

The table below gives the molecular formula and the boiling point for a number of organic compounds called *alkanes*. Refer to the table and then answer the questions that follow.

Organic compound	Molecular formula	Boiling point ( $^{\circ}\text{C}$ )
Methane	$\text{CH}_4$	-161.6
Ethane	$\text{C}_2\text{H}_6$	-88.6
Propane	$\text{C}_3\text{H}_8$	-45
Butane	$\text{C}_4\text{H}_{10}$	-0.5
Pentane	$\text{C}_5\text{H}_{12}$	36.1
Hexane	$\text{C}_6\text{H}_{14}$	69
Heptane	$\text{C}_7\text{H}_{16}$	98.42
Octane	$\text{C}_8\text{H}_{18}$	125.52

Data from: <http://www.wikipedia.com>

- Draw a graph to show the relationship between the number of carbon atoms in each alkane, and its boiling point (Number of carbon atoms will go on the x-axis and boiling point on the y-axis).
- Describe what you see.
- Suggest a reason for what you have observed.
- Why was it enough for us to use 'number of carbon atoms' as a measure of the molecular weight of the molecules?

### 3. Density and viscosity

**Density** is a measure of the mass of a substance per unit volume. The density of a solid is generally higher than that of a liquid because the particles are held much more closely

together and therefore there are more particles packed together in a particular volume. In other words, there is a greater mass of the substance in a particular volume. In general, density increases as the strength of the intermolecular forces increases. **Viscosity** is a measure of how resistant a liquid is to flowing (in other words, how easy it is to pour the liquid from one container to another). Viscosity is also sometimes described as the 'thickness' of a fluid. Think for example of syrup and how slowly it pours from one container into another. Now compare this to how easy it is to pour water. The viscosity of syrup is greater than the viscosity of water. Once again, the stronger the intermolecular forces in the liquid, the greater its viscosity.

It should be clear now that we can explain a lot of the **macroscopic properties** of matter (i.e. the characteristics we can see or observe) by understanding their **microscopic structure** and the way in which the atoms and molecules that make up matter are held together.

---

**Activity :: Investigation : Determining the density of liquids:**

Density is a very important property because it helps us to identify different materials. Every material, depending on the elements that make it up, and the arrangement of its atoms, will have a different density.

The equation for density is:

$$\text{Density} = \text{Mass/Volume}$$

**Discussion questions:**

To calculate the density of liquids and solids, we need to be able to first determine their mass and volume. As a group, think about the following questions:

- How would you determine the mass of a liquid?
- How would you determine the volume of an irregular solid?

**Apparatus:**

Laboratory mass balance, 10 ml and 100 ml graduated cylinders, thread, distilled water, two different liquids.

**Method:**

Determine the density of the distilled water and two liquids as follows:

1. Measure and record the mass of a 10 ml graduated cylinder.
2. Pour an amount of distilled water into the cylinder.
3. Measure and record the combined mass of the water and cylinder.
4. Record the volume of distilled water in the cylinder
5. Empty, clean and dry the graduated cylinder.
6. Repeat the above steps for the other two liquids you have.
7. Complete the table below.

Liquid	Mass (g)	Volume (ml)	Density (g.ml <sup>-1</sup> )
Distilled water			
Liquid 1			
Liquid 2			

---

**Activity :: Investigation : Determining the density of irregular solids:**

**Apparatus:**

Use the same materials and equipment as before (for the liquids). Also find a number of solids that have an irregular shape.

**Method:**

Determine the density of irregular solids as follows:

1. Measure and record the mass of one of the irregular solids.
2. Tie a piece of thread around the solid.
3. Pour some water into a 100 ml graduated cylinder and record the volume.
4. Gently lower the solid into the water, keeping hold of the thread. Record the combined volume of the solid and the water.
5. Determine the volume of the solid by subtracting the combined volume from the original volume of the water only.
6. Repeat these steps for the second object.
7. Complete the table below.

Solid	Mass (g)	Volume (ml)	Density ( $g.ml^{-1}$ )
Solid 1			
Solid 2			
Solid 3			

### 3.6 Summary

- The smallest unit of matter is the **atom**. Atoms can combine to form **molecules**.
- A **molecule** is a group of two or more atoms that are attracted to each other by chemical bonds.
- A **small molecule** consists of a few atoms per molecule. A **giant molecule** consists of millions of atoms per molecule, for example metals and diamonds.
- The structure of a molecule can be represented in a number of ways.
- The **chemical formula** of a molecule is an abbreviated way of showing a molecule, using the symbols for the elements in the molecule. There are two types of chemical formulae: molecular and empirical formula.
- The **molecular formula** of a molecule gives the exact number of atoms of each element that are in the molecule.
- The **empirical formula** of a molecule gives the relative number of atoms of each element in the molecule.
- Molecules can also be represented using **diagrams**.
- A **ball and stick** diagram is a 3-dimensional molecular model that uses 'balls' to represent atoms and 'sticks' to represent the bonds between them.
- A **space-filling model** is also a 3-dimensional molecular model. The atoms are represented by multi-coloured spheres.
- In a molecule, atoms are held together by **chemical bonds** or **intramolecular forces**. Covalent bonds, ionic bonds and metallic bonds are examples of chemical bonds.
- A **covalent bond** exists between non-metal atoms. An **ionic bond** exists between non-metal and metal atoms, and a **metallic bond** exists between metal atoms.
- **Intermolecular forces** are the bonds that hold *molecules* together.
- The **kinetic theory of matter** attempts to explain the behaviour of matter in different phases.
- The theory says that all matter is composed of **particles** which have a certain amount of **energy** which allows them to **move** at different speeds depending on the temperature (energy). There are **spaces** between the particles, and also **attractive forces** between particles when they come close together.

- Understanding chemical bonds, intermolecular forces and the kinetic theory of matter, can help to explain many of the **macroscopic properties** of matter.
- **Melting point** is the temperature at which a *solid* changes its phase to become a *liquid*. The reverse process (change in phase from liquid to solid) is called **freezing**. The stronger the chemical bonds and intermolecular forces in a substance, the higher the melting point will be.
- **Boiling point** is the temperature at which a liquid changes phase to become a gas. The stronger the chemical bonds and intermolecular forces in a substance, the higher the boiling point will be.
- **Density** is a measure of the mass of a substance per unit volume.
- **Viscosity** is a measure of how resistant a liquid is to flowing.



### Exercise: Summary exercise

1. Give one word or term for each of the following descriptions.
  - (a) The property that determines how easily a liquid flows.
  - (b) The change in phase from liquid to gas.
  - (c) A composition of two or more atoms that act as a unit.
  - (d) Chemical formula that gives the relative number of atoms of each element that are in a molecule.
2. For each of the following questions, choose the one correct answer from the list provided.
  - A Ammonia, an ingredient in household cleaners, can be broken down to form one part nitrogen (N) and three parts hydrogen (H). This means that ammonia...
    - i. is a colourless gas
    - ii. is not a compound
    - iii. cannot be an element
    - iv. has the formula  $N_3H$
  - B If one substance A has a melting point that is *lower* than the melting point of substance B, this suggests that...
    - i. A will be a liquid at room temperature.
    - ii. The chemical bonds in substance A are weaker than those in substance B.
    - iii. The chemical bonds in substance A are stronger than those in substance B.
    - iv. B will be a gas at room temperature.
3. Boiling point is an important concept to understand.
  - a Define 'boiling point'.
  - b What change in phase takes place when a liquid reaches its boiling point?
  - c What is the boiling point of water?
  - d Use the kinetic theory of matter and your knowledge of intermolecular forces, to explain why water changes phase at this temperature.
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 from <http://www.chemicalelements.com>*)

Element	Melting point	Boiling point ( $^{\circ}C$ )
copper	1083	2567
magnesium	650	1107
oxygen	-218.4	-183
carbon	3500	4827
helium	-272	-268.6
sulfur	112.8	444.6



- a What state of matter (i.e. solid, liquid or gas) will each of these elements be in at room temperature?
  - 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.
-



## Chapter 4

# The Atom - Grade 10

We have now looked at many examples of the types of matter and materials that exist around us, and we have investigated some of the ways that materials are classified. But what is it that makes up these materials? And what makes one material different from another? In order to understand this, we need to take a closer look at the building block of matter, the **atom**. Atoms are the basis of all the structures and organisms in the universe. The planets, the sun, grass and trees, the air we breathe, and people are all made up of different combinations of atoms.

### 4.1 Models of the Atom

It is important to realise that a lot of what we know about the structure of atoms has been developed over a long period of time. This is often how scientific knowledge develops, with one person building on the ideas of someone else. We are going to look at how our modern understanding of the atom has evolved over time.

The idea of atoms was invented by two Greek philosophers, Democritus and Leucippus in the fifth century BC. The Greek word *ατομον* (atom) means *indivisible* because they believed that atoms could not be broken into smaller pieces.

Nowadays, we know that atoms are made up of a *positively charged nucleus* in the centre surrounded by *negatively charged electrons*. However, in the past, before the structure of the atom was properly understood, scientists came up with lots of different *models* or *pictures* to describe what atoms look like.



#### Definition: Model

A model is a representation of a system in the real world. Models help us to understand systems and their properties. For example, an *atomic model* represents what the structure of an atom *could* look like, based on what we know about how atoms behave. It is not necessarily a true picture of the exact structure of an atom.

#### 4.1.1 The Plum Pudding Model

After the electron was discovered by J.J. Thomson in 1897, people realised that atoms were made up of even smaller particles than they had previously thought. However, the atomic nucleus had not been discovered yet, and so the 'plum pudding model' was put forward in 1904. In this model, the atom is made up of negative electrons that float in a soup of positive charge, much like plums in a pudding or raisins in a fruit cake (figure 4.1). In 1906, Thomson was awarded the Nobel Prize for his work in this field. However, even with the Plum Pudding Model, there was still no understanding of how these electrons in the atom were arranged.

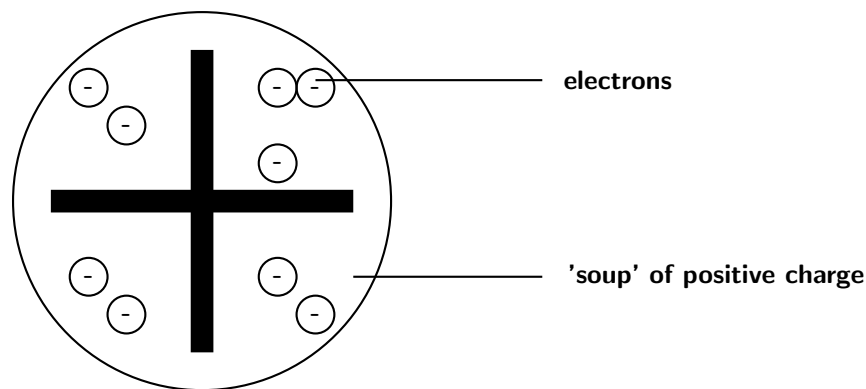


Figure 4.1: A schematic diagram to show what the atom looks like according to the Plum Pudding model

The discovery of **radiation** was the next step along the path to building an accurate picture of atomic structure. In the early twentieth century, Marie Curie and her husband discovered that some elements (the *radioactive* elements) emit particles, which are able to pass through matter in a similar way to X-rays (read more about this in Grade 11). It was Ernest Rutherford who, in 1911, used this discovery to revise the model of the atom.

#### 4.1.2 Rutherford's model of the atom

Radioactive elements emit different types of particles. Some of these are positively charged alpha ( $\alpha$ ) particles. Rutherford carried out a series of experiments where he bombarded sheets of gold foil with these particles, to try to get a better understanding of where the positive charge in the atom was. A simplified diagram of his experiment is shown in figure 4.2.

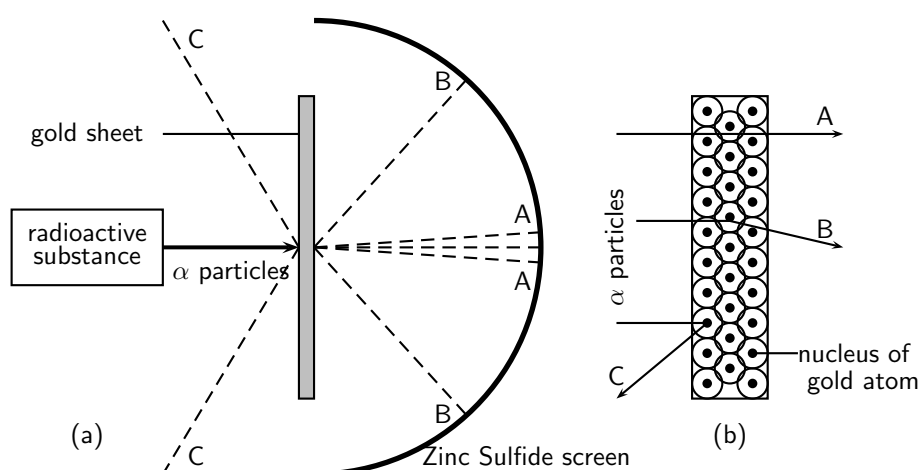


Figure 4.2: Rutherford's gold foil experiment. Figure (a) shows the path of the  $\alpha$  particles after they hit the gold sheet. Figure (b) shows the arrangement of atoms in the gold sheets, and the path of the  $\alpha$  particles in relation to this.

Rutherford set up his experiment so that a beam of alpha particles was directed at the gold sheets. Behind the gold sheets, was a screen made of zinc sulfide. This screen allowed Rutherford to see where the alpha particles were landing. Rutherford knew that the *electrons* in the gold atoms would not really affect the path of the alpha particles, because the mass of an electron is so much smaller than that of a proton. He reasoned that the positively charged *protons* would be the ones to *repel* the positively charged alpha particles and alter their path.

What he discovered was that most of the alpha particles passed through the foil undisturbed, and could be detected on the screen directly behind the foil (A). Some of the particles ended up being slightly deflected onto other parts of the screen (B). But what was even more interesting was that some of the particles were deflected straight back in the direction from where they had come (C)! These were the particles that had been repelled by the positive protons in the gold atoms. If the Plum Pudding model of the atom were true, then Rutherford would have expected much more repulsion since the positive charge, according to that model, is distributed throughout the atom. But this was not the case. The fact that most particles passed straight through suggested that the positive charge was concentrated in one part of the atom only.

Rutherford's work led to a change in ideas around the atom. His new model described the atom as a tiny, dense, positively charged core called a nucleus, surrounded by lighter, negatively charged electrons. Another way of thinking about this model was that the atom was seen to be like a mini solar system where the electrons orbit the nucleus like planets orbiting around the sun. A simplified picture of this is shown in figure 4.3.

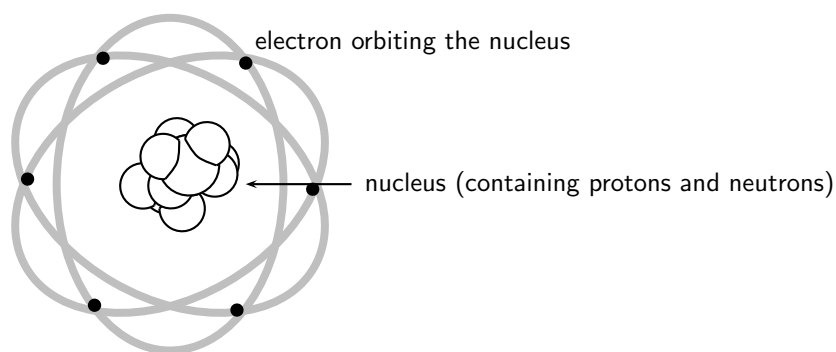
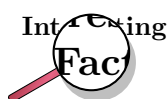


Figure 4.3: Rutherford's model of the atom

### 4.1.3 The Bohr Model

There were, however, some problems with this model: for example it could not explain the very interesting observation that atoms only emit light at certain wavelengths or frequencies. Niels Bohr solved this problem by proposing that the electrons could only orbit the nucleus in certain special orbits at different energy levels around the nucleus. The exact energies of the orbitals in each energy level depends on the type of atom. Helium for example, has different energy levels to Carbon. If an electron jumps down from a higher energy level to a lower energy level, then light is emitted from the atom. The energy of the light emitted is the same as the gap in the energy between the two energy levels. You can read more about this in section 4.6. The distance between the nucleus and the electron in the lowest energy level of a hydrogen atom is known as the **Bohr radius**.



Light has the properties of both a particle *and* a wave! Einstein discovered that light comes in energy packets which are called **photons**. When an electron in an atom changes energy levels, a photon of light is emitted. This photon has the same energy as the difference between the two electron energy levels.

## 4.2 How big is an atom?

It is difficult sometimes to imagine the size of an atom, or its mass, because we cannot see them, and also because we are not used to working with such small measurements.

### 4.2.1 How heavy is an atom?

It is possible to determine the mass of a single atom in kilograms. But to do this, you would need very modern *mass spectrometers*, and the values you would get would be very clumsy and difficult to use. The mass of a carbon atom, for example, is about  $1.99 \times 10^{-26}$  kg, while the mass of an atom of hydrogen is about  $1.67 \times 10^{-27}$  kg. Looking at these very small numbers makes it difficult to compare how much bigger the mass of one atom is when compared to another.

To make the situation simpler, scientists use a different unit of mass when they are describing the mass of an atom. This unit is called the **atomic mass unit** (amu). We can abbreviate (shorten) this unit to just 'u'. If we give carbon an atomic mass of 12 u, then the mass of an atom of hydrogen will be 1 u. You can check this by dividing the mass of a carbon atom in kilograms (see above) by the mass of a hydrogen atom in kilograms (you will need to use a calculator for this!). If you do this calculation, you will see that the mass of a carbon atom is twelve times greater than the mass of a hydrogen atom. When we use atomic mass units instead of kilograms, it becomes easier to see this. Atomic mass units are therefore not giving us the *actual* mass of an atom, but rather its mass *relative* to the mass of other atoms in the Periodic Table. The atomic masses of some elements are shown in table 4.1 below.

Table 4.1: The atomic mass of a number of elements

Element	Atomic mass (u)
Nitrogen (N)	14
Bromine (Br)	80
Magnesium (Mg)	24
Potassium (K)	39
Calcium (Ca)	40
Oxygen (O)	16

The actual value of 1 atomic mass unit is  $1.67 \times 10^{-24}$  g or  $1.67 \times 10^{-27}$  kg. This is a very tiny mass!

### 4.2.2 How big is an atom?

*pm* stands for  
*picometres*.  $1$   
 $\text{pm} = 10^{-12}$   
 $\text{m}$

Atomic diameter also varies depending on the element. On average, the diameter of an atom ranges from 100 pm (Helium) to 670 pm (Caesium). Using different units,  $100 \text{ pm} = 1 \text{ Angstrom}$ , and  $1 \text{ Angstrom} = 10^{-10} \text{ m}$ . That is the same as saying that  $1 \text{ Angstrom} = 0,0000000010 \text{ m}$  or that  $100 \text{ pm} = 0,0000000010 \text{ m}$ ! In other words, the diameter of an atom ranges from  $0.0000000010 \text{ m}$  to  $0.0000000067 \text{ m}$ . This is very small indeed.

## 4.3 Atomic structure

As a result of the models that we discussed in section 4.1, 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. Let us now take a closer look at the microscopic structure of the atom.

So far, we have discussed that atoms are made up of a positively charged **nucleus** surrounded by one or more negatively charged **electrons**. These electrons orbit the nucleus.

### 4.3.1 The Electron

The electron is a very light particle. It has a mass of  $9.11 \times 10^{-31}$  kg. Scientists believe that the electron can be treated as a *point particle* or *elementary particle* meaning that it can't be broken down into anything smaller. The electron also carries one unit of **negative** electric charge which is the same as  $1.6 \times 10^{-19}$  C (Coulombs).

### 4.3.2 The Nucleus

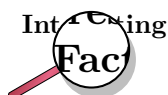
Unlike the electron, the nucleus *can* be broken up into smaller building blocks called **protons** and **neutrons**. Together, the protons and neutrons are called **nucleons**.

#### The Proton

Each proton carries one unit of **positive** electric charge. Since we know that atoms are *electrically neutral*, i.e. 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 to zero. The total positive charge of a nucleus is equal to the number of protons in the nucleus. The proton is much heavier than the electron (10 000 times heavier!) and has a mass of  $1.6726 \times 10^{-27}$  kg. When we talk about the atomic mass of an atom, we are mostly referring to the combined mass of the protons and neutrons, i.e. the nucleons.

#### The Neutron

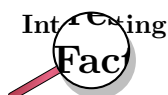
The neutron is electrically neutral i.e. it carries no charge at all. Like the proton, it is much heavier than the electron and its mass is  $1.6749 \times 10^{-27}$  kg (slightly heavier than the proton).



Rutherford predicted (in 1920) that another kind of particle must be present in the nucleus along with the proton. He predicted this because if there were only positively charged protons in the nucleus, then it should break into bits because of the repulsive forces between the like-charged protons! Also, if protons were the only particles in the nucleus, then a helium nucleus (atomic number 2) would have two protons and therefore only twice the mass of hydrogen. However, it is actually *four* times heavier than hydrogen. This suggested that there must be something else inside the nucleus as well as the protons. To make sure that the atom stays electrically neutral, this particle would have to be neutral itself. In 1932 James Chadwick discovered the neutron and measured its mass.

	proton	neutron	electron
<b>Mass (kg)</b>	$1.6726 \times 10^{-27}$	$1.6749 \times 10^{-27}$	$9.11 \times 10^{-31}$
<b>Units of charge</b>	+1	0	-1
<b>Charge (C)</b>	$1.6 \times 10^{-19}$	0	$-1.6 \times 10^{-19}$

Table 4.2: Summary of the particles inside the atom



Unlike the electron which is thought to be a *point particle* and unable to be broken up into smaller pieces, the proton and neutron **can** be divided. Protons and neutrons are built up of smaller particles called *quarks*. The proton and neutron are made up of 3 quarks each.

## 4.4 Atomic number and atomic mass number

The chemical properties of an element are determined by the charge of its nucleus, i.e. by the *number of protons*. This number is called the **atomic number** and is denoted by the letter **Z**.

**Definition: Atomic number (Z)**

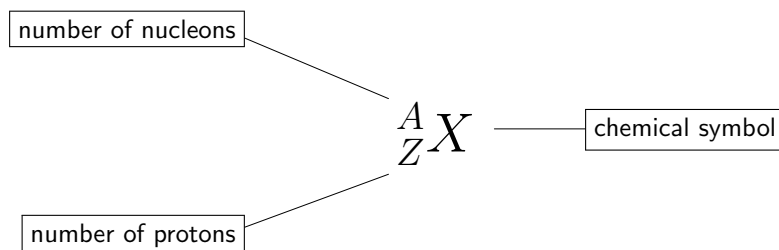
The number of protons in an atom

The mass of an atom depends on how many nucleons its nucleus contains. The number of nucleons, i.e. the total number of protons *plus* neutrons, is called the **atomic mass number** and is denoted by the letter **A**.

**Definition: Atomic mass number (A)**

The number of protons and neutrons in the nucleus of an atom

Standard notation shows the chemical symbol, the atomic mass number and the atomic number of an element as follows:



For example, the iron nucleus which has 26 protons and 30 neutrons, is denoted as:



where the total nuclear charge is  $Z = 26$  and the mass number  $A = 56$ . The number of neutrons is simply the difference  $N = A - Z$ .



**Important:**

Don't confuse the notation we have used above, with the way this information appears on the Periodic Table. On the Periodic Table, the atomic number usually appears in the top lefthand corner of the block or immediately above the element's symbol. The number below the element's symbol is its **relative atomic mass**. This is not exactly the same as the atomic mass number. This will be explained in section 4.5. The example of iron is shown again below.

26
<b>Fe</b>
55.85

You will notice in the example of iron that the atomic mass number is more or less the same as its atomic mass. Generally, an atom that contains  $n$  nucleons (protons and neutrons), will have a mass approximately equal to  $nu$ . For example the mass of a C-12 atom which has 6 protons, 6 neutrons and 6 electrons is  $12u$ , where the protons and neutrons have about the same mass and the electron mass is negligible.

**Exercise: The structure of the atom**

- Explain the meaning of each of the following terms:
  - nucleus
  - electron
  - atomic mass
- Complete the following table: (Note: You will see that the atomic masses on the Periodic Table are not *whole numbers*. This will be explained later. For now, you can round off to the nearest whole number.)

Element	Atomic mass	Atomic number	Number of protons	Number of electrons	Number of neutrons
Mg	24	12			
O			8		
		17			
Ni				28	
	40				20
Zn					
					0
C	12			6	

- Use standard notation to represent the following elements:
  - potassium
  - copper
  - chlorine
- For the element  ${}^{35}_{17}\text{Cl}$ , give the number of ...
  - protons
  - neutrons
  - electrons
 ... in the atom.

5. Which of the following atoms has 7 electrons?

- (a)  ${}^5_2\text{He}$
- (b)  ${}^{13}_6\text{C}$
- (c)  ${}^7_3\text{Li}$
- (d)  ${}^{15}_7\text{N}$

6. In each of the following cases, give the number or the element symbol represented by 'X'.

- (a)  ${}^{40}_{18}\text{X}$
- (b)  ${}_x^{20}\text{Ca}$
- (c)  ${}_x^{31}\text{P}$

7. Complete the following table:

	A	Z	N
${}^{235}_{92}\text{U}$			
${}^{238}_{92}\text{U}$			

In these two different forms of Uranium...

- (a) What is the *same*?
- (b) What is *different*?

Uranium can occur in different forms, called *isotopes*. You will learn more about isotopes in section 4.5.

## 4.5 Isotopes

### 4.5.1 What is an isotope?

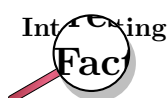
If a few neutrons are added to or removed from a nucleus, the chemical properties of the atom will stay the same because its charge is still the same. Therefore, the chemical properties of an element depend on the number of protons inside the atom. This means that such an atom should remain in the same 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 Table of Elements). Atoms which have the same number of protons, but a different number of neutrons, are called **isotopes**.



#### Definition: Isotope

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.

The different isotopes of an element have the same atomic number  $Z$  but different mass numbers  $A$  because they have a different number of neutrons  $N$ . The chemical properties of the different isotopes of an element are the same, but they might vary in how stable their nucleus is. Note that if an element is written for example as C-12, the '12' is the atomic mass of that atom. So, Cl-35 has an atomic mass of 35 u, while Cl-37 has an atomic mass of 37 u.



In Greek, "same place" reads as *ἰσος τόπος* (isos topos). This is why atoms which have the same number of protons, but different numbers of neutrons, are called *isotopes*. They are in the same place on the Periodic Table!

The following worked examples will help you to understand the concept of an isotope better.



#### Worked Example 5: Isotopes

**Question:** For the element  ${}_{92}^{234}\text{U}$  (uranium), use standard notation to describe:

1. the isotope with 2 fewer neutrons
2. the isotope with 4 more neutrons

#### Answer

##### Step 1 : Go over the definition of isotope

We know that isotopes of any element have the *same* number of protons (same atomic number) in each atom which means that they have the same chemical symbol. However, they have a different number of neutrons, and therefore a different mass number.

##### Step 2 : Rewrite the notation for the isotopes

Therefore, any isotope of uranium will have the symbol:



Also, since the number of protons in uranium isotopes is always the same, we can write down the atomic number:



Now, if the isotope we want has 2 fewer neutrons than  ${}_{92}^{234}\text{U}$ , then we take the original mass number and subtract 2, which gives:



Following the steps above, we can write the isotope with 4 more neutrons as:



#### Worked Example 6: Isotopes

**Question:** Which of the following are isotopes of  ${}_{20}^{40}\text{Ca}$ ?

- ${}_{19}^{40}\text{K}$
- ${}_{20}^{42}\text{Ca}$
- ${}_{18}^{40}\text{Ar}$

#### Answer

##### Step 1 : Go over the definition of isotope:

We know that isotopes have the same atomic number but different mass numbers.

##### Step 2 : Determine which of the elements listed fits the definition of an isotope.

You need to look for the element that has the same atomic number but a different atomic mass number. The only element is  $^{42}_{20}\text{Ca}$ . What is different is that there are 2 more neutrons than in the original element.



### Worked Example 7: Isotopes

**Question:** For the sulfur isotope  $^{33}_{16}\text{S}$ , give the number of...

1. protons
2. nucleons
3. electrons
4. neutrons

#### Answer

**Step 1 : Determine the number of protons by looking at the atomic number, Z.**

$Z = 16$ , therefore the number of protons is 16 (answer to (a)).

**Step 2 : Determine the number of nucleons by looking at the atomic mass number, A.**

$A = 33$ , therefore the number of nucleons is 33 (answer to (b)).

**Step 3 : Determine the number of electrons**

The atom is neutral, and therefore the number of electrons is the same as the number of protons. The number of electrons is 16 (answer to (c)).

**Step 4 : Calculate the number of neutrons**

$$N = A - Z = 33 - 16 = 17$$

The number of neutrons is 17 (answer to (d)).



### Exercise: Isotopes

1. Atom A has 5 protons and 5 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 sulfur isotopes,  $^{32}_{16}\text{S}$  and  $^{34}_{16}\text{S}$ , give the number of...
  - (a) protons
  - (b) nucleons
  - (c) electrons
  - (d) neutrons

3. Which of the following are isotopes of  $^{35}\text{Cl}$ ?
- (a)  $^{17}_{35}\text{Cl}$
  - (b)  $^{35}_{17}\text{Cl}$
  - (c)  $^{37}_{17}\text{Cl}$
4. Which of the following are isotopes of U-235? (X represents an element symbol)
- (a)  $^{238}_{92}\text{X}$
  - (b)  $^{238}_{90}\text{X}$
  - (c)  $^{235}_{92}\text{X}$
- 

### 4.5.2 Relative atomic mass

It is important to realise that the atomic mass of isotopes of the same element will be different because they have a different number of nucleons. Chlorine, for example, has two common isotopes which are chlorine-35 and chlorine-37. Chlorine-35 has an atomic mass of 35 u, while chlorine-37 has an atomic mass of 37 u. In the world around us, both of these isotopes occur naturally. It doesn't make sense to say that the element chlorine has an atomic mass of 35 u, or that it has an atomic mass of 37 u. Neither of these are absolutely true since the mass varies depending on the form in which the element occurs. We need to look at how much more common one is than the other in order to calculate the **relative atomic mass** for the element chlorine. This is then the number that will appear on the Periodic Table.



**Definition: Relative atomic mass**

Relative atomic mass is the average mass of one atom of all the naturally occurring isotopes of a particular chemical element, expressed in atomic mass units.



**Worked Example 8: The relative atomic mass of an isotopic element**

**Question:** The element chlorine has two isotopes, chlorine-35 and chlorine-37. The abundance of these isotopes when they occur naturally is 75% chlorine-35 and 25% chlorine-37. Calculate the *average* relative atomic mass for chlorine.

**Answer**

**Step 1 :** Calculate the mass contribution of chlorine-35 to the average relative atomic mass

$$\text{Contribution of Cl-35} = (75/100 \times 35) = 26,25 \text{ u}$$

**Step 2 :** Calculate the contribution of chlorine-37 to the average relative atomic mass

$$\text{Contribution of Cl-37} = (25/100 \times 37) = 9,25 \text{ u}$$

**Step 3 :** Add the two values to arrive at the average relative atomic mass of chlorine

$$\text{Relative atomic mass of chlorine} = 26,25 \text{ u} + 9,25 \text{ u} = 35,5 \text{ u}$$

If you look on the periodic table, the average relative atomic mass for chlorine is 35,5 u. You will notice that for many elements, the relative atomic mass that is shown is not a whole number. You should now understand that this number is the *average* relative atomic mass for those elements that have naturally occurring isotopes.



### Exercise: Isotopes

You are given a sample that contains carbon-12 and carbon-14.

1. Complete the table below:

Isotope	Z	A	Protons	Neutrons	Electrons
Carbon-12					
Carbon-14					
Chlorine-35					
Chlorine-37					

- (a) If the sample you have contains 90% carbon-12 and 10% carbon-14, calculate the relative atomic mass of an atom in that sample.
- (b) In another sample, you have 22.5% Cl-37 and 77.5% Cl-35. Calculate the relative atomic mass of an atom in that sample.

### Activity :: Group Discussion : The changing nature of scientific knowledge

Scientific knowledge is not static: it changes and evolves over time as scientists build on the ideas of others to come up with revised (and often improved) theories and ideas. In this chapter for example, we saw how peoples' understanding of atomic structure changed as more information was gathered about the atom. There are many more examples like this one in the field of science. For example, think about our knowledge of the solar system and the origin of the universe, or about the particle and wave nature of light.

Often, these changes in scientific thinking can be very controversial because they disturb what people have come to know and accept. It is important that we realise that what we know *now* about science may also change. An important part of being a scientist is to be a *critical thinker*. This means that you need to question information that you are given and decide whether it is accurate and whether it can be accepted as true. At the same time, you need to learn to be open to new ideas and not to become stuck in what you believe is right... there might just be something new waiting around the corner that you have not thought about!

In groups of 4-5, discuss the following questions:

- Think about some other examples where scientific knowledge has changed because of new ideas and discoveries:
  - What were these new ideas?
  - Were they controversial? If so, why?
  - What role (if any) did *technology* play in developing these new ideas?
  - How have these ideas affected the way we understand the world?

- Many people come up with their own ideas about how the world works. The same is true in science. So how do we, and other scientists, know what to believe and what not to? How do we know when new ideas are 'good' science or 'bad' science? In your groups, discuss some of the things that would need to be done to check whether a new idea or theory was worth listening to, or whether it was not.
  - Present your ideas to the rest of the class.
- 

## 4.6 Energy quantisation and electron configuration

### 4.6.1 The energy of electrons

You will remember from our earlier discussions, that an atom is made up of a central nucleus, which contains protons and neutrons, and that this nucleus is surrounded by electrons. Although these electrons all have the same charge and the same mass, each electron in an atom has a different amount of *energy*. Electrons that have the *lowest* energy are found closest to the nucleus where the attractive force of the positively charged nucleus is the greatest. Those electrons that have *higher* energy, and which are able to overcome the attractive force of the nucleus, are found further away.

### 4.6.2 Energy quantisation and line emission spectra

If the energy of an atom is increased (for example when a substance is heated), the energy of the electrons inside the atom can be increased (when an electron has a higher energy than normal it is said to be "excited"). For the excited electron to go back to its original energy (called the ground state), it needs to release energy. It releases energy by emitting light. If one heats up different elements, one will see that for each element, light is emitted only at certain frequencies (or wavelengths). Instead of a smooth continuum of frequencies, we see lines (called emission lines) at particular frequencies. These frequencies correspond to the energy of the emitted light. If electrons could be excited to any energy and lose any amount of energy, there would be a continuous spread of light frequencies emitted. However, the sharp lines we see mean that there are only certain particular energies that an electron can be excited to, or can lose, for each element.

You can think of this like going up a flight of steps: you can't lift your foot by *any* amount to go from the ground to the first step. If you lift your foot too low you'll bump into the step and be stuck on the ground level. You have to lift your foot just the right amount (the height of the step) to go to the next step, and so on. The same goes for electrons and the amount of energy they can have. This is called **quantisation of energy** because there are only certain quantities of energy that an electron can have in an atom. Like steps, we can think of these quantities as **energy levels** in the atom. The energy of the light released when an electron drops down from a higher energy level to a lower energy level is the same as the difference in energy between the two levels.

### 4.6.3 Electron configuration

Electrons are arranged in energy levels around the nucleus of an atom. Electrons that are in the energy level that is closest to the nucleus, will have the lowest energy and those further away will have a higher energy. Each energy level can only hold a certain number of electrons, and an electron will only be found in the second energy level once the first energy level is full. The same rule applies for the higher energy levels. You will need to learn the following rules:

- The 1st energy level can hold a maximum of 2 electrons

- The 2nd energy level can hold a maximum of 8 electrons
- The 3rd energy level can hold a maximum of 8 electrons
- If the number of electrons in the atom is greater than 18, they will need to move to the 4th energy level.

In the following examples, the energy levels are shown as concentric circles around the central nucleus.

### 1. Lithium

Lithium (Li) has an atomic number of 3, meaning that in a neutral atom, the number of electrons will also be 3. The first two electrons are found in the first energy level, while the third electron is found in the second energy level (figure 4.11).

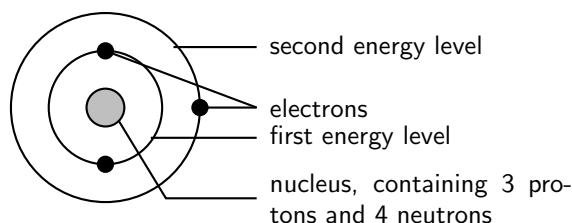


Figure 4.4: The arrangement of electrons in a lithium atom.

### 2. Fluorine

Fluorine (F) has an atomic number of 9, meaning that a neutral atom also has 9 electrons. The first 2 electrons are found in the first energy level, while the other 7 are found in the second energy level (figure 4.12).

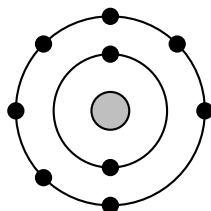


Figure 4.5: The arrangement of electrons in a fluorine atom.

### 3. Argon

Argon has an atomic number of 18, meaning that a neutral atom also has 18 electrons. The first 2 electrons are found in the first energy level, the next 8 are found in the second energy level, and the last 8 are found in the third energy level (figure 4.6).

But the situation is slightly more complicated than this. Within each energy level, the electrons move in **orbitals**. An orbital defines the spaces or regions where electrons move.



#### Definition: Atomic orbital

An atomic orbital is the region in which an electron may be found around a single atom.

There are different orbital shapes, but we will be dealing with only two. These are the 's' and 'p' orbitals (there are also 'd' and 'f' orbitals). The first energy level contains only one 's' orbital, the second energy level contains one 's' orbital and three 'p' orbitals and the third energy level



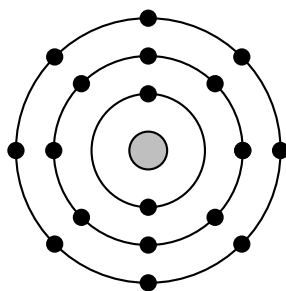


Figure 4.6: The arrangement of electrons in an argon atom.

also contains one 's' orbital and three 'p' orbitals. Within each energy level, the 's' orbital is at a lower energy than the 'p' orbitals. This arrangement is shown in figure 4.7.

When we want to show how electrons are arranged in an atom, we need to remember the following principles:

- Each orbital can only hold **two electrons**. Electrons that occur together in an orbital are called an **electron pair**. These electrons spin in opposite directions around their own axes.
- An electron will always try to enter an orbital with the lowest possible energy.
- An electron will occupy an orbital on its own, rather than share an orbital with another electron. An electron would also rather occupy a lower energy orbital *with* another electron, before occupying a higher energy orbital. In other words, within one energy level, electrons will fill an 's' orbital before starting to fill 'p' orbitals.

The way that electrons are arranged in an atom is called its **electron configuration**.



**Definition: Electron configuration**

Electron configuration is the arrangement of electrons in an atom, molecule, or other physical structure.

An element's electron configuration can be represented using **Aufbau diagrams** or energy level diagrams. An Aufbau diagram uses arrows to represent electrons. You can use the following steps to help you to draw an Aufbau diagram:

1. Determine the number of electrons that the atom has.
2. Fill the 's' orbital in the first energy level (the 1s orbital) with the first two electrons.
3. Fill the 's' orbital in the second energy level (the 2s orbital) with the second two electrons.
4. Put one electron in each of the three 'p' orbitals in the second energy level (the 2p orbitals), and then if there are still electrons remaining, go back and place a second electron in each of the 2p orbitals to complete the electron pairs.
5. Carry on in this way through each of the successive energy levels until all the electrons have been drawn.



**Important:**

When there are two electrons in an orbital, the electrons are called an **electron pair**. If the orbital only has one electron, this electron is said to be an **unpaired electron**. Electron pairs are shown with arrows in opposite directions. This is because when two electrons occupy the same orbital, they spin in opposite directions on their axes.

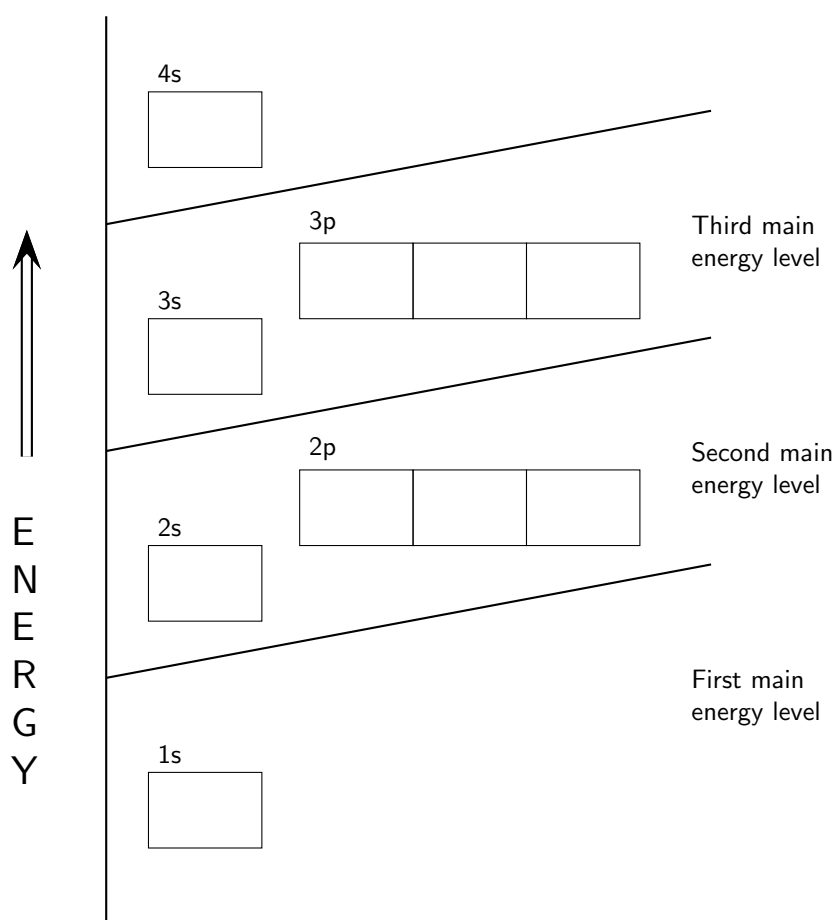


Figure 4.7: The positions of the first ten orbits of an atom on an energy diagram. Note that each block is able to hold two electrons.

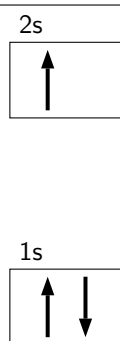


Figure 4.8: The electron configuration of Lithium, shown on an Aufbau diagram

An Aufbau diagram for the element Lithium is shown in figure 4.8.

A special type of notation is used to show an atom's electron configuration. The notation describes the energy levels, orbitals and the number of electrons in each. For example, the electron configuration of lithium is  $1s^2 2s^1$ . The number and letter describe the energy level and orbital, and the number above the orbital shows how many electrons are in that orbital.

Aufbau diagrams for the elements fluorine and argon are shown in figures 4.9 and 4.10 respectively. Using standard notation, the electron configuration of fluorine is  $1s^2 2s^2 2p^5$  and the electron configuration of argon is  $1s^2 2s^2 2p^6 3s^2 3p^6$ .

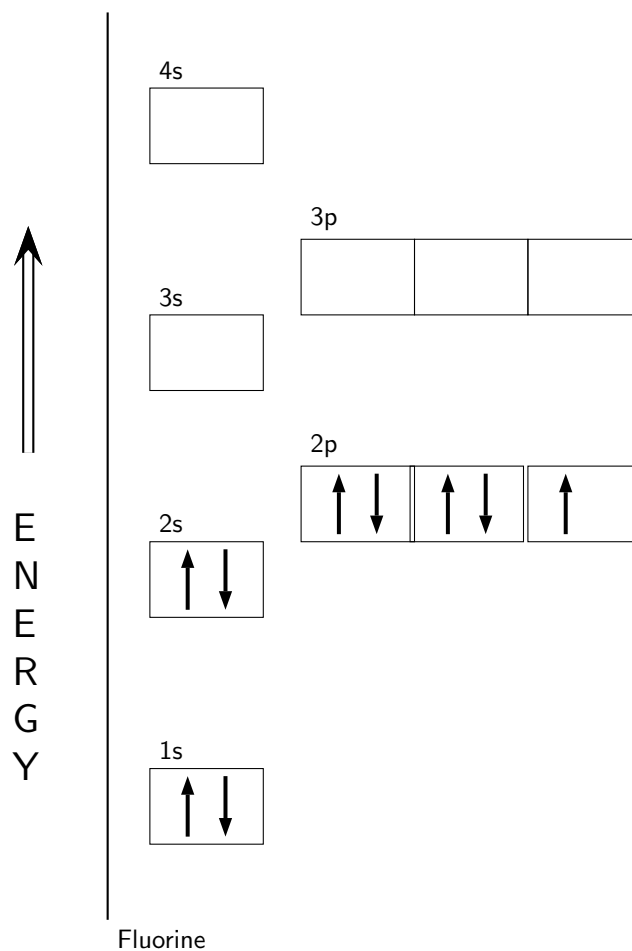


Figure 4.9: An Aufbau diagram showing the electron configuration of fluorine

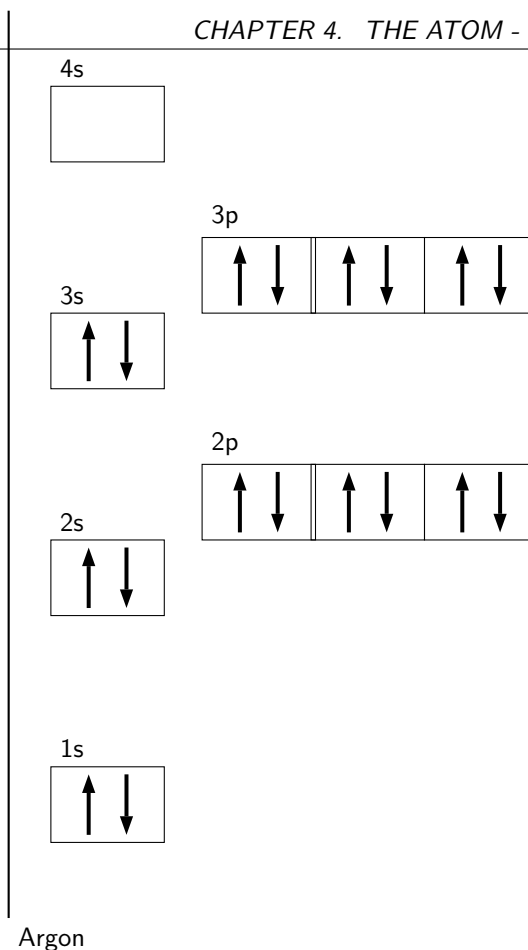


Figure 4.10: An Aufbau diagram showing the electron configuration of argon

#### 4.6.4 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.



**Definition: Valence electrons**

The electrons in the outer energy level of an atom



**Definition: Core electrons**

All the electrons in an atom, excluding the valence electrons

#### 4.6.5 The importance of understanding electron configuration

By this stage, you may well be wondering why it is important for you to understand how electrons are arranged around the nucleus of an atom. Remember that 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.

To take this a step further, an atom is at its most stable (and therefore *unreactive*) when all its orbitals are full. On the other hand, an atom is least stable (and therefore most *reactive*) when its valence electron orbitals are not full. This will make more sense when we go on to

look at chemical bonding in a later chapter. To put it simply, 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.



### Exercise: Energy diagrams and electrons

- Draw Aufbau diagrams to show the electron configuration of each of the following elements:
  - magnesium
  - potassium
  - sulfur
  - neon
  - nitrogen
- Use the Aufbau diagrams you drew to help you complete the following table:

Element	No. of energy levels	No. of core electrons	No. of valence electrons	Electron configuration (standard notation)
Mg				
K				
S				
Ne				
N				

- Rank the elements used above in order of *increasing reactivity*. Give reasons for the order you give.

### Activity :: Group work : Building a model of an atom

Earlier in this chapter, we talked about different 'models' of the atom. In science, one of the uses of models is that they can help us to understand the structure of something that we can't see. In the case of the atom, models help us to build a picture in our heads of what the atom looks like.

Models are often simplified. The small toy cars that you may have played with as a child are models. They give you a good idea of what a real car looks like, but they are much smaller and much simpler. A model cannot always be absolutely accurate and it is important that we realise this so that we don't build up a false idea about something.

In groups of 4-5, you are going to build a model of an atom. Before you start, think about these questions:

- What information do I know about the structure of the atom? (e.g. what parts make it up? how big is it?)
- What materials can I use to represent these parts of the atom as accurately as I can?
- How will I put all these different parts together in my model?

As a group, share your ideas and then plan how you will build your model. Once you have built your model, discuss the following questions:

- Does our model give a good idea of what the atom actually looks like?

- In what ways is our model *inaccurate*? For example, we know that electrons *move* around the atom's nucleus, but in your model, it might not have been possible for you to show this.
- Are there any ways in which our model could be improved?

Now look at what other groups have done. Discuss the same questions for each of the models you see and record your answers.

## 4.7 Ionisation Energy and the Periodic Table

### 4.7.1 Ions

In the previous section, we focused our attention on the electron configuration of *neutral* atoms. In a neutral atom, the number of protons is the same as the number of electrons. But what happens if an atom *gains* or *loses* electrons? Does it mean that the atom will still be part of the same element?

A change in the number of electrons of an atom does not change the type of atom that it is. However, the *charge* of the atom will change. 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 cases is called an **ion**. Put simply, an ion is a charged atom.



#### Definition: Ion

An ion is a charged atom. A positively charged ion is called a **cation** e.g.  $\text{Na}^+$ , and a negatively charged ion is called an **anion** e.g.  $\text{F}^-$ . The charge on an ion depends on the number of electrons that have been lost or gained.

Look at the following examples. Notice the number of valence electrons in the neutral atom, the number of electrons that are lost or gained, and the final charge of the ion that is formed.

#### Lithium

A lithium atom loses one electron to form a positive ion (figure 4.11).

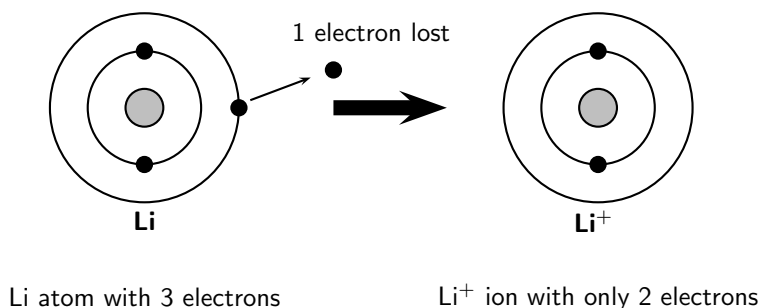


Figure 4.11: The arrangement of electrons in a lithium ion.

In this example, the lithium atom loses an electron to form the cation  $\text{Li}^+$ .

#### Fluorine

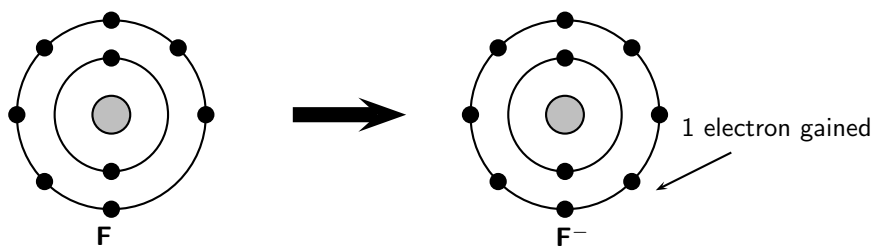


Figure 4.12: The arrangement of electrons in a fluorine ion.

A fluorine atom gains one electron to form a negative ion (figure 4.12).

---

#### Activity :: Investigation : The formation of ions

1. Use the diagram for lithium as a guide and draw similar diagrams to show how each of the following ions is formed:
    - (a)  $\text{Mg}^{2+}$
    - (b)  $\text{Na}^+$
    - (c)  $\text{Cl}^-$
    - (d)  $\text{O}^{2-}$
  2. Do you notice anything interesting about the charge on each of these ions?  
Hint: Look at the number of valence electrons in the neutral atom and the charge on the final ion.
- 

#### Observations:

Once you have completed the activity, you should notice that:

- In each case the number of electrons that is either gained or lost, is the same as the number of electrons that are needed for the atoms to achieve a full or an empty valence energy level.
- If you look at an energy level diagram for sodium (Na), you will see that in a neutral atom, there is only one valence electron. In order to achieve an empty valence level, and therefore a more stable state for the atom, this electron will be *lost*.
- In the case of oxygen (O), there are six valence electrons. To fill the valence energy level, it makes more sense for this atom to *gain* two electrons. A negative ion is formed.

#### 4.7.2 Ionisation Energy

Ionisation energy is the energy that is needed to remove one electron from an atom. The ionisation energy will be different for different atoms.

The second ionisation energy is the energy that is needed to remove a second electron from an atom, and so on. As an energy level becomes more full, it becomes more and more difficult to remove an electron and the ionisation energy *increases*. On the Periodic Table of the Elements, a *group* is a vertical column of the elements, and a *period* is a horizontal row. In the periodic table, ionisation energy *increases* across a period, but *decreases* as you move down a group. The lower the ionisation energy, the more reactive the element will be because there is a greater chance of electrons being involved in chemical reactions. We will look at this in more detail in the next section.



### Exercise: The formation of ions

Match the information in column A with the information in column B by writing only the letter (A to I) next to the question number (1 to 7)

1. A positive ion that has 3 less electrons than its neutral atom	A. $\text{Mg}^{2+}$
2. An ion that has 1 more electron than its neutral atom	B. $\text{Cl}^-$
3. The anion that is formed when bromine gains an electron	C. $\text{CO}_3^{2-}$
4. The cation that is formed from a magnesium atom	D. $\text{Al}^{3+}$
5. An example of a compound ion	E. $\text{Br}^{2-}$
6. A positive ion with the electron configuration of argon	F. $\text{K}^+$
7. A negative ion with the electron configuration of neon	G. $\text{Mg}^+$
	H. $\text{O}^{2-}$
	I. $\text{Br}^-$

## 4.8 The Arrangement of Atoms in the Periodic Table

The **periodic table of the elements** is a tabular method of showing the chemical elements. Most of the work that was done to arrive at the periodic table that we know, can be attributed to a man called **Dmitri Mendeleev** in 1869. Mendeleev was a Russian chemist who designed the table in such a way that recurring ("periodic") trends in the properties of the elements could be shown. Using the trends he observed, he even left gaps for those elements that he thought were 'missing'. He even 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 began 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**. One important feature to note in the periodic table is that all the non-metals are to the right of the zig-zag line drawn under the element boron. The rest of the elements are metals, with the exception of hydrogen which occurs in the first block of the table despite being a non-metal.

### 4.8.1 Groups in the periodic table

A *group* is a vertical column in the periodic table, and is considered to be the most important way of classifying the elements. If you look at a periodic table, you will see the groups numbered at the top of each column. The groups are numbered from left to right as follows: 1, 2, then an open space which contains the **transition elements**, followed by groups 3 to 8. These numbers are normally represented using Roman numerals. In some periodic tables, all the groups are numbered from left to right from number 1 to number 18. In some groups, the elements display very similar chemical properties, and the groups are even given separate names to identify them.

The characteristics of each group are mostly determined by the electron configuration of the atoms of the element.

- *Group 1:* These elements are known as the **alkali metals** and they are very reactive.



group number																		8			
Group		H	2													3	4	5	6	7	He
		Li	Be													B	C	N	O	F	Ne
		Na	Mg													Al	Si	P	S	Cl	Ar
		K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr		
		Period																			

Figure 4.13: A simplified diagram showing part of the Periodic Table

**Activity :: Investigation : The properties of elements**

Refer to figure 4.14.

1. Use a Periodic Table to help you to complete the last two diagrams for sodium (Na) and potassium (K).
2. What do you notice about the number of electrons in the valence energy level in each case?
3. Explain why elements from group 1 are more reactive than elements from group 2 on the periodic table (Hint: Think back to 'ionisation energy').

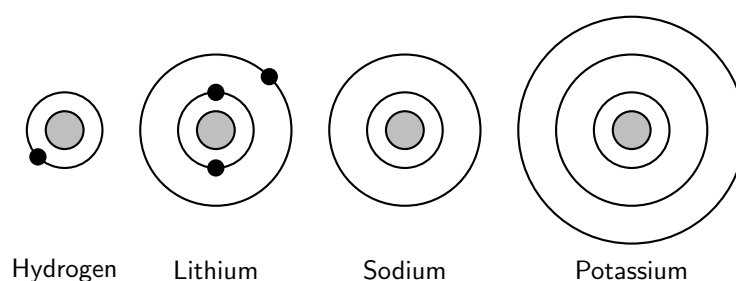


Figure 4.14: Electron diagrams for some of the Group 1 elements, with sodium and potassium incomplete; to be completed as an exercise.

- **Group 2:** These elements are known as the **alkali earth metals**. Each element only has two valence electrons and so in chemical reactions, the group 2 elements tend to *lose* these electrons so that the energy shells are complete. These elements are less reactive than those in group 1 because it is more difficult to lose two electrons than it is to lose one.
- **Group 3** elements have three valence electrons.



**Important:** The number of valence electrons of an element corresponds to its group number on the periodic table.

- **Group 7:** These elements are known as the **halogens**. Each element is missing just one electron from its outer energy shell. These elements tend to *gain* electrons to fill this shell, rather than losing them.

- *Group 8:* These elements are the **noble gases**. All of the energy shells of the halogens are full, and so these elements are very unreactive.

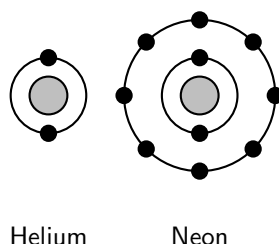


Figure 4.15: Electron diagrams for two of the noble gases, helium (He) and neon (Ne).

- *Transition metals:* The differences between groups in the transition metals are not usually dramatic.

It is worth noting that in each of the groups described above, the **atomic diameter** of the elements increases as you move down the group. This is because, while the number of valence electrons is the same in each element, the number of core electrons increases as one moves down the group.

### 4.8.2 Periods in the periodic table

A **period** is a horizontal row in the periodic table of the elements. Some of the trends that can be observed within a period are highlighted below:

- As you move from one group to the next within a period, the number of valence electrons increases by one each time.
- Within a single period, all the valence electrons occur in the same energy shell. If the period increases, so does the energy shell in which the valence electrons occur.
- In general, the diameter of atoms decreases as one moves from left to right across a period. Consider the attractive force between the positively charged nucleus and the negatively charged electrons in an atom. As you move across a period, the number of protons in each atom increases. The number of electrons also increases, but these electrons will still be in the same energy shell. As the number of protons increases, the force of attraction between the nucleus and the electrons will increase and the atomic diameter will decrease.
- Ionisation energy increases as one moves from left to right across a period. As the valence electron shell moves closer to being full, it becomes more difficult to remove electrons. The opposite is true when you move down a *group* in the table because more energy shells are being added. The electrons that are closer to the nucleus 'shield' the outer electrons from the attractive force of the positive nucleus. Because these electrons are not being held to the nucleus as strongly, it is easier for them to be removed and the ionisation energy decreases.
- In general, the reactivity of the elements decreases from left to right across a period.



#### Exercise: Trends in ionisation energy

Refer to the data table below which gives the ionisation energy (in  $\text{kJ}\cdot\text{mol}^{-1}$ ) and atomic number ( $Z$ ) for a number of elements in the periodic table:

Z	Ionisation energy	Z	Ionisation energy
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

1. Draw a line graph to show the relationship between atomic number (on the x-axis) and ionisation energy (y-axis).
2. Describe any trends that you observe.
3. Explain why...
  - (a) the ionisation energy for  $Z=2$  is higher than for  $Z=1$
  - (b) the ionisation energy for  $Z=3$  is lower than for  $Z=2$
  - (c) the ionisation energy increases between  $Z=5$  and  $Z=7$

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### Exercise: Elements in the Periodic Table

Refer to the elements listed below:

Lithium (Li); Chlorine (Cl); Magnesium (Mg); Neon (Ne); Oxygen (O); Calcium (Ca); Carbon (C)

Which of the elements listed above:

1. belongs to Group 1
2. is a halogen
3. is a noble gas
4. is an alkali metal
5. has an atomic number of 12
6. has 4 neutrons in the nucleus of its atoms
7. contains electrons in the 4th energy level
8. has only one valence electron
9. has all its energy orbitals full
10. will have chemical properties that are most similar
11. will form positive ions

---

## 4.9 Summary

- Much of what we know today about the atom, has been the result of the work of a number of scientists who have added to each other's work to give us a good understanding of atomic structure.

- Some of the important scientific contributors include **J.J.Thomson** (discovery of the electron, which led to the Plum Pudding Model of the atom), **Ernest Rutherford** (discovery that positive charge is concentrated in the centre of the atom) and **Niels Bohr** (the arrangement of electrons around the nucleus in energy levels).
- Because of the very small mass of atoms, their mass is measured in **atomic mass units** (u).  $1 \text{ u} = 1,67 \times 10^{-24} \text{ g}$ .
- An atom is made up of a central **nucleus** (containing **protons** and **neutrons**), surrounded by **electrons**.
- 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  ${}_Z^AX$ , where X 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.
- The **relative atomic mass** of an element is the average mass of one atom of all the naturally occurring isotopes of a particular chemical element, expressed in atomic mass units. The relative atomic mass is written under the elements' symbol on the Periodic Table.
- The energy of electrons in an atom is **quantised**. Electrons occur in specific energy levels around an atom's nucleus.
- Within each energy level, an electron may move within a particular shape of **orbital**. An orbital defines the space in which an electron is most likely to be found. There are different orbital shapes, including s, p, d and f orbitals.
- Energy diagrams such as **Aufbau diagrams** are used to show the electron configuration of atoms.
- The electrons in the outermost energy level are called **valence electrons**.
- The electrons that are not valence electrons are called **core electrons**.
- Atoms whose outermost energy level is full, are less chemically reactive and therefore more stable, than those atoms whose outer energy level is not full.
- An **ion** is a charged atom. A **cation** is a positively charged ion and an **anion** is a negatively charged ion.
- When forming an ion, an atom will lose or gain the number of electrons that will make its valence energy level full.
- An element's **ionisation energy** is the energy that is needed to remove one electron from an atom.
- Ionisation energy increases across a **period** in the Periodic Table.
- Ionisation energy decreases down a **group** in the Periodic Table.



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### Exercise: Summary

1. 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
2. For each of the following, say whether the statement is True or False. If it is False, re-write the statement correctly.
- $^{20}_{10}\text{Ne}$  and  $^{22}_{10}\text{Ne}$  each have 10 protons, 12 electrons and 12 neutrons.
  - The atomic mass of any atom of a particular element is always the same.
  - It is safer to use helium gas rather than hydrogen gas in balloons.
  - Group 1 elements readily form negative ions.
3. Multiple choice questions: In each of the following, choose the **one** correct answer.
- The three basic components of an atom are:
    - protons, neutrons, and ions
    - protons, neutrons, and electrons
    - protons, neutrinos, and ions
    - protium, deuterium, and tritium
  - The charge of an atom is...
    - positive
    - neutral
    - negative
  - If Rutherford had used neutrons instead of alpha particles in his scattering experiment, the neutrons would...
    - not deflect because they have no charge
    - have deflected more often
    - have been attracted to the nucleus easily
    - have given the same results
  - Consider the isotope  $^{234}_{92}\text{U}$ . Which of the following statements is *true*?
    - The element is an isotope of  $^{234}_{94}\text{Pu}$
    - The element contains 234 neutrons
    - The element has the same electron configuration as  $^{238}_{92}\text{U}$
    - The element has an atomic mass number of 92
  - The electron configuration of an atom of chlorine can be represented using the following notation:
    - $1s^2 2s^8 3s^7$
    - $1s^2 2s^2 2p^6 3s^2 3p^5$
    - $1s^2 2s^2 2p^6 3s^2 3p^6$
    - $1s^2 2s^2 2p^5$
4. The following table shows the first ionisation energies for the elements of period 1 and 2.

Period	Element	First ionisation energy ( $\text{kJ.mol}^{-1}$ )
1	H	1312
	He	2372
2	Li	520
	Be	899
	B	801
	C	1086
	N	1402
	O	1314
	F	1681
	Ne	2081

- What is the meaning of the term *first ionisation energy*?
- Identify the pattern of first ionisation energies in a period.
- Which TWO elements exert the strongest attractive forces on their electrons? Use the data in the table to give a reason for your answer.

- (d) Draw Aufbau diagrams for the TWO elements you listed in the previous question and explain why these elements are so stable.
  - (e) It is safer to use helium gas than hydrogen gas in balloons. Which property of helium makes it a safer option?
  - (f) 'Group 1 elements readily form positive ions'.  
Is this statement correct? Explain your answer by referring to the table.
-

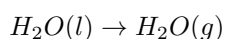
## Chapter 5

# Physical and Chemical Change - Grade 10

Matter is all around us. The desks we sit at, the air we breathe and the water we drink, are all examples of matter. But matter doesn't always stay the same. It can change in many different ways. In this chapter, we are going to take a closer look at **physical** and **chemical** changes that occur in matter.

### 5.1 Physical changes in matter

A **physical change** is one where the particles of the substances that are involved in the change are not broken up in any way. When water is heated for example, the temperature and energy of the water molecules increases and the liquid water evaporates to form water vapour. When this happens, some kind of change has taken place, but the molecular structure of the water has not changed. This is an example of a *physical change*.



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.

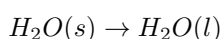
**Definition: Physical change**

A change that can be seen or felt, but that doesn't involve the break up of the particles in the reaction. During a physical change, the *form* of matter may change, but not its *identity*. A change in temperature is an example of a physical change.

There are some important things to remember about physical changes in matter:

- *Arrangement of particles*

When a physical change occurs, the particles (e.g. atoms, molecules) may re-arrange themselves without actually breaking up in any way. In the example of evaporation that we used earlier, the water molecules move further apart as their temperature (and therefore energy) increases. The same would be true if ice were to melt. In the solid phase, water molecules are packed close together in a very ordered way, but when the ice is heated, the molecules overcome the forces holding them together and they move apart. Once again, the particles have re-arranged themselves, but have not broken up.



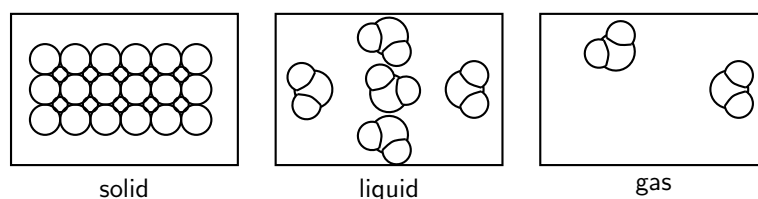


Figure 5.1: The arrangement of water molecules in the three phases of matter

Figure 5.1 shows this more clearly. In each phase of water, the water molecule itself stays the same, but the way the molecules are arranged has changed.

In a physical change, the total mass, the number of atoms and the number of molecules will always stay the same.

- *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.

- *Reversibility*

Physical changes in matter are usually easier to reverse than chemical changes. Water vapour for example, can be changed back to liquid water if the temperature is lowered. Liquid water can be changed into ice by simply decreasing the temperature.

## 5.2 Chemical Changes in Matter

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.

The breakdown of copper(II) chloride to form copper and chlorine is an example of chemical change. A simplified diagram of this reaction is shown in figure 5.2. In this reaction, the initial substance is copper(II) chloride but, once the reaction is complete, the products are copper and chlorine.

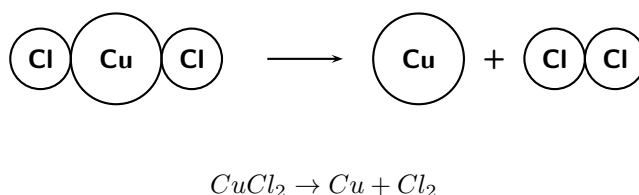


Figure 5.2: The decomposition of copper(II) chloride to form copper and chlorine



**Definition: Chemical change**

The formation of new substances in a chemical reaction. One type of matter is changed into something different.

There are some important things to remember about chemical changes:

- *Arrangement of particles*



During a chemical change, the particles themselves are changed in some way. In the example of copper (II) chloride that was used earlier, the  $\text{CuCl}_2$  molecules were split up into their component atoms. The number of particles will change because each  $\text{CuCl}_2$  molecule breaks down into one copper atom (Cu) and one chlorine molecule ( $\text{Cl}_2$ ). However, what you should have noticed, is that the number of atoms of each element stays the same, as does the total mass of the atoms. This will be discussed in more detail in a later section.

- *Energy changes*

The energy changes that take place during a chemical reaction are much greater than those that take place during a physical change in matter. During a chemical reaction, energy is used up in order to break bonds, and then energy is released when the new product is formed. This will be discussed in more detail in section 5.3.

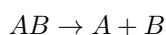
- *Reversibility*

Chemical changes are far more difficult to reverse than physical changes.

Two types of chemical reactions are **decomposition reactions** and **synthesis reactions**.

### 5.2.1 Decomposition reactions

A **decomposition reaction** occurs when a chemical compound is broken down into elements or smaller compounds. The generalised equation for a decomposition reaction is:



One example of such a reaction is the decomposition of hydrogen peroxide (figure 5.3) to form hydrogen and oxygen according to the following equation:

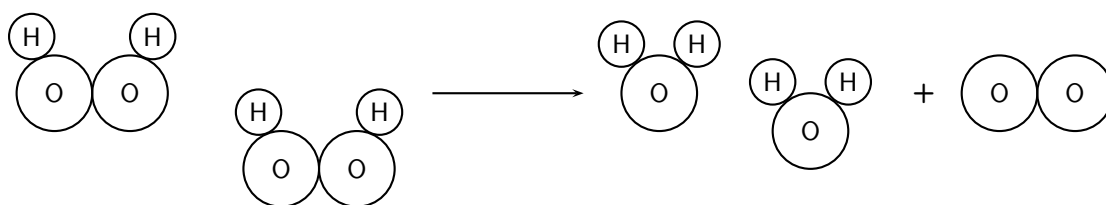
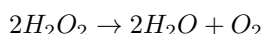


Figure 5.3: The decomposition of  $\text{H}_2\text{O}_2$  to form  $\text{H}_2\text{O}$  and  $\text{O}_2$

The decomposition of mercury (II) oxide is another example.

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#### Activity :: Experiment : The decomposition of mercury (II) oxide

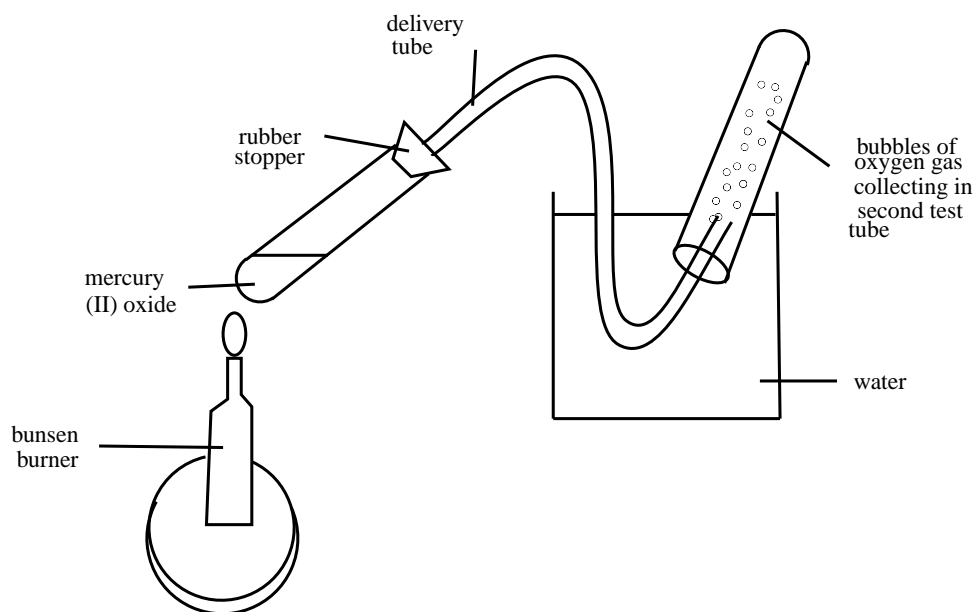
##### Aim:

To observe the decomposition of mercury (II) oxide when it is heated.

**Note:** Because this experiment involves mercury, which is a poisonous substance, it should be done in a fume cupboard, and all the products of the reaction must be very carefully disposed of.

##### Apparatus:

Mercury (II) oxide (an orange-red product); two test tubes; a large beaker; stopper and delivery tube; Bunsen burner; wooden splinter.

**Method:**

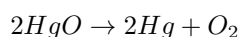
1. Put a small amount of mercury (II) oxide in a test tube and heat it gently over a Bunsen burner. Then allow it to cool. What do you notice about the colour of the mercury (II) oxide?
2. Heat the test tube again, and note what happens. Do you notice anything on the walls of the test tube? Record these observations.
3. Test for the presence of oxygen using a glowing splinter.

**Results:**

- During the first heating of mercury (II) oxide, the only change that took place was a change in colour from orange-red to black and then back to its original colour.
- When the test tube was heated again, deposits of mercury formed on the inner surface of the test tube. What colour is this mercury?
- The glowing splinter burst into flame when it was placed in the test tube, meaning that oxygen is present.

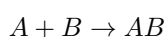
**Conclusions:**

When mercury oxide is heated, it decomposes to form mercury and oxygen. The chemical decomposition reaction that takes place can be written as follows:



### 5.2.2 Synthesis reactions

During a **synthesis reaction**, a new product is formed from elements or smaller compounds. The generalised equation for a synthesis reaction is as follows:



One example of a synthesis reaction is the burning of magnesium in oxygen to form magnesium oxide. The equation for the reaction is:

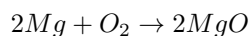


Figure 5.4 shows the chemical changes that take place at a microscopic level during this chemical reaction.

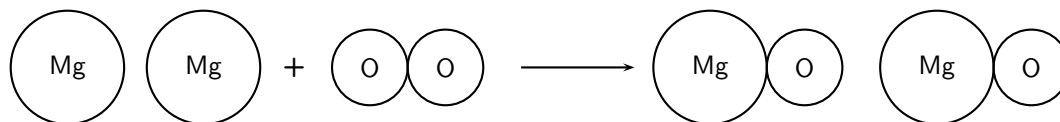


Figure 5.4: The synthesis of magnesium oxide (MgO) from magnesium and oxygen

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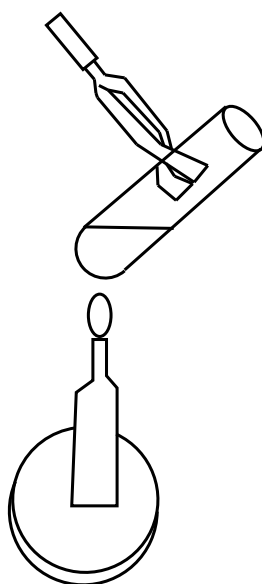
### Activity :: Experiment : Chemical reactions involving iron and sulfur

#### Aim:

To demonstrate the synthesis of iron sulfide from iron and sulfur.

#### Apparatus:

5,6 g iron filings and 3,2 g powdered sulfur; porcelain dish; test tube; bunsen burner



#### Method:

1. Before you carry out the experiment, write a balanced equation for the reaction you expect will take place.
2. Measure the quantity of iron and sulfur that you need and mix them in a porcelain dish.
3. Take some of this mixture and place it in the test tube. The test tube should be about 1/3 full.
4. This reaction should ideally take place in a fume cupboard. Heat the test tube containing the mixture over the Bunsen burner. Increase the heat if no reaction takes place. Once the reaction begins, you will need to remove the test tube from the flame. Record your observations.

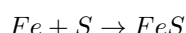
- Wait for the product to cool before breaking the test tube with a hammer. Make sure that the test tube is rolled in paper before you do this, otherwise the glass will shatter everywhere and you may be hurt.
- What does the product look like? Does it look anything like the original reactants? Does it have any of the properties of the reactants (e.g. the magnetism of iron)?

**Results:**

- After you removed the test tube from the flame, the mixture glowed a bright red colour. The reaction is exothermic and *produces energy*.
- The product, iron sulfide, is a dark colour and does not share any of the properties of the original reactants. It is an entirely new product.

**Conclusions:**

A synthesis reaction has taken place. The equation for the reaction is:

**Activity :: Investigation : Physical or chemical change?****Apparatus:**

Bunsen burner, 4 test tubes, a test tube rack and a test tube holder, small spatula, pipette, magnet, a birthday candle, NaCl (table salt), 0,1M AgNO<sub>3</sub>, 6M HCl, magnesium ribbon, iron filings, sulfur.

**Method:**

- Place a small amount of wax from a birthday candle into a test tube and heat it over the bunsen burner until it melts. Leave it to cool.
- Add a small spatula of NaCl to 5 ml water in a test tube and shake. Then use the pipette to add 10 drops of AgNO<sub>3</sub> to the sodium chloride solution. NOTE: Please be carefull AgNO<sub>3</sub> causes bad stains!!
- Take a 5 cm piece of magnesium ribbon and tear it into 1 cm pieces. Place two of these pieces into a test tube and add a few drops of 6M HCl. NOTE: Be very careful when you handle this acid because it can cause major burns.
- Take about 0,5 g iron filings and 0,5 g sulfur. Test each substance with a magnet. Mix the two samples in a test tube, and run a magnet alongside the outside of the test tube.
- Now heat the test tube that contains the iron and sulfur. What changes do you see? What happens now, if you run a magnet along the outside of the test tube?
- In each of the above cases, record your observations.

**Questions:**

Decide whether each of the following changes are physical or chemical and give a reason for your answer in each case. Record your answers in the table below:

Description	Physical or chemical change	Reason
melting candle wax		
dissolving NaCl		
mixing NaCl with AgNO <sub>3</sub>		
tearing magnesium ribbon		
adding HCl to magnesium ribbon		
mixing iron and sulfur		
heating iron and sulfur		

## 5.3 Energy changes in chemical reactions

All reactions involve some change in energy. During a *physical* change in matter, such as the evaporation of liquid water to water vapour, the energy of the water molecules increases. However, the change in energy is much smaller than in chemical reactions.

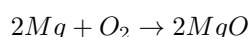
When a chemical reaction occurs, some bonds will *break*, while new bonds may *form*. Energy changes in chemical reactions result from the breaking and forming of bonds. For bonds to *break*, energy must be *absorbed*. When new bonds *form*, energy will be *released* because the new product has a lower energy than the 'inbetween' stage of the reaction when the bonds in the reactants have just been broken.

In some reactions, the energy that must be *absorbed* to break the bonds in the reactants, is less than the total energy that is *released* when new bonds are formed. This means that in the overall reaction, energy is *released*. This type of reaction is known as an **exothermic** reaction. In other reactions, the energy that must be *absorbed* to break the bonds in the reactants, is more than the total energy that is *released* when new bonds are formed. This means that in the overall reaction, energy must be *absorbed* from the surroundings. This type of reaction is known as an **endothermic** reaction. In the earlier part of this chapter, most decomposition reactions were endothermic, and heating was needed for the reaction to occur. Most of the synthesis reactions were exothermic, meaning that energy was given off in the form of heat or light.

More simply, we can describe the energy changes that take place during a chemical reaction as:

$$\text{Total energy absorbed to break bonds} - \text{Total energy released when new bonds form}$$

So, for example, in the reaction...



Energy is needed to break the O-O bonds in the oxygen molecule so that new Mg-O bonds can be formed, and energy is released when the product (MgO) forms.

Despite all the energy changes that seem to take place during reactions, it is important to remember that energy cannot be created or destroyed. Energy that enters a system will have come from the surrounding environment, and energy that leaves a system will again become part of that environment. This principle is known as the principle of **conservation of energy**.

**Definition: Conservation of energy principle**

Energy cannot be created or destroyed. It can only be changed from one form to another.

Chemical reactions may produce some very visible, and often violent, changes. An explosion, for example, is a sudden increase in volume and release of energy when high temperatures are generated and gases are released. For example,  $\text{NH}_4\text{NO}_3$  can be heated to generate nitrous oxide. Under these conditions, it is highly sensitive and can detonate easily in an explosive exothermic reaction.

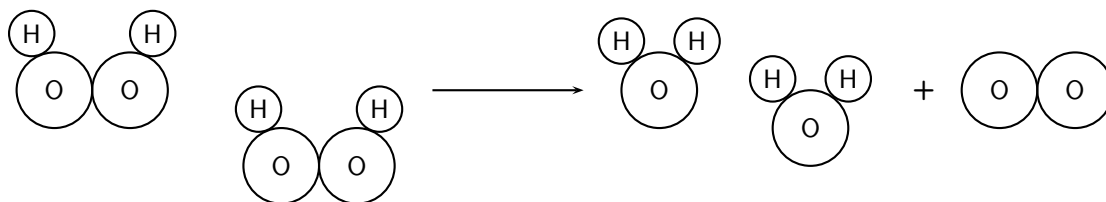
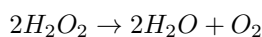
## 5.4 Conservation of atoms and mass in reactions

The total mass of all the substances taking part in a chemical reaction is conserved during a chemical reaction. This is known as the **law of conservation of mass**. The total number of

**atoms** of each element also remains the same during a reaction, although these may be arranged differently in the products.

We will use two of our earlier examples of chemical reactions to demonstrate this:

- The decomposition of hydrogen peroxide into water and oxygen



*Left hand side of the equation*

Total atomic mass =  $(4 \times 1) + (4 \times 16) = 68 \text{ u}$

Number of atoms of each element =  $(4 \times H) + (4 \times O)$

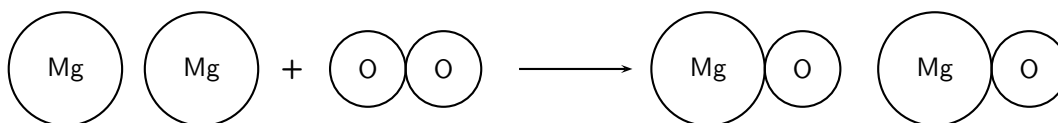
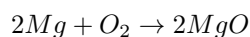
*Right hand side of the equation*

Total atomic mass =  $(4 \times 1) + (2 \times 16) + (2 \times 16) = 68 \text{ u}$

Number of atoms of each element =  $(4 \times H) + (4 \times O)$

Both the atomic mass and the number of atoms of each element are conserved in the reaction.

- The synthesis of magnesium and oxygen to form magnesium oxide



*Left hand side of the equation*

Total atomic mass =  $(2 \times 24,3) + (2 \times 16) = 80,6 \text{ u}$

Number of atoms of each element =  $(2 \times Mg) + (2 \times O)$

*Right hand side of the equation*

Total atomic mass =  $(2 \times 24,3) + (2 \times 16) = 80,6 \text{ u}$

Number of atoms of each element =  $(2 \times Mg) + (2 \times O)$

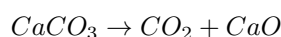
Both the atomic mass and the number of atoms of each element are conserved in the reaction.

**Activity :: Demonstration : The conservation of atoms in chemical reactions****Materials:**

- Coloured marbles or small balls to represent atoms. Each colour will represent a different element.
- Prestik

**Method:**

1. Choose a reaction from any that have been used in this chapter or any other *balanced* chemical reaction that you can think of. To help to explain this activity, we will use the decomposition reaction of calcium carbonate to produce carbon dioxide and calcium oxide.



2. Stick marbles together to represent the reactants and put these on one side of your table. In this example you may for example join one red marble (calcium), one green marble (carbon) and three yellow marbles (oxygen) together to form the molecule calcium carbonate ( $\text{CaCO}_3$ ).
3. Leaving your reactants on the table, use marbles to make the product molecules and place these on the other side of the table.
4. Now count the number of atoms on each side of the table. What do you notice?
5. Observe whether there is any difference between the molecules in the reactants and the molecules in the products.

**Discussion**

You should have noticed that the number of atoms in the reactants is the same as the number of atoms in the product. The number of atoms is conserved during the reaction. However, you will also see that the molecules in the reactants and products is not the same. The *arrangement of atoms* is not conserved during the reaction.

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## 5.5 Law of constant composition

In any given chemical compound, the elements always combine in the same proportion with each other. This is the **law of constant proportions**.

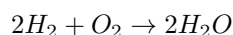
The **law of constant composition** says that, in any particular chemical compound, all samples of that compound will be made up of the same elements in the same proportion or ratio. For example, any water molecule is always made up of two hydrogen atoms and one oxygen atom in a 2:1 ratio. If we look at the relative masses of oxygen and hydrogen in a water molecule, we see that 94% of the mass of a water molecule is accounted for by oxygen, and the remaining 6% is the mass of hydrogen. This mass proportion will be the same for any water molecule.

This does not mean that hydrogen and oxygen always combine in a 2:1 ratio to form  $\text{H}_2\text{O}$ . Multiple proportions are possible. For example, hydrogen and oxygen may combine in different proportions to form  $\text{H}_2\text{O}_2$  rather than  $\text{H}_2\text{O}$ . In  $\text{H}_2\text{O}_2$ , the H:O ratio is 1:1 and the mass ratio of hydrogen to oxygen is 1:16. This will be the same for any molecule of hydrogen peroxide.

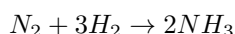
## 5.6 Volume relationships in gases

In a chemical reaction between gases, the relative volumes of the gases in the reaction are present in a ratio of small whole numbers if all the gases are at the same temperature and pressure. This relationship is also known as **Gay-Lussac's Law**.

For example, in the reaction between hydrogen and oxygen to produce water, two volumes of  $H_2$  react with 1 volume of  $O_2$  to produce 2 volumes of  $H_2O$ .



In the reaction to produce ammonia, one volume of nitrogen gas reacts with three volumes of hydrogen gas to produce two volumes of ammonia gas.



This relationship will also be true for all other chemical reactions.

## 5.7 Summary

- Matter does not stay the same. It may undergo physical or chemical changes.
- A **physical change** means that the form of matter may change, but not its identity. For example, when water evaporates, the energy and the arrangement of water molecules will change, but not the structure of the water molecules themselves.
- 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 materials. A chemical reaction involves the formation of new substances with **different properties**. For example, carbon dioxide reacts with water to form carbonic acid.



- A chemical change may involve a **decomposition** or **synthesis** reaction. During chemical change, the mass and number of atoms is conserved, but the number of molecules is not always the same.
- Chemical reactions involve larger changes in energy. During a reaction, energy is needed to break bonds in the reactants, and energy is released when new products form. If the energy released is greater than the energy absorbed, then the reaction is exothermic. If the energy released is less than the energy absorbed, then the reaction is endothermic. Chemical reactions are not easily reversible.
- Decomposition reactions are usually **endothermic** and synthesis reactions are usually **exothermic**.
- The **law of conservation of mass** states that the total mass of all the substances taking part in a chemical reaction is conserved and the number of atoms of each element in the reaction does not change when a new product is formed.
- The **conservation of energy principle** states that energy cannot be created or destroyed, it can only change from one form to another.
- The **law of constant composition** states that in any particular compound, all samples of that compound will be made up of the same elements in the same proportion or ratio.



- **Gay-Lussac's Law** states that in a chemical reaction between gases, the relative volumes of the gases in the reaction are present in a ratio of small whole numbers if all the gases are at the same temperature and pressure.



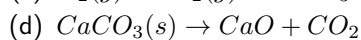
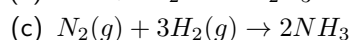
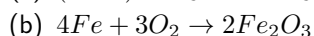
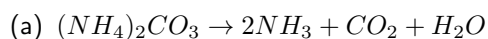

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**Exercise: Summary exercise**

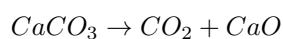
1. Complete the following table by saying whether each of the descriptions is an example of a physical or chemical change:

Description	Physical or chemical
hot and cold water mix together	
milk turns sour	
a car starts to rust	
food digests in the stomach	
alcohol disappears when it is placed on your skin	
warming food in a microwave	
separating sand and gravel	
fireworks exploding	

2. For each of the following reactions, say whether it is an example of a synthesis or decomposition reaction:



3. For the following equation:



Show that the 'law of conservation of mass' applies.

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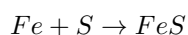
## Chapter 6

# Representing Chemical Change - Grade 10

As we have already mentioned, a number of changes can occur when elements react with one another. These changes may either be *physical* or *chemical*. One way of representing these changes is through **balanced chemical equations**. A chemical equation describes a chemical reaction by using symbols for the elements involved. For example, if we look at the reaction between iron (Fe) and sulfur (S) to form iron sulfide (FeS), we could represent these changes either in words or using chemical symbols:

iron + sulfur  $\rightarrow$  iron sulfide

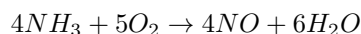
or



Another example would be:

ammonia + oxygen  $\rightarrow$  nitric oxide + water

or



Compounds on the left of the arrow are called the **reactants** and these are needed for the reaction to take place. In this equation, the reactants are ammonia and oxygen. The compounds on the right are called the **products** and these are what is formed from the reaction.

In order to be able to write a balanced chemical equation, there are a number of important things that need to be done:

1. Know the chemical symbols for the elements involved in the reaction
2. Be able to write the chemical formulae for different reactants and products
3. Balance chemical equations by understanding the laws that govern chemical change
4. Know the state symbols for the equation

We will look at each of these steps separately in the next sections.

### 6.1 Chemical symbols

It is very important to know the chemical symbols for common elements in the Periodic Table so that you are able to write chemical equations and to recognise different compounds.



---

**Exercise: Revising common chemical symbols**

- Write down the chemical symbols and names of all the elements that you know.
  - Compare your list with another learner and add any symbols and names that you don't have.
  - Spend some time, either in class or at home, learning the symbols for at least the first twenty elements in the periodic table. You should also learn the symbols for other common elements that are not in the first twenty.
  - Write a short test for someone else in the class and then exchange tests with them so that you each have the chance to answer one.
- 

## 6.2 Writing chemical formulae

A **chemical formula** is a concise way of giving information about the atoms that make up a particular chemical compound. A chemical formula shows each element by its symbol, and also shows how many atoms of each element are found in that compound. The number of atoms (if greater than one) is shown as a subscript.

*Examples:*

**CH<sub>4</sub>** (methane)

Number of atoms: (1 x carbon) + (4 x hydrogen) = 5 atoms in one methane molecule

**H<sub>2</sub>SO<sub>4</sub>** (sulfuric acid)

Number of atoms: (2 x hydrogen) + (1 x sulfur) + (4 x oxygen) = 7 atoms in one molecule of sulfuric acid

A chemical formula may also give information about how the atoms are arranged in a molecule if it is written in a particular way. A molecule of ethane, for example, has the chemical formula C<sub>2</sub>H<sub>6</sub>. This formula tells us how many atoms of each element are in the molecule, but doesn't tell us anything about how these atoms are arranged. In fact, each carbon atom in the ethane molecule is bonded to three hydrogen atoms. Another way of writing the formula for ethane is CH<sub>3</sub>CH<sub>3</sub>. The number of atoms of each element has not changed, but this formula gives us more information about how the atoms are arranged in relation to each other.

The slightly tricky part of writing chemical formulae comes when you have to work out the ratio in which the elements combine. For example, you may know that sodium (Na) and chlorine (Cl) react to form sodium chloride, but how do you know that in each molecule of sodium chloride there is only *one* atom of sodium for every *one* atom of chlorine? It all comes down to the **valency** of an atom or group of atoms. Valency is the number of bonds that an element can form with another element. Working out the chemical formulae of chemical compounds using their valency, will be covered in Grade 11. For now, we will use formulae that you already know.

## 6.3 Balancing chemical equations

### 6.3.1 The law of conservation of mass

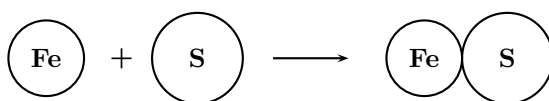
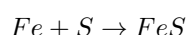
In order to balance a chemical equation, it is important to understand the law of conservation of mass.

**Definition: The law of conservation of mass**

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. For any chemical process in a closed system, the mass of the reactants must equal the mass of the products.

In a chemical equation then, the **mass** of the reactants must be equal to the mass of the products. In order to make sure that this is the case, the number of **atoms** of each element in the reactants must be equal to the number of atoms of those same elements in the products. Some examples are shown below:

*Example 1:*

*Reactants*

Atomic mass of reactants =  $55.8 \text{ u} + 32.1 \text{ u} = 87.9 \text{ u}$

Number of atoms of each element in the reactants:  $(1 \times \text{Fe})$  and  $(1 \times \text{S})$

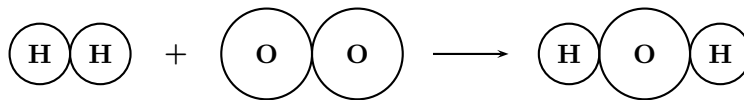
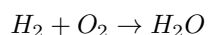
*Products*

Atomic mass of product =  $55.8 \text{ u} + 32.1 \text{ u} = 87.9 \text{ u}$

Number of atoms of each element in the products:  $(1 \times \text{Fe})$  and  $(1 \times \text{S})$

Since the number of atoms of each element is the same in the reactants and in the products, we say that the equation is **balanced**.

*Example 2:*

*Reactants*

Atomic mass of reactants =  $(1 + 1) + (16 + 16) = 34 \text{ u}$

Number of atoms of each element in the reactants:  $(2 \times \text{H})$  and  $(2 \times \text{O})$

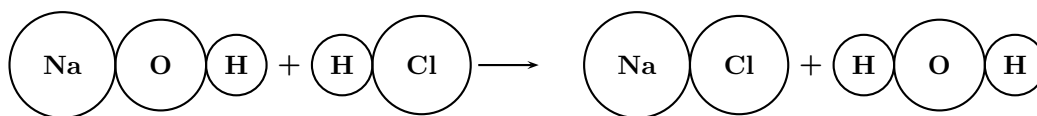
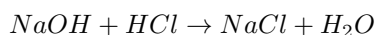
*Product*

Atomic mass of product =  $(1 + 1 + 16) = 18 \text{ u}$

Number of atoms of each element in the products:  $(2 \times \text{H})$  and  $(1 \times \text{O})$

Since the total atomic mass of the reactants and the products is not the same, and since there are more oxygen atoms in the reactants than there are in the product, the equation is **not balanced**.

Example 3:



#### Reactants

Atomic mass of reactants =  $(23 + 16 + 1) + (1 + 35.4) = 76.4 \text{ u}$

Number of atoms of each element in the reactants:  $(1 \times \text{Na}) + (1 \times \text{O}) + (2 \times \text{H}) + (1 \times \text{Cl})$

#### Products

Atomic mass of products =  $(23 + 35.4) + (1 + 1 + 16) = 76.4 \text{ u}$

Number of atoms of each element in the products:  $(1 \times \text{Na}) + (1 \times \text{O}) + (2 \times \text{H}) + (1 \times \text{Cl})$

Since the number of atoms of each element is the same in the reactants and in the products, we say that the equation is **balanced**.

We now need to find a way to balance those equations that are not balanced so that the number of atoms of each element in the reactants is the same as that for the products. This can be done by changing the **coefficients** of the molecules until the atoms on each side of the arrow are balanced. You will see later in Grade 11 that these coefficients tell us something about the **mole ratio** in which substances react. They also tell us about the volume relationship between gases in the reactants and products.

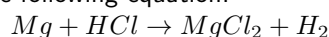
#### Important: Coefficients

Remember that if you put a number in front of a molecule, that number applies to the *whole* molecule. For example, if you write  $2\text{H}_2\text{O}$ , this means that there are 2 molecules of water. In other words, there are 4 hydrogen atoms and 2 oxygen atoms. If we write  $3\text{HCl}$ , this means that there are 3 molecules of HCl. In other words there are 3 hydrogen atoms and 3 chlorine atoms in total. In the first example, 2 is the coefficient and in the second example, 3 is the coefficient.

### 6.3.2 Steps to balance a chemical equation

When balancing a chemical equation, there are a number of steps that need to be followed.

- STEP 1: Identify the reactants and the products in the reaction, and write their chemical formulae.
- STEP 2: Write the equation by putting the reactants on the left of the arrow, and the products on the right.
- STEP 3: Count the number of atoms of each element in the reactants and the number of atoms of each element in the products.
- STEP 4: If the equation is not balanced, change the coefficients of the molecules until the number of atoms of each element on either side of the equation balance.
- STEP 5: Check that the atoms are in fact balanced.
- STEP 6 (we will look at this a little later): Add any extra details to the equation e.g. phase.

**Worked Example 9: Balancing chemical equations 1****Question:** Balance the following equation:**Answer**

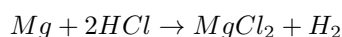
**Step 1 :** Because the equation has been written for you, you can move straight on to counting the number of atoms of each element in the reactants and products

Reactants: Mg = 1 atom; H = 1 atom and Cl = 1 atom

Products: Mg = 1 atom; H = 2 atoms and Cl = 2 atoms

**Step 2 : Balance the equation**

The equation is not balanced since there are 2 chlorine atoms in the product and only 1 in the reactants. If we add a coefficient of 2 to the HCl to increase the number of H and Cl atoms in the reactants, the equation will look like this:

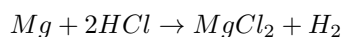
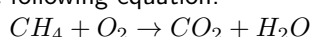
**Step 3 : Check that the atoms are balanced**

If we count the atoms on each side of the equation, we find the following:

Reactants: Mg = 1; H = 2; Cl = 2

Products: Mg = 1; H = 2; Cl = 2

The equation is balanced. The final equation is:

**Worked Example 10: Balancing chemical equations 2****Question:** Balance the following equation:**Answer**

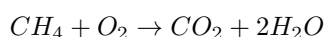
**Step 1 :** Count the number of atoms of each element in the reactants and products

Reactants: C = 1; H = 4; O = 2

Products: C = 1; H = 2; O = 3

**Step 2 : Balance the equation**

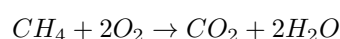
If we add a coefficient of 2 to  $\text{H}_2\text{O}$ , then the number of hydrogen atoms in the reactants will be 4, which is the same as for the reactants. The equation will be:

**Step 3 : Check that the atoms balance**

Reactants: C = 1; H = 4; O = 2

Products: C = 1; H = 4; O = 4

You will see that, although the number of *hydrogen* atoms now balances, there are more oxygen atoms in the products. You now need to repeat the previous step. If we put a coefficient of 2 in front of  $\text{O}_2$ , then we will increase the number of oxygen atoms in the reactants by 2. The new equation is:



When we check the number of atoms again, we find that the number of atoms of each element in the reactants is the same as the number in the products. The equation is now balanced.

**Worked Example 11: Balancing chemical equations 3**

**Question:** Nitrogen gas reacts with hydrogen gas to form ammonia. Write a balanced chemical equation for this reaction.

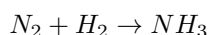
**Answer**

**Step 1 : Identify the reactants and the products, and write their chemical formulae**

The reactants are nitrogen ( $N_2$ ) and hydrogen ( $H_2$ ), and the product is ammonia ( $NH_3$ ).

**Step 2 : Write the equation so that the reactants are on the left and products on the right of the arrow**

The equation is as follows:



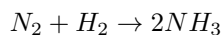
**Step 3 : Count the atoms of each element in the reactants and products**

Reactants: N = 2; H = 2

Products: N = 1; H = 3

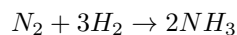
**Step 4 : Balance the equation**

In order to balance the number of nitrogen atoms, we could rewrite the equation as:



**Step 5 : Check that the atoms are balanced**

In the above equation, the nitrogen atoms now balance, but the hydrogen atoms don't (there are 2 hydrogen atoms in the reactants and 6 in the product). If we put a coefficient of 3 in front of the hydrogen ( $H_2$ ), then the hydrogen atoms and the nitrogen atoms balance. The final equation is:

**Worked Example 12: Balancing chemical equations 4**

**Question:** In our bodies, sugar ( $C_6H_{12}O_6$ ) reacts with the oxygen we breathe in to produce carbon dioxide, water and energy. Write the balanced equation for this reaction.

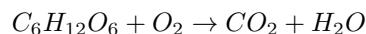
**Answer**

**Step 1 : Identify the reactants and products in the reaction, and write their chemical formulae.**



Reactants: sugar ( $C_6H_{12}O_6$ ) and oxygen ( $O_2$ )  
 Products: carbon dioxide ( $CO_2$ ) and water ( $H_2O$ )

**Step 2 : Write the equation by putting the reactants on the left of the arrow, and the products on the right**

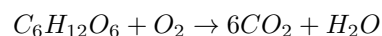


**Step 3 : Count the number of atoms of each element in the reactants and the number of atoms of each element in the products**

Reactants: C=6; H=12; O=8;  
 Products: C=1; H=2; O=3;

**Step 4 : Change the coefficients of the molecules until the number of atoms of each element on either side of the equation balance.**

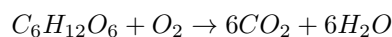
It is easier to start with carbon as it only appears once on each side. If we add a 6 in front of  $CO_2$ , the equation looks like this:



Reactants: C=6; H=12; O=8;  
 Products: C=6; H=2; O=13;

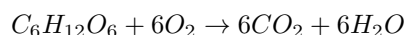
**Step 5 : Change the coefficients again to try to balance the equation.**

Let's try to get the number of hydrogens the same this time.



Reactants: C=6; H=12; O=8;  
 Products: C=6; H=12; O=18;

**Step 6 : Now we just need to balance the oxygen atoms.**



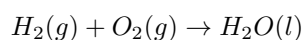
Reactants: C=6; H=12; O=18;  
 Products: C=6; H=12; O=18;



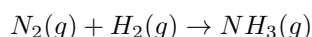
### Exercise: Balancing simple chemical equations

Balance the following equations:

1. Hydrogen fuel cells are extremely important in the development of alternative energy sources. Many of these cells work by reacting hydrogen and oxygen gases together to form water, a reaction which also produces electricity. Balance the following equation:

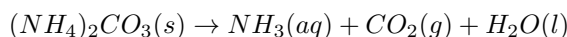


2. The synthesis of ammonia ( $NH_3$ ), made famous by the German chemist Fritz Haber in the early 20th century, is one of the most important reactions in the chemical industry. Balance the following equation used to produce ammonia:



3.  $Mg + P_4 \rightarrow Mg_3P_2$
4.  $Ca + H_2O \rightarrow Ca(OH)_2 + H_2$

5.  $\text{CuCO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{CuSO}_4 + \text{H}_2\text{O} + \text{CO}_2$
6.  $\text{CaCl}_2 + \text{Na}_2\text{CO}_3 \rightarrow \text{CaCO}_3 + \text{NaCl}$
7.  $\text{C}_{12}\text{H}_{22}\text{O}_{11} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O}$
8. Barium chloride reacts with sulphuric acid to produce barium sulphate and hydrochloric acid.
9. Ethane ( $\text{C}_2\text{H}_6$ ) reacts with oxygen to form carbon dioxide and steam.
10. Ammonium carbonate is often used as a smelling salt. Balance the following reaction for the decomposition of ammonium carbonate:



## 6.4 State symbols and other information

The state (phase) of the compounds can be expressed in the chemical equation. This is done by placing the correct label on the right hand side of the formula. There are only four labels that can be used:

1. (g) for gaseous compounds
2. (l) for liquids
3. (s) for solid compounds
4. (aq) for an aqueous (water) solution

Occasionally, a catalyst is added to the reaction. A catalyst is a substance that speeds up the reaction without undergoing any change to itself. In a chemical equation, this is shown by using the symbol of the catalyst above the arrow in the equation.

To show that heat was needed for the reaction, a Greek delta ( $\Delta$ ) is placed above the arrow in the same way as the catalyst.



**Important:** You may remember from chapter 5 that energy cannot be created or destroyed during a chemical reaction but it may change form. In an exothermic reaction,  $\Delta H$  is less than zero, and in an endothermic reaction,  $\Delta H$  is greater than zero. This value is often written at the end of a chemical equation.



### Worked Example 13: Balancing chemical equations 4

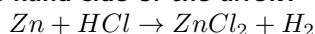
**Question:** Solid zinc metal reacts with aqueous hydrochloric acid to form an aqueous solution of zinc chloride ( $\text{ZnCl}_2$ ) and hydrogen gas. Write a balanced equation for this reaction.

#### Answer

**Step 1 : Identify the reactants and products and their chemical formulae**

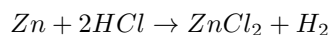
The reactants are zinc (Zn) and hydrochloric acid (HCl). The products are zinc chloride ( $\text{ZnCl}_2$ ) and hydrogen ( $\text{H}_2$ ).

**Step 2 : Place the reactants on the left of the equation and the products on the right hand side of the arrow.**



**Step 3 : Balance the equation**

You will notice that the zinc atoms balance but the chlorine and hydrogen atoms don't. Since there are two chlorine atoms on the right and only one on the left, we will give HCl a coefficient of 2 so that there will be two chlorine atoms on each side of the equation.

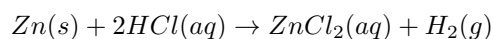


**Step 4 : Check that all the atoms balance**

When you look at the equation again, you will see that all the atoms are now balanced.

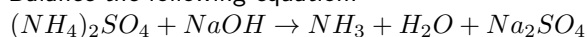
**Step 5 : Ensure all details (e.g. state symbols) are added**

In the initial description, you were told that zinc was a metal, hydrochloric acid and zinc chloride were in aqueous solutions and hydrogen was a gas.



#### Worked Example 14: Balancing chemical equations 5 (advanced)

**Question:** Balance the following equation:

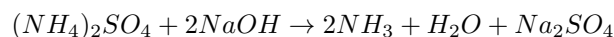


In this example, the first two steps are not necessary because the reactants and products have already been given.

**Answer**

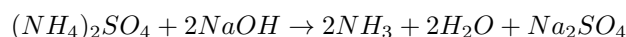
**Step 1 : Balance the equation**

With a complex equation, it is always best to start with atoms that appear only once on each side i.e. Na, N and S atoms. Since the S atoms already balance, we will start with Na and N atoms. There are two Na atoms on the right and one on the left. We will add a second Na atom by giving NaOH a coefficient of two. There are two N atoms on the left and one on the right. To balance the N atoms,  $\text{NH}_3$  will be given a coefficient of two. The equation now looks as follows:



**Step 2 : Check that all atoms balance**

N, Na and S atoms balance, but O and H atoms do not. There are six O atoms and ten H atoms on the left, and five O atoms and eight H atoms on the right. We need to add one O atom and two H atoms on the right to balance the equation. This is done by adding another  $\text{H}_2\text{O}$  molecule on the right hand side. We now need to check the equation again:



The equation is now balanced.



### Exercise: Balancing more advanced chemical equations

Write balanced equations for each of the following reactions:

1.  $Al_2O_3(s) + H_2SO_4(aq) \rightarrow Al_2(SO_4)_3(aq) + 3H_2O(l)$
2.  $Mg(OH)_2(aq) + HNO_3(aq) \rightarrow Mg(NO_3)_2(aq) + 2H_2O(l)$
3. Lead(II)nitrate solution reacts with potassium iodide solution.
4. When heated, aluminium reacts with solid copper oxide to produce copper metal and aluminium oxide ( $Al_2O_3$ ).
5. When calcium chloride solution is mixed with silver nitrate solution, a white precipitate (solid) of silver chloride appears. Calcium nitrate ( $Ca(NO_3)_2$ ) is also produced in the solution.

## 6.5 Summary

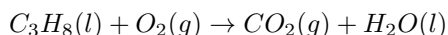
- A **chemical equation** uses symbols to describe a chemical reaction.
- In a chemical equation, **reactants** are written on the left hand side of the equation, and the **products** on the right. The arrow is used to show the direction of the reaction.
- When representing chemical change, it is important to be able to write the **chemical formula** of a compound.
- In any chemical reaction, the **law of conservation of mass** applies. This means that the total atomic mass of the reactants must be the same as the total atomic mass of the products. This also means that the number of atoms of each element in the reactants must be the same as the number of atoms of each element in the product.
- If the number of atoms of each element in the reactants is the same as the number of atoms of each element in the product, then the equation is **balanced**.
- If the number of atoms of each element in the reactants is not the same as the number of atoms of each element in the product, then the equation is **not balanced**.
- In order to balance an equation, **coefficients** can be placed in front of the reactants and products until the number of atoms of each element is the same on both sides of the equation.



### Exercise: Summary exercise

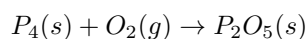
Balance each of the following chemical equations:

1.  $NH_4 + H_2O \rightarrow NH_4OH$
2. Sodium chloride and water react to form sodium hydroxide, chlorine and hydrogen.
3. Propane is a fuel that is commonly used as a heat source for engines and homes. Balance the following equation for the combustion of propane:



4. Aspartame, an artificial sweetener, has the formula  $C_{14}H_{18}N_2O_5$ . Write the balanced equation for its combustion (reaction with  $O_2$ ) to form  $CO_2$  gas, liquid  $H_2O$ , and  $N_2$  gas.

5.  $Fe_2(SO_4)_3 + K(SCN) \rightarrow K_3Fe(SCN)_6 + K_2SO_4$
6. Chemical weapons were banned by the Geneva Protocol in 1925. According to this protocol, all chemicals that release suffocating and poisonous gases are not to be used as weapons. White phosphorus, a very reactive allotrope of phosphorus, was recently used during a military attack. Phosphorus burns vigorously in oxygen. Many people got severe burns and some died as a result. The equation for this spontaneous reaction is:



- (a) Balance the chemical equation.
- (b) Prove that the law of conservation of mass is obeyed during this chemical reaction.
- (c) Name the product formed during this reaction.
- (d) Classify the reaction as endothermic or exothermic. Give a reason for your answer.
- (e) Classify the reaction as a synthesis or decomposition reaction. Give a reason for your answer.

(DoE Exemplar Paper 2 2007)

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## Chapter 7

# The Water Cycle - Grade 10

### 7.1 Introduction

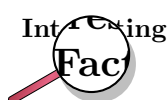
You may have heard the word 'cycle' many times before. Think for example of the word 'bicycle' or the regular 'cycle tests' that you may have at school. A cycle is a series of events that repeats itself. In the case of a bicycle, the wheel turns through a full circle before beginning the motion again, while cycle tests happen regularly, normally every week or every two weeks. Because a cycle repeats itself, it doesn't have a beginning or an end.

Our Earth is a **closed system**. This means that it can exchange *energy* with its surroundings (i.e. the rest of the solar system), but no new *matter* is brought into the system. For this reason, it is important that all the elements and molecules on Earth are recycled so that they are never completely used up. In the next two sections, we are going to take a closer look at two cycles that are very important for life on Earth. They are the **water cycle** and the **nitrogen cycle**.

### 7.2 The importance of water

For many people, it is so easy to take water for granted, and yet life on Earth would not exist were it not for this extraordinary compound. Not only is it believed that the first forms of life actually *started* in water, but most of the cells in living organisms contain between 70% and 95% water. Here in the cells, water acts as a solvent and helps to transport vital materials such as food and oxygen to where they are needed, and also removes waste products such as carbon dioxide and ammonia from the body. For many animals and plants, water is their home. Think for example of fish and amphibians that live either all or part of the time in rivers, dams and the oceans. In other words, if water did not exist, life as we know it would not be possible.

Apart from allowing life to exist, water also has a number of other functions. Water shapes the landscape around us by wearing away at rocks and also transports and deposits sediments on floodplains and along coastal regions. Water also plays a very important role in helping to regulate Earth's climate. We will discuss this again later in the chapter. As humans we use water in our homes, in industry, in mining, irrigation and even as a source of electricity in hydro-electric schemes. In fact, if we were able to view Earth from space, we would see that almost three quarters of our planet's surface is covered in water. It is because of this that Earth is sometimes called the 'Blue Planet'. Most of this water is stored in the oceans, with the rest found in ice (e.g. glaciers), groundwater (e.g. boreholes), surface water (e.g. rivers, lakes, estuaries, dams) and in the atmosphere as clouds and water vapour.



In the search for life on other planets, one of the first things that scientists look for is water. However, most planets are either too close to the sun (and therefore

too hot) for water to exist in liquid form, or they are too far away and therefore too cold. So, even if water were to be found, the conditions are unlikely to allow it to exist in a form that can support the diversity of life that we see on Earth.

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## 7.3 The movement of water through the water cycle

The water cycle is the continuous movement of water over, above, and beneath the Earth's surface. As water moves, it changes phase between liquid (water), solid (ice) and gas (water vapour). It is powered by solar energy and, because it is a cycle, it has no beginning or end.



### Definition: The Water Cycle

The water cycle is the continuous circulation of water across the Earth. The water cycle is driven by solar radiation and it includes the atmosphere, land, surface water and groundwater. As water moves through the cycle, it changes state between liquid, solid, and gas phases. The actual movement of water from one part of the cycle to another (e.g. from river to ocean) is the result of processes such as evaporation, precipitation, infiltration and runoff.

The movement of water through the water cycle is shown in figure 7.1. In the figure, each process within this cycle is numbered. Each process will be described below.

#### 1. The source of energy

The water cycle is driven by the sun, which provides the heat energy that is needed for many of the other processes to take place.

#### 2. Evaporation

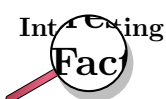
When water on the earth's surface is heated by the sun, the average energy of the water molecules increases and some of the molecules are able to leave the liquid phase and become water vapour. This is called evaporation. Evaporation is the change of water from a liquid to a gas as it moves from the ground, or from bodies of water like the ocean, rivers and dams, into the atmosphere.

#### 3. Transpiration

Transpiration is the evaporation of water from the aerial parts of plants, especially the leaves but also from the stems, flowers and fruits. This is another way that liquid water can enter the atmosphere as a gas.

#### 4. Condensation

When evaporation takes place, water vapour rises in the atmosphere and cools as the altitude (height above the ground) increases. As the temperature drops, the energy of the water vapour molecules also decreases, until the molecules don't have enough energy to stay in the gas phase. At this point, condensation occurs. Condensation is the change of water from water vapour (gas) into liquid water droplets in the air. *Clouds, fog and mist* are all examples of condensation. A cloud is actually a collection of lots and lots of tiny water droplets. This mostly takes place in the upper atmosphere but can also take place close to the ground if there is a significant temperature change.



Have you ever tried breathing out on a very cold day? It looks as though you are breathing out smoke! The moist air that you breathe out is much warmer than the air outside your body. As this warm, moist air comes into



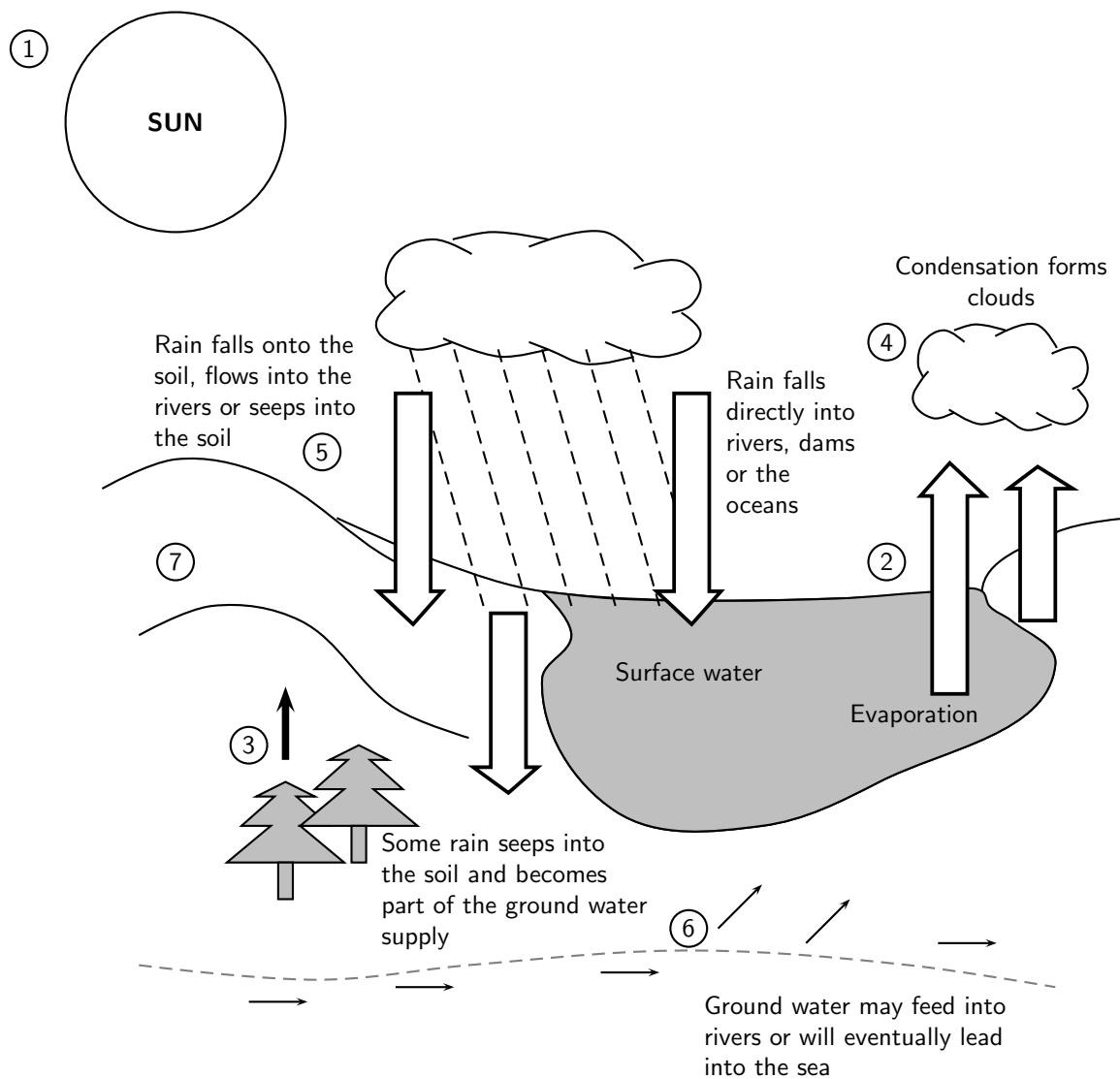


Figure 7.1: The water cycle

contact with the colder air outside, its temperature drops very quickly and the water vapour in the air you breathe out condenses. The 'smoke' that you see is actually formed in much the same way as clouds form in the upper atmosphere.

### 5. Precipitation

Precipitation occurs when water falls back to the earth's surface in the form of rain or snow. Rain will fall as soon as a cloud becomes too saturated with water droplets. Snow is similar to rain, except that it is frozen. Snow only falls if temperatures in the atmosphere are around freezing. The freezing point of water is  $0^{\circ}\text{C}$ .

### 6. Infiltration

If precipitation occurs, some of this water will filter into the soil and collect underground. This is called infiltration. This water may evaporate again from the soil at a later stage, or the underground water may seep into another water body.

### 7. Surface runoff

This refers to the many ways that water moves across the land. This includes *surface runoff* such as when water flows along a road and into a drain, or when water flows straight across the sand. It also includes *channel runoff* when water flows in rivers and streams. As it flows, the water may infiltrate into the ground, evaporate into the air, become stored in lakes or reservoirs, or be extracted for agricultural or other human uses.



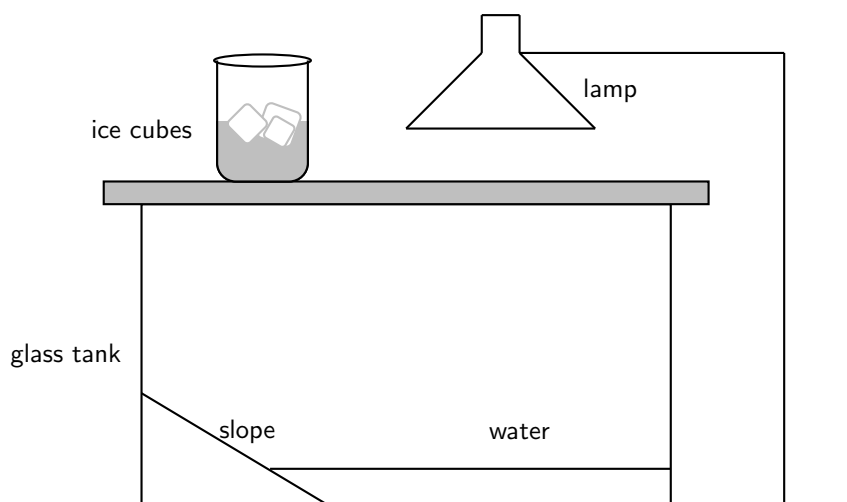
**Important:** It is important to realise that the water cycle is all about **energy exchanges**. The sun is the original energy *source*. Energy from the sun heats the water and causes evaporation. This energy is stored in water vapour as *latent heat*. When the water vapour condenses again, the latent heat is released, and helps to drive circulation in the atmosphere. The liquid water falls to earth, and will evaporate again at a later stage. The atmospheric circulation patterns that occur because of these exchanges of heat are very important in influencing climate patterns.

#### Activity :: Experiment : The Water Cycle

##### Materials:

Tile or piece of plastic (e.g. lid of ice-cream container) to make a hill slope; glass fish tank with a lid; beaker with ice cubes; lamp; water

Set up a model of the water cycle as follows:



1. Lean the plastic against one side so that it creates a 'hill slope' as shown in the diagram.
2. Pour water into the bottom of the tank until about a quarter of the hill slope is covered.
3. Close the fish tank lid.
4. Place the beaker with ice on the lid directly above the hill slope.
5. Turn the lamp on and position it so that it shines over the water.
6. Leave the model like this for 20-30 minutes and then observe what happens.  
Make sure that you don't touch the lamp as it will be very hot!

##### Observation questions:

1. Which parts of the water cycle can you see taking place in the model?
2. Which parts of the water cycle are *not* represented in the model?

3. Can you think of how those parts that are not shown *could* be represented?
  4. What is the energy source in the model? What would the energy source be in reality?
  5. What do you think the function of the ice is in the beaker?
- 

## 7.4 The microscopic structure of water

In many ways, water behaves very differently from other liquids. These properties are directly related to the microscopic structure of water, and more specifically to the *shape* of the molecule and its *polar nature*, and to the *bonds* that hold water molecules together.

### 7.4.1 The polar nature of water

Every water molecule is made up of one oxygen atom that is bonded to two hydrogen atoms. When atoms bond, the nucleus of each atom has an attractive force on the electrons of the other atoms. This 'pull' is stronger in some atoms than in others and is called the **electronegativity** of the atom. In a water molecule, the oxygen atom has a higher electronegativity than the hydrogen atoms and therefore attracts the electrons more strongly. The result is that the oxygen atom has a slightly negative charge and the two hydrogen atoms each have a slightly positive charge. The water molecule is said to be **polar** because the electrical charge is not evenly distributed in the molecule. One part of the molecule has a different charge to other parts. You will learn more about this in Grade 11.

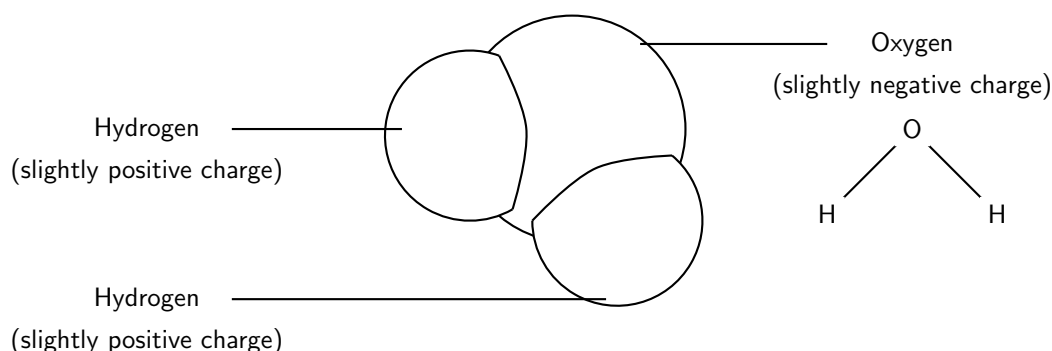


Figure 7.2: Diagrams showing the structure of a water molecule. Each molecule is made up of two hydrogen atoms that are attached to one oxygen atom.

### 7.4.2 Hydrogen bonding in water molecules

In every water molecule, the forces that hold the individual atoms together are called **intramolecular forces**. But there are also forces *between* different water molecules. These are called **intermolecular forces** (figure 7.3). You will learn more about these at a later stage, but for now it is enough to know that in water, molecules are held together by **hydrogen bonds**. Hydrogen bonds are a much stronger type of intermolecular force than those found in many other substances, and this affects the properties of water.

**Important:** Intramolecular and intermolecular forces

If you find these terms confusing, remember that 'intra' means *within* (i.e. the forces within a molecule). An **introvert** is someone who doesn't express emotions and feelings outwardly. They tend to be quieter and keep to themselves. 'Inter' means *between* (i.e. the forces between molecules). An **international** cricket match is a match between two different countries.

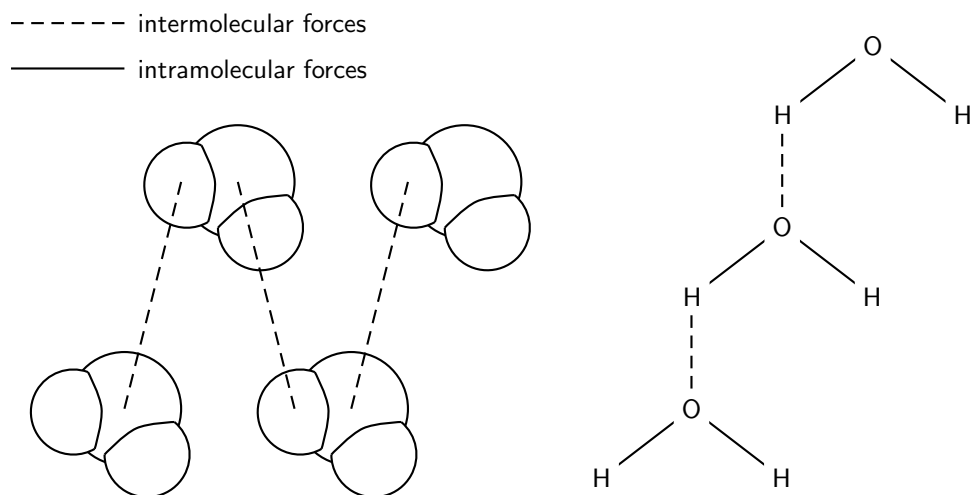


Figure 7.3: Intermolecular and intramolecular forces in water. Note that the diagram on the left only shows *intermolecular* forces. The intramolecular forces are between the atoms of each water molecule.

## 7.5 The unique properties of water

Because of its polar nature and the strong hydrogen bonds between its molecules, water has some special properties that are quite different to those of other substances.

### 1. Absorption of infra-red radiation

The polar nature of the water molecule means that it is able to absorb infra-red radiation (heat) from the sun. As a result of this, the oceans and other water bodies act as heat reservoirs, and are able to help moderate the Earth's climate.

### 2. Specific heat



#### Definition: Specific heat

Specific heat is the amount of heat energy that is needed to increase the temperature of a substance by one degree.

Water has a high specific heat, meaning that a lot of energy must be absorbed by water before its temperature changes.

#### Activity :: Demonstration : The high specific heat of water

- Pour about 100 ml of water into a glass beaker.
- Place the beaker on a stand and heat it over a bunsen burner for about 2 minutes.
- After this time, carefully touch the side of the beaker (Make sure you touch the glass very lightly because it will be very hot and may burn you!). Then use the end of a finger to test the temperature of the water.

What do you notice? Which of the two (glass or water) is the hottest?

---

You have probably observed this phenomenon if you have boiled water in a pot on the stove. The metal of the pot heats up very quickly, and can burn your fingers if you touch it, while the water may take several minutes before its temperature increases even slightly. How can we explain this in terms of hydrogen bonding? Remember that increasing the temperature of a substance means that its particles will move more quickly. However, before they can move faster, the bonds between them must be broken. In the case of water, these bonds are strong hydrogen bonds, and so a lot of energy is needed just to break these, before the particles can start moving faster.

It is the high specific heat of water and its ability to absorb infra-red radiation that allows it to regulate climate. Have you noticed how places that are closer to the sea have less extreme daily temperatures than those that are inland? During the day, the oceans heat up slowly, and so the air moving from the oceans across land is cool. Land temperatures are cooler than they would be if they were further from the sea. At night, the oceans lose the heat that they have absorbed very slowly, and so sea breezes blowing across the land are relatively warm. This means that at night, coastal regions are generally slightly warmer than areas that are further from the sea.

By contrast, places further from the sea experience higher maximum temperatures, and lower minimum temperatures. In other words, their *temperature range* is higher than that for coastal regions. The same principle also applies on a *global* scale. The large amount of water across Earth's surface helps to regulate temperatures by storing infra-red radiation (heat) from the sun, and then releasing it very slowly so that it never becomes too hot or too cold, and life is able to exist comfortably. In a similar way, water also helps to keep the temperature of the *internal* environment of living organisms relatively constant. This is very important. In humans, for example, a change in body temperature of only a few degrees can be deadly.

### 3. Melting point and boiling point

The melting point of water is  $0^{\circ}\text{C}$  and its boiling point is  $100^{\circ}\text{C}$ . This large difference between the melting and boiling point is very important because it means that water can exist as a liquid over a large range of temperatures. The three phases of water are shown in figure 7.4.

### 4. High heat of vaporisation

**Definition: Heat of vaporisation**

Heat of vaporisation is the energy that is needed to change a given quantity of a substance into a gas.

The strength of the hydrogen bonds between water molecules also means that it has a high heat of vaporisation. 'Heat of vaporisation' is the heat energy that is needed to change water from the liquid to the gas phase. Because the bonds between molecules are strong, water has to be heated to  $100^{\circ}\text{C}$  before it changes phase. At this temperature, the molecules have enough energy to break the bonds that hold the molecules together. The heat of vaporisation for water is  $40.65 \text{ kJ/mol}$ . It is very lucky for life on earth that water does have a high heat of vaporisation. Can you imagine what a problem it would be if water's heat of vaporisation was much lower? All the water that makes up the cells in our bodies would evaporate and most of the water on earth would no longer be able to exist as a liquid!

### 5. Less dense solid phase

Another unusual property of water is that its solid phase (ice) is *less dense* than its liquid phase. You can observe this if you put ice into a glass of water. The ice doesn't sink to

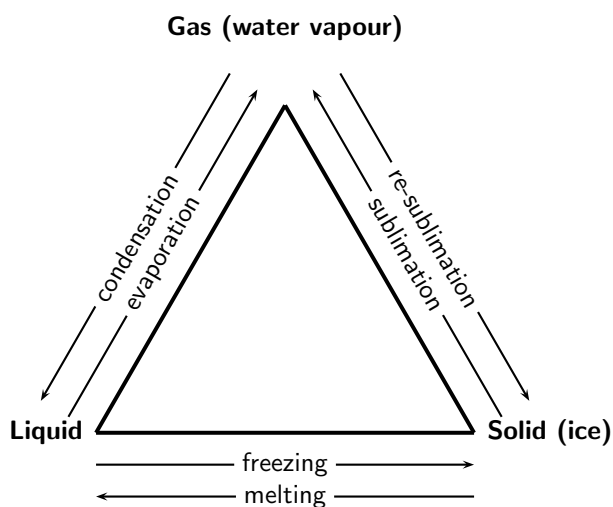


Figure 7.4: Changes in phase of water

the bottom of the glass, but floats on top of the liquid. This phenomenon is also related to the hydrogen bonds between water molecules. While other materials contract when they solidify, water expands. The ability of ice to float as it solidifies is a very important factor in the environment. If ice sank, then eventually all ponds, lakes, and even the oceans would freeze solid as soon as temperatures dropped below freezing, making life as we know it impossible on Earth. During summer, only the upper few inches of the ocean would thaw. Instead, when a deep body of water cools, the floating ice insulates the liquid water below, preventing it from freezing and allowing life to exist under the frozen surface.

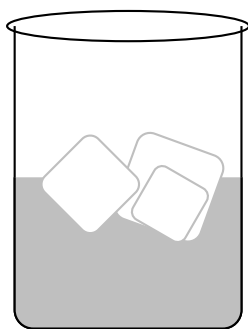
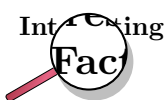


Figure 7.5: Ice cubes floating in water



Antarctica, the 'frozen continent', has one of the world's largest and deepest freshwater lakes. And this lake is hidden beneath 4 kilometres of ice! Lake Vostok is 200 km long and 50 km wide. The thick, glacial blanket of ice acts as an insulator, preventing the water from freezing.

## 6. Water as a solvent

Water is also a very good solvent, meaning that it is easy for other substances to dissolve in it. It is very seldom, in fact, that we find pure water. Most of the time, the water that we drink and use has all kinds of substances dissolved in it. It is these that make water taste different in different areas. So why, then, is it important that water is such a good solvent? We will look at just a few examples.

- Firstly, think about the animals and plants that live in aquatic environments such as rivers, dams or in the sea. All of these living organisms either need oxygen for respiration or carbon dioxide for photosynthesis, or both. How do they get these gases from the water in which they live? Oxygen and carbon dioxide are just two of the substances that dissolve easily in water, and this is how plants and animals obtain the gases that they need to survive. Instead of being available as gases in the atmosphere, they are present in solution in the surrounding water.
- Secondly, consider the fact that all plants need nitrogen to grow, and that they absorb this nitrogen from compounds such as nitrates and nitrites that are present in the soil. The question remains, however, as to how these nitrates and nitrites are able to be present in the soil at all, when most of the Earth's nitrogen is in a gaseous form in the atmosphere. Part of the answer lies in the fact that nitrogen oxides, which are formed during flashes of lightning, can be dissolved in rainwater and transported into the soil in this way, to be absorbed by plants. The other part of the answer lies in the activities of nitrogen-fixing bacteria in the soil, but this is a topic that we will return to in a later section.

It should be clear now, that water is an amazing compound, and that without its unique properties, life on Earth would definitely not be possible.



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#### Exercise: The properties of water

1. A learner returns home from school on a hot afternoon. In order to get cold water to drink, she adds ice cubes to a glass of water. She makes the following observations:
    - The ice cubes float in the water.
    - After a while the water becomes cold and the ice cubes melt.
    - (a) What property of ice cubes allows them to float in the water?
    - (b) Briefly explain why the water gets cold when the ice cubes melt.
    - (c) Briefly describe how the property you mentioned earlier affects the survival of aquatic life during winter.
  2. Which properties of water allow it to remain in its liquid phase over a large temperature range? Explain why this is important for life on earth.
- 

## 7.6 Water conservation

Water is a very precious substance and yet far too often, earth's water resources are abused and taken for granted. How many times have you walked past polluted rivers and streams, or seen the flow of water in a river reduced to almost nothing because of its extraction for industrial and other uses? And if you were able to test the *quality* of the water you see, you would probably be shocked. Often our water resources are contaminated with chemicals such as pesticides and fertilisers. If water is to continue playing all the important functions that were discussed earlier, it is vital that we reduce the impact of humans on these resources.

**Activity :: Group work : Human impacts on the water cycle**

Read the following extract from an article, entitled 'The Effects of Urbanisation on the Water Cycle' by Susan Donaldson, and then answer the questions that follow.

As our communities grow, we notice many visible changes including housing developments, road networks, expansion of services and more. These changes have an impact on our precious water resources, with *pollution* of water being one of many such impacts. To understand these impacts you will need to have a good knowledge of the water cycle!

It is interesting to note that the oceans contain most of earth's water (about 97%). Of the freshwater supplies on earth, 78% is tied up in polar ice caps and snow, leaving only a very small fraction available for use by humans. Of the available fresh water, 98% is present as groundwater, while the remaining 2% is in the form of surface water. Because our usable water supply is so limited, it is vitally important to protect water *quality*. Within the water cycle, there is no 'new' water ever produced on the earth. The water we use today has been in existence for billions of years. The water cycle continually renews and refreshes this finite water supply.

So how exactly does urbanisation affect the water cycle? The increase in hard surfaces (e.g. roads, roofs, parking lots) decreases the amount of water that can soak into the ground. This increases the amount of surface runoff. The runoff water will collect many of the pollutants that have accumulated on these surfaces (e.g. oil from cars) and carry them into other water bodies such as rivers or the ocean. Because there is less infiltration, peak flows of stormwater runoff are larger and arrive earlier, increasing the size of urban floods. If groundwater supplies are reduced enough, this may affect stream flows during dry weather periods because it is the groundwater that seeps to the surface at these times.

Atmospheric pollution can also have an impact because condensing water vapour will pick up these pollutants (e.g. SO<sub>2</sub>, CO<sub>2</sub> and NO<sub>2</sub>) and return them to earth into other water bodies. However, while the effects of urbanisation on water quality can be major, these impacts can be reduced if wise decisions are made during the process of development.

**Questions**

1. In groups, try to explain...
    - (a) what is meant by 'urbanisation'
    - (b) how urbanisation can affect water quality
  2. Explain why it is so important to preserve the quality of our water supplies.
  3. The article gives some examples of human impacts on water quality. In what *other* ways do human activities affect water quality?
  4. What do you think some of the *consequences* of these impacts might be for humans and other forms of life?
  5. Imagine that you are the city manager in your own city or the city closest to you. What changes would you introduce to try to protect the quality of water resources in your urban area?
  6. What measures could be introduced in rural areas to protect water quality?
- 

Apart from the *pollution* of water resources, the *overuse* of water is also a problem. In looking at the water cycle, it is easy sometimes to think that water is a never-ending resource. In a sense this is true because water cannot be destroyed. However, the *availability* of water may vary from place to place. In South Africa for example, many regions are extremely dry and receive very little rainfall. The same is true for many other parts of the world, where the scarcity of water



is a life and death issue. The present threat of **global warming** is also likely to affect water resources. Some climate models suggest that rising temperatures could increase the variability of climate and decrease rainfall in South Africa. With this in mind, and remembering that South Africa is already a dry country, it is vitally important that we manage our water use carefully. In addition to this, the less water there is available, the more likely it is that water *quality* will also decrease. A decrease in water quality limits how water can be used and developed.

At present, the demands being placed on South Africa's water resources are large. Table 7.1 shows the water requirements that were predicted for the year 2000. The figures in the table were taken from South Africa's *National Water Resource Strategy*, produced by the Department of Water Affairs and Forestry in 2004. In the table, 'rural' means water for domestic use and stock watering in rural areas, while 'urban' means water for domestic, industrial and commercial use in the urban area. 'Afforestation' is included because many plantations reduce stream flow because of the large amounts of water they need to survive.

Table 7.1: The predicted water requirements for various water management areas in South Africa for 2000 (million m<sup>3</sup>/annum)

Water management area	Irrigation	Urban	Rural	Mining and bulk industrial	Power generation	Afforestation	Total
Limpopo	238	34	28	14	7	1	322
Thukela	204	52	31	46	1	0	334
Upper Vaal	114	635	43	173	80	0	1045
Upper Orange	780	126	60	2	0	0	968
Breede	577	39	11	0	0	6	633
<b>Country total</b>	<b>7920</b>	<b>2897</b>	<b>574</b>	<b>755</b>	<b>297</b>	<b>428</b>	<b>12871</b>

### Activity :: Case Study : South Africa's water requirements

Refer to table 7.1 and then answer the following questions:

- Which water management area in South Africa has the highest need for water...
  - in the *mining and industry* sector?
  - for *power generation*?
  - in the *irrigation* sector?
  - Suggest reasons for each of your answers above.
- For South Africa as a whole...
  - Which activity uses the *most* water?
  - Which activity uses the *least* water?
- Complete the following table, by calculating the percentage (%) that each activity contributes to the total water requirements in South Africa for the year 2000.

Water use activity	% of SA's total water requirements
Irrigation	
Urban	
Rural	
Mining and bulk industry	
Power generation	
Afforestation	

Table 7.2: The available water yield in South Africa in 2000 for various water management areas (million m<sup>3</sup>/annum)

Water management area	Surface water	Ground	Irrigation	Urban	Mining and bulk industrial	Total local yield
Limpopo	160	98	8	15	0	281
Thukela	666	15	23	24	9	737
Upper Vaal	598	32	11	343	146	1130
Upper Orange	4311	65	34	37	0	4447
Breede	687	109	54	16	0	866
<b>Country total</b>	<b>10240</b>	<b>1088</b>	<b>675</b>	<b>970</b>	<b>254</b>	<b>13227</b>

Now look at table 7.2, which shows the amount of water *available* in South Africa during 2000. In the table, 'usable return flow' means the amount of water that can be reused after it has been used for irrigation, urban or mining.

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### Activity :: Case Study : Water conservation

Refer to table 7.2 and then answer the following questions:

- Explain what is meant by...
    - surface water
    - ground water
  - Which water management area has the...
    - lowest surface water yield?
    - highest surface water yield?
    - lowest *total* yield?
    - highest *total* yield?
  - Look at the country's *total water requirements* for 2000 and the *total available yield*.
    - Calculate what percentage of the country's water yield is already being used up.
    - Do you think that the country's total water requirements will increase or decrease in the coming years? Give a reason for your answer.
  - South Africa is already placing a huge strain on existing water resources. In groups of 3-4, discuss ways that the country's demand for water could be reduced. Present your ideas to the rest of the class for discussion.
- 

## 7.7 Summary

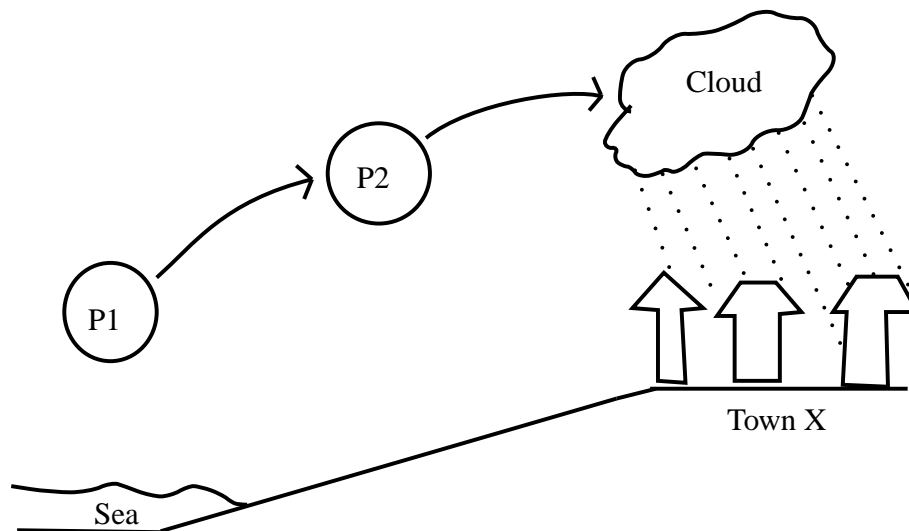
- Water is critical for the survival of life on Earth. It is an important part of the cells of living organisms and is used by humans in homes, industry, mining and agriculture.
- Water moves between the land and sky in the **water cycle**. The water cycle describes the changes in phase that take place in water as it circulates across the Earth. The water cycle is driven by solar radiation.

- Some of the important processes that form part of the water cycle are evaporation, transpiration, condensation, precipitation, infiltration and surface runoff. Together these processes ensure that water is cycled between the land and sky.
- It is the microscopic structure of water that determines its unique properties.
- Water molecules are **polar** and are held together by **hydrogen bonds**. These characteristics affect the properties of water.
- Some of the unique properties of water include its ability to absorb infra-red radiation, its high specific heat, high heat of vaporisation and the fact that the solid phase of water is less dense than its liquid phase.
- These properties of water help it to sustain life on Earth by moderating climate, regulating the internal environment of living organisms and allowing liquid water to exist below ice, even if temperatures are below zero.
- Water is also a good **solvent**. This property means that it is a good transport medium in the cells of living organisms, and that it can dissolve gases and other compounds that may be needed by aquatic plants and animals.
- Human activities threaten the quality of water resources through pollution and altered runoff patterns.
- As human populations grow, there is a greater demand for water. In many areas, this demand exceeds the amount of water available for use. Managing water wisely is important in ensuring that there will always be water available both for human use, and to maintain natural ecosystems.



### Exercise: Summary Exercise

1. Give a word or term for each of the following phrases:
  - (a) The continuous circulation of water across the earth.
  - (b) The change in phase of water from gas to liquid.
  - (c) The movement of water across a land surface.
  - (d) The temperature at which water changes from liquid to gas.
2. In each of the following multiple choice questions, choose the one correct answer from the list provided.
  - (a) Many of the unique properties of water (e.g. its high specific heat and high boiling point) are due to:
    - i. strong covalent bonds between the hydrogen and oxygen atoms in each water molecule
    - ii. the equal distribution of charge in a water molecule
    - iii. strong hydrogen bonds between water molecules
    - iv. the linear arrangement of atoms in a water molecule
  - (b) Which of the following statements is **false**?
    - i. Most of the water on earth is in the oceans.
    - ii. The hardening of surfaces in urban areas results in increased surface runoff.
    - iii. Water conservation is important because water cannot be recycled.
    - iv. Irrigation is one of the largest water users in South Africa.
3. The sketch below shows a process that leads to rainfall in town X. The town has been relying only on rainfall for its water supply because it has no access to rivers or tap water. A group of people told the community that they will never run out of rainwater *because it will never stop raining*.



- (a) List the processes labelled  $P_1$  and  $P_2$  that lead to rainfall in town X.
- (b) Is this group of people correct in saying that town X will never run out of rainwater? Justify your answer using the sketch.  
Recently, the amount of rainwater has decreased significantly. Various reasons have been given to explain the drought. Some of the community members are blaming this group who told them that it will never stop raining.
- (c) What scientific arguments can you use to convince the community members that this group of people should not be blamed for the drought?
- (d) What possible strategies can the community leaders adopt to ensure that they have a regular supply of water.
- \_\_\_\_\_

## Chapter 8

# Global Cycles: The Nitrogen Cycle - Grade 10

### 8.1 Introduction

The earth's atmosphere is made up of about 78% nitrogen, making it the largest pool of this gas. Nitrogen is essential for many biological processes. It is in all amino acids, proteins and nucleic acids. As you will see in a later chapter, these compounds are needed to build tissues, transport substances around the body, and control what happens in living organisms. In plants, much of the nitrogen is used in chlorophyll molecules which are needed for photosynthesis and growth.

So, if nitrogen is so essential for life, how does it go from being a gas in the atmosphere to being part of living organisms such as plants and animals? The problem with nitrogen is that it is an 'inert' gas, which means that it is unavailable to living organisms in its gaseous form. This is because of the strong triple bond between its atoms that makes it difficult to break. Something needs to happen to the nitrogen gas to change it into a form that it can be used. And at some later stage, these new compounds must be converted back into nitrogen gas so that the amount of nitrogen in the atmosphere stays the same. This process of changing nitrogen into different forms is called the **nitrogen cycle** (figure 8.1).



#### **Definition: The nitrogen cycle**

The nitrogen cycle is a biogeochemical cycle that describes how nitrogen and nitrogen-containing compounds are changed in nature.

Very broadly, the nitrogen cycle is made up of the following processes:

- **Nitrogen fixation** - The process of converting inert nitrogen gas into more useable nitrogen compounds such as ammonia.
- **Nitrification** - The conversion of ammonia into nitrites and then into nitrates, which can be absorbed and used by plants.
- **Denitrification** - The conversion of nitrates back into nitrogen gas in the atmosphere.

We are going to look at each of these processes in more detail.

### 8.2 Nitrogen fixation

Nitrogen fixation is needed to change gaseous nitrogen into forms such as ammonia that are more useful to living organisms. Some fixation occurs in lightning strikes and in industrial processes,

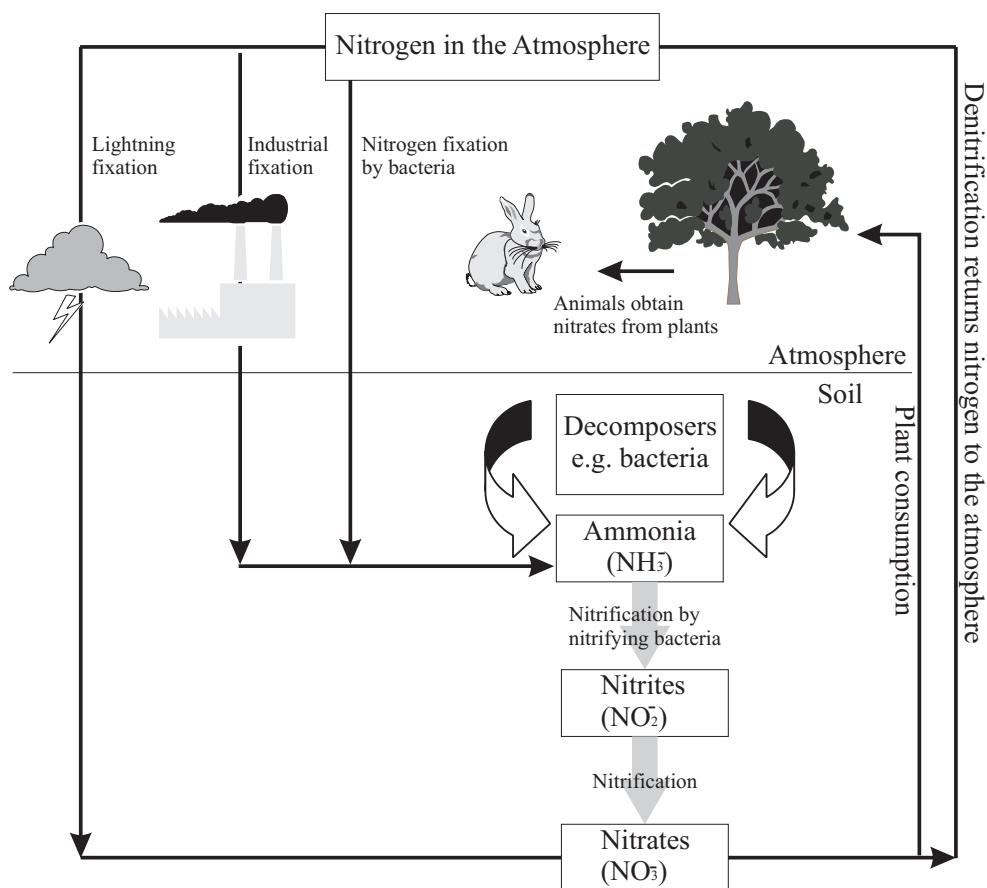


Figure 8.1: A simplified diagram of the nitrogen cycle

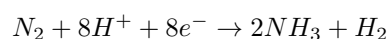
but most fixation is done by different types of bacteria living either in the soil or in parts of the plants.

### 1. Biological fixation

Some bacteria are able to fix nitrogen. They use an enzyme called *nitrogenase* to combine gaseous nitrogen with hydrogen to form ammonia. The bacteria then use some of this ammonia to produce their own organic compounds, while what is left of the ammonia becomes available in the soil.

Some of these bacteria are free-living, in other words they live in the soil. Others live in the root nodules of legumes (e.g. soy, peas and beans). Here they form a mutualistic relationship with the plant. The bacteria get carbohydrates (food) from the plant and, in exchange, produce ammonia which can be converted into nitrogen compounds that are essential for the survival of the plant. In nutrient-poor soils, planting lots of legumes can help to enrich the soil with nitrogen compounds.

A simplified equation for biological nitrogen fixation is:



In this equation the  $8e^-$  means 8 electrons.

Energy is used in the process, but this is not shown in the above equation.

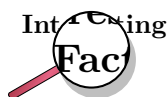
Another important source of ammonia in the soil is **decomposition**. When animals and plants die, the nitrogen compounds that were present in them are broken down and converted into ammonia. This process is carried out by decomposition bacteria and fungi in the soil.

## 2. Industrial nitrogen fixation

In the Haber-Bosch process, nitrogen ( $N_2$ ) is converted together with hydrogen gas ( $H_2$ ) into ammonia ( $NH_3$ ) fertiliser. This is an artificial process.

## 3. Lightning

In the atmosphere, lightning and photons are important in the reaction between nitrogen ( $N_2$ ) and oxygen ( $O_2$ ) to form nitric oxide (NO) and then nitrates.



It is interesting to note that by cultivating legumes, using the Haber-Bosch process to manufacture chemical fertilisers and increasing pollution from vehicles and industry, humans have more than doubled the amount of nitrogen that would normally be changed from nitrogen gas into a biologically useful form. This has serious environmental consequences.

# 8.3 Nitrification

Nitrification involves two biological oxidation reactions: firstly, the oxidation of ammonia with oxygen to form nitrite ( $NO_2^-$ ) and secondly the oxidation of these nitrites into nitrates.

1.  $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$  (production of *nitrites*)
2.  $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$  (production of *nitrates*)

Nitrification is an important step in the nitrogen cycle in soil because it converts the ammonia (from the nitrogen fixing part of the cycle) into nitrates, which are easily absorbed by the roots of plants. This absorption of nitrates by plants is called **assimilation**. Once the nitrates have been assimilated by the plants, they become part of the plants' proteins. These plant proteins are then available to be eaten by animals. In other words, animals (including humans) obtain their own nitrogen by feeding on plants. Nitrification is performed by bacteria in the soil, called *nitrifying bacteria*.

### Activity :: Case Study : Nitrates in drinking water

Read the information below and then carry out your own research to help you answer the questions that follow.

The negatively charged nitrate ion is not held onto soil particles and so can be easily washed out of the soil. This is called **leaching**. In this way, valuable nitrogen can be lost from the soil, reducing the soil's fertility. The nitrates can then accumulate in groundwater, and eventually in drinking water. There are strict regulations that control how much nitrate can be present in drinking water, because nitrates can be reduced to highly reactive nitrites by microorganisms in the gut. Nitrites are absorbed from the gut and bind to haemoglobin (the pigment in blood that helps to transport oxygen around the body). This reduces the ability of the haemoglobin to carry oxygen. In young babies this can lead to respiratory distress, a condition known as "blue baby syndrome".

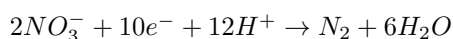
1. How is nitrate concentration in water measured?

2. What concentration of nitrates in drinking water is considered acceptable? You can use drinking water standards for any part of the world, if you can't find any for South Africa.
  3. What is 'blue baby syndrome' and what are the symptoms of the disease?
- 

## 8.4 Denitrification

Denitrification is the process of reducing nitrate and nitrite into gaseous nitrogen. The process is carried out by *denitrification bacteria*. The nitrogen that is produced is returned to the atmosphere to complete the nitrogen cycle.

The equation for the reaction is:



## 8.5 Human Influences on the Nitrogen Cycle

Humans have contributed significantly to the nitrogen cycle in a number of ways.

- Both **artificial fertilisation** and the planting of **nitrogen fixing crops**, increase the amount of nitrogen in the soil. In some ways this has positive effects because it increases the fertility of the soil, and means that agricultural productivity is high. On the other hand, however, if there is too much nitrogen in the soil, it can run off into nearby water courses such as rivers, or can become part of the groundwater supply as we mentioned earlier. Increased nitrogen in rivers and dams can lead to a problem called **eutrophication**. Eutrophication is the contamination of a water system with excess nutrients, which stimulates excessive algae growth at the expense of other parts of the ecosystem. This occurs as eutrophication reduces oxygen levels in the water. Sometimes this can cause certain plant species to be favoured over the others and one species may 'take over' the ecosystem, resulting in a decrease in plant diversity. This is called a 'bloom'. Eutrophication also affects water quality. When the plants die and decompose, large amounts of oxygen are used up and this can cause other animals in the water to die.

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### Activity :: Case Study : Fertiliser use in South Africa

Refer to the data table below, which shows the average fertiliser use (in kilograms per hectare or kg/ha) over a number of years for South Africa and the world. Then answer the questions that follow:

	1965	1970	1975	1980	1985	1990	1995	2000	2002
<b>SA</b>	27.9	42.2	57.7	80.3	66.6	54.9	48.5	47.1	61.4
<b>World</b>	34.0	48.9	63.9	80.6	86.7	90.9	84.9	88.2	91.9

1. On the same set of axes, draw two line graphs to show how fertiliser use has changed in SA and the world between 1965 and 2002.
2. Describe the trend you see for...
  - (a) the world
  - (b) South Africa
3. Suggest a reason why the world's fertiliser use has changed in this way over time.
4. Do you see the same pattern for South Africa?



5. Try to suggest a reason for the differences you see in the fertiliser use data for South Africa.
  6. One of the problems with increased fertiliser use is that there is a greater chance of nutrient runoff into rivers and dams, and therefore a greater danger of eutrophication. In groups of 5-6, discuss the following questions:
    - (a) What could farmers do to try to reduce the risk of nutrient runoff from fields into water systems? Try to think of at least 3 different strategies that they could use.
    - (b) Imagine you are going to give a presentation on eutrophication to a group of farmers who know nothing about it. How will you educate them about the dangers? How will you convince them that it is in their interests to change their farming practices? Present your ideas to the class.
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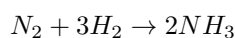
- **Atmospheric pollution** is another problem. The main culprits are nitrous oxide ( $N_2O$ ), nitric oxide (NO) and nitrogen dioxide ( $NO_2$ ). Most of these gases result either from emissions from agricultural soils (and particularly artificial fertilisers), or from the combustion of fossil fuels in industry or motor vehicles. The combustion (burning) of nitrogen-bearing fuels such as coal and oil releases this nitrogen as  $NO_2$  or NO gases. Both  $NO_2$  and NO can combine with water droplets in the atmosphere to form **acid rain**. Furthermore, both NO and  $NO_2$  contribute to the depletion of the ozone layer and some are **greenhouse gases**. In high concentrations these gases can contribute towards **global warming**.

## 8.6 The industrial fixation of nitrogen

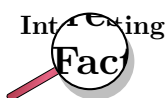
A number of industrial processes are able to fix nitrogen into different compounds and then convert these compounds into fertilisers. In the descriptions below, you will see how atmospheric nitrogen is fixed to produce ammonia, how ammonia is then reacted with oxygen to form nitric acid and how nitric acid and ammonia are then used to produce the fertiliser, ammonium nitrate.

- **Preparation of ammonia ( $NH_3$ )**

The industrial preparation of ammonia is known as the **Haber-Bosch process**. At a high pressure and a temperature of approximately  $500^{\circ}C$ , and in the presence of a suitable catalyst (usually iron), nitrogen and hydrogen react according to the following equation:



Ammonia is used in the preparation of artificial fertilisers such as  $(NH_4)_2SO_4$  and is also used in cleaning agents and cooling installations.



Fritz Haber and Carl Bosch were the two men responsible for developing the Haber-Bosch process. In 1918, Haber was awarded the Nobel Prize in Chemistry for his work. The Haber-Bosch process was a milestone in industrial chemistry because it meant that nitrogenous fertilisers were cheaper and much more easily available. At the time, this was very important in providing food for the growing human population.

Haber also played a major role in the development of chemical warfare in World War I. Part of this work included the development of gas masks with absorbent filters. He also led the teams that developed chlorine gas and other deadly gases for use in trench warfare. His wife, Clara Immerwahr, also a chemist, opposed his work on poison gas and committed suicide with his service weapon in their garden. During the 1920s, scientists working at

his institute also developed the cyanide gas formulation Zyklon B, which was used as an insecticide and also later, after he left the programme, in the Nazi extermination camps.

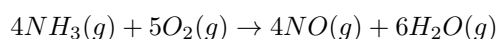
Haber was Jewish by birth, but converted from Judaism in order to be more accepted in Germany. Despite this, he was forced to leave the country in 1933 because he was Jewish 'by definition' (his mother was Jewish). He died in 1934 at the age of 65. Many members of his extended family died in the Nazi concentration camps, possibly gassed by Zyklon B.

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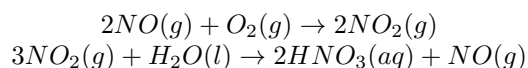
- **Preparation of nitric acid ( $\text{HNO}_3$ )**

Nitric acid is used to prepare fertilisers and explosives. The industrial preparation of nitric acid is known as the **Ostwald process**. The Ostwald process involves the conversion of ammonia into nitric acid in various stages:

Firstly, ammonia is heated with oxygen in the presence of a platinum catalyst to form nitric oxide and water.



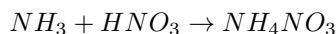
Secondly, nitric oxide reacts with oxygen to form nitrogen dioxide. This gas is then readily absorbed by the water to produce nitric acid. A portion of nitrogen dioxide is reduced back to nitric oxide.



The NO is recycled, and the acid is concentrated to the required strength by a process called *distillation*.

- **Preparation of ammonium nitrate**

Ammonium nitrate is used as a fertiliser, as an explosive and also in the preparation of 'laughing gas' which is used as an anaesthetic. Ammonium nitrate is prepared by reacting ammonia with nitric acid:



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### Activity :: Debate : Fertiliser use

Divide the class into two groups to debate the following topic:

*Increasing the use of artificial fertilisers is the best solution to meet the growing food needs of the world's human population.*

One group should take the position of *agreeing* with the statement, and the other should *disagree*. In your groups, discuss reasons why you have the opinion that you do, and record some notes of your discussion. Your teacher will then explain to you how to proceed with the debate.

---

## 8.7 Summary

- **Nitrogen** is essential for life on earth, since it forms part of **amino acids**, **proteins** and **nucleic acids**.
- The **atmosphere** is composed mostly of nitrogen gas, but the gas is **inert**, meaning that it is not available to living organisms in its gaseous form.
- The **nitrogen cycle** describes how nitrogen and nitrogen-containing compounds are changed into different forms in nature.
- The nitrogen cycle consists of three major processes: **nitrogen fixation**, **nitrification** and **denitrification**.
- **Nitrogen fixation** is the conversion of atmospheric nitrogen into compounds such as ammonia, that are more easily used.
- Nitrogen can be fixed **biologically** through the actions of **bacteria**, **industrially** through the **Haber-Bosch process** or by **lightning**.
- **Nitrification** converts ammonia into **nitrites** and **nitrates**, which can be easily **assimilated** by plants.
- **Denitrification** converts nitrites and nitrates back into gaseous nitrogen to complete the nitrogen cycle.
- **Humans** have had a number of **impacts** on the nitrogen cycle. The production of **artificial fertilisers** for example, means that there is a greater chance of runoff into water systems. In some cases, **eutrophication** may occur.
- **Eutrophication** is the contamination of a water system with excess nutrients, which stimulates excessive algae growth at the expense of other parts of the ecosystem. This occurs as eutrophication reduces oxygen levels in the water.
- Many nitrogen gases such as NO, N<sub>2</sub>O and NO<sub>2</sub> are released by agricultural soils and artificial fertilisers. These gases may combine with water vapour in the atmosphere and result in **acid rain**. Some of these gases are also greenhouse gases and may contribute towards **global warming**.
- A number of **industrial processes** are used to produce **artificial fertilisers**.
- The **Haber-Bosch process** converts atmospheric nitrogen into **ammonia**.
- The **Ostwald process** reacts ammonia with oxygen to produce **nitric acid**, which is used in the preparation of fertilisers and explosives.
- If ammonia and nitric acid react, the product is **ammonium nitrate**, which is used as a fertiliser and as an explosive.

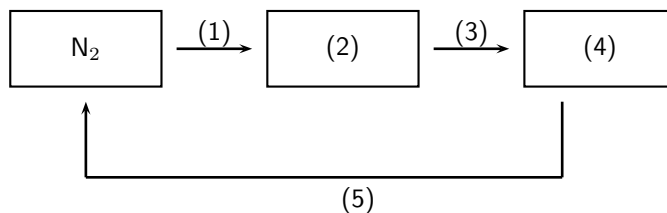


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### Exercise: Summary Exercise

1. Look at the diagram and the descriptions of the nitrogen cycle earlier in the chapter:
  - (a) Would you describe the changes that take place in the nitrogen cycle as *chemical* or *physical* changes? Explain your answer.
  - (b) Are the changes that take place in the water cycle *physical* or *chemical* changes? Explain your answer.
2. Explain what is meant by each of the following terms:
  - (a) nitrogen fixing
  - (b) fertiliser
  - (c) eutrophication

3. Explain why the fixing of atmospheric nitrogen is so important for the survival of life on earth.
4. Refer to the diagram below and then answer the questions that follow:



- (a) Explain the role of *decomposers* in the nitrogen cycle.
  - (b) If the process taking place at (3) is *nitrification*, then label the processes at (1) and (5).
  - (c) Identify the nitrogen products at (2) and (4).
  - (d) On the diagram, indicate the type of *bacteria* that are involved in each stage of the nitrogen cycle.
  - (e) In industry, what process is used to produce the compound at 2?
  - (f) Does the diagram above show a 'cycle'? Explain your answer.
5. NO and NO<sub>2</sub> are both nitrogen compounds:
    - (a) Explain how each of these compounds is formed?
    - (b) What effect does each of these compounds have in the environment?
  6. There are a number of arguments both 'for' and 'against' the use of artificial fertilisers. Draw a table to summarise the advantages and disadvantages of their use.

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## Chapter 9

# The Hydrosphere - Grade 10

### 9.1 Introduction

As far as we know, the Earth we live on is the only planet that is able to support life. Among other things, 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 type of gases in the right amounts for life to survive. Our planet also has **water** on its surface, which is something very 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**.

### 9.2 Interactions of the hydrosphere

It is important to realise that the hydrosphere interacts with other global systems, including the *atmosphere*, *lithosphere* and *biosphere*.

- *Atmosphere*

When water is heated (e.g. by energy from the sun), it evaporates and forms water vapour. When water vapour cools again, it condenses to form liquid water which eventually returns to the surface by precipitation e.g. rain or snow. This cycle of water moving through the atmosphere, and the energy changes that accompany it, is what drives weather patterns on earth.

- *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. This is called *erosion*. These two processes i.e. weathering and erosion, help to shape the earth's surface. You can see this for example 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. 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.

- *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.

## 9.3 Exploring the Hydrosphere

The large amount of water on our planet is something quite unique. In fact, about 71% of the earth is covered by water. Of this, almost 97% is found in the oceans as saltwater, about 2.2% occurs as a solid in ice sheets, while the remaining amount (less than 1%) is available as freshwater. So from a human perspective, despite the vast amount of water on the planet, only a very small amount is actually available for human consumption (e.g. drinking water). Before we go on to look more closely at the chemistry of the hydrosphere, we are going to spend some time exploring a part of the hydrosphere, in order to start appreciating what a complex and beautiful part of the world it is.

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### Activity :: Investigation : Investigating the hydrosphere

#### 1. Choosing a study site:

For this exercise, you can choose any part of the hydrosphere that you would like to explore. This may be a rock pool, a lake, river, wetland or even just a small pond. The guidelines below will apply best to a river investigation, but you can ask similar questions and gather similar data in other areas. When choosing your study site, consider how accessible it is (how easy is it to get to?) and the problems you may experience (e.g. tides, rain).

#### 2. Collecting data:

Your teacher will provide you with the equipment you need to collect the following data. You should have at least one study site where you will collect data, but you might decide to have more if you want to compare your results in different areas. This works best in a river, where you can choose sites down its length.

##### (a) Chemical data

Measure and record data such as temperature, pH, conductivity and dissolved oxygen at each of your sites. You may not know exactly what these measurements mean right now, but it will become clearer later in the chapter.

##### (b) Hydrological data

Measure the water velocity of the river and observe how the volume of water in the river changes as you move down its length. You can also collect a water sample in a clear bottle, hold it to the light and see whether the water is clear or whether it has particles in it.

##### (c) Biological data

What types of animals and plants are found in or near this part of the hydrosphere? Are they specially adapted to their environment?

Record your data in a table like the one shown below:

	Site 1	Site 2	Site 3
Temperature			
pH			
Conductivity			
Dissolved oxygen			
Animals and plants			

#### 3. Interpreting the data:

Once you have collected and recorded your data, think about the following questions:

- How does the data you have collected vary at different sites?
- Can you explain these differences?
- What effect do you think *temperature*, *dissolved oxygen* and *pH* have on animals and plants that are living in the hydrosphere?

- Water is seldom 'pure'. It usually has lots of things dissolved (e.g. Mg, Ca and  $\text{NO}_3^-$  ions) or suspended (e.g. soil particles, debris) in it. Where do these substances come from?
  - Are there any human activities near this part of the hydrosphere? What effect could these activities have on the hydrosphere?
- 

## 9.4 The Importance of the Hydrosphere

It is so easy sometimes to take our hydrosphere for granted, and we seldom take the time to really think about the role that this part of the planet plays in keeping us alive. Below are just some of the very important functions of water in the hydrosphere:

- *Water is a part of living cells*

Each cell in a living organism is made up of almost 75% water, and this allows the cell to function normally. In fact, most of the chemical reactions that occur in life, involve substances that are dissolved in water. Without water, cells would not be able to carry out their normal functions, and life could not exist.

- *Water provides a habitat*

The hydrosphere provides an important place for many animals and plants to live. Many gases (e.g.  $\text{CO}_2$ ,  $\text{O}_2$ ), nutrients e.g. nitrate ( $\text{NO}_3^-$ ), nitrite ( $\text{NO}_2^-$ ) and ammonium ( $\text{NH}_4^+$ ) ions, as well as other ions (e.g.  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ ) are dissolved in water. The presence of these substances is critical for life to exist in water.

- *Regulating climate*

One of water's unique characteristics is its high *specific heat*. This means that water takes a long time to heat up, and also a long time to cool down. This is important in helping to regulate temperatures on earth so that they stay within a range that is acceptable for life to exist. *Ocean currents* also help to disperse heat.

- *Human needs*

Humans use water in a number of ways. Drinking water is obviously very important, but water is also used domestically (e.g. washing and cleaning) and in industry. Water can also be used to generate electricity through hydropower.

These are just a few of the very important functions that water plays on our planet. Many of the functions of water relate to its chemistry and to the way in which it is able to dissolve substances in it.

## 9.5 Ions in aqueous solution

As we mentioned earlier, water is seldom pure. Because of the structure of the water molecule, it is able to dissolve substances in it. This is very important because if water wasn't able to do this, life would not be able to survive. In rivers and the oceans for example, dissolved oxygen means that organisms (such as fish) are still able to respire (breathe). For plants, dissolved nutrients are also available. In the human body, water is able to carry dissolved substances from one part of the body to another.

Many of the substances that dissolve are *ionic*, and when they dissolve they form ions in solution. We are going to look at how water is able to dissolve ionic compounds, and how these ions maintain a balance in the human body, how they affect water hardness, and how specific ions determine the pH of solutions.

### 9.5.1 Dissociation in water

Water is a **polar molecule** (figure 9.1). This means that one part of the molecule has a slightly positive charge and the other part has a slightly negative charge.

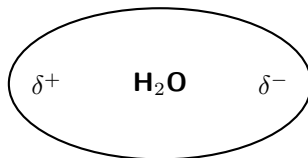


Figure 9.1: Water is a polar molecule

It is the polar nature of water that allows ionic compounds to dissolve in it. In the case of sodium chloride (NaCl) for example, the positive sodium ions ( $\text{Na}^+$ ) will be attracted to the negative pole of the water molecule, while the negative chloride ions ( $\text{Cl}^-$ ) will be attracted to the positive pole of the water molecule. In the process, the ionic bonds between the sodium and chloride ions are weakened and the water molecules are able to work their way between the individual ions, surrounding them and slowly dissolving the compound. This process is called **dissociation**. A simplified representation of this is shown in figure 9.2.



**Definition: Dissociation**

Dissociation in chemistry and biochemistry is a general process in which ionic compounds separate or split into smaller molecules or ions, usually in a reversible manner.

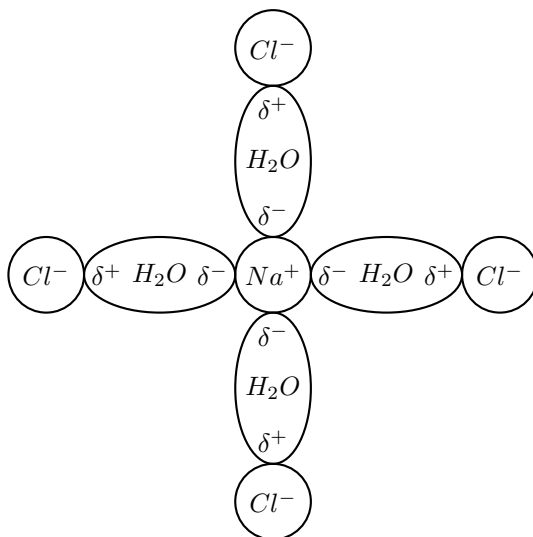
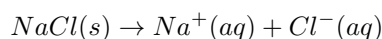


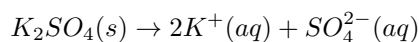
Figure 9.2: Sodium chloride dissolves in water

The dissolution of sodium chloride can be represented by the following equation:

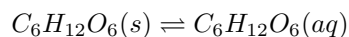


The symbols **s** (solid), **l** (liquid), **g** (gas) and **aq** (material is dissolved in water) are written after the chemical formula to show the state or phase of the material. The dissolution of potassium sulfate into potassium and sulfate ions is shown below as another example:

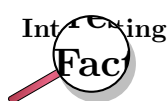
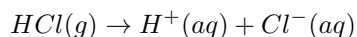




Remember that **molecular** substances (e.g. covalent compounds) may also dissolve, but most will not form ions. One example is sugar.



There are exceptions to this and some molecular substances *will* form ions when they dissolve. Hydrogen chloride for example can ionise to form hydrogen and chloride ions.



The ability of ionic compounds to dissolve in water is extremely important in the human body! The body is made up of *cells*, each of which is surrounded by a *membrane*. Dissolved ions are found inside and outside of body cells, in different concentrations. Some of these ions are positive (e.g.  $Mg^{2+}$ ) and some are negative (e.g.  $Cl^-$ ). If there is a difference in the charge that is inside and outside the cell, then there is a *potential difference* across the cell membrane. This is called the **membrane potential** of the cell. The membrane potential acts like a battery and affects the movement of all charged substances across the membrane. Membrane potentials play a role in muscle functioning, digestion, excretion and in maintaining blood pH, to name just a few. The movement of ions across the membrane can also be converted into an electric signal that can be transferred along *neurons* (nerve cells), which control body processes. If ionic substances were not able to dissociate in water, then none of these processes would be possible! It is also important to realise that our bodies can *lose* ions such as  $Na^+$ ,  $K^+$ ,  $Ca^{2+}$ ,  $Mg^{2+}$ , and  $Cl^-$ , for example when we sweat during exercise. Sports drinks such as Lucozade and Powerade are designed to replace these lost ions so that the body's normal functioning is not affected.



#### Exercise: Ions in solution

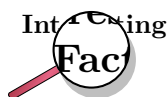
- For each of the following, say whether the substance is ionic or molecular.
  - potassium nitrate ( $KNO_3$ )
  - ethanol ( $C_2H_5OH$ )
  - sucrose (a type of sugar) ( $C_{12}H_{22}O_{11}$ )
  - sodium bromide ( $NaBr$ )
- Write a balanced equation to show how each of the following ionic compounds dissociate in water.
  - sodium sulphate ( $Na_2SO_4$ )
  - potassium bromide ( $KBr$ )
  - potassium permanganate ( $KMnO_4$ )
  - sodium phosphate ( $Na_3PO_4$ )

### 9.5.2 Ions and water hardness


**Definition: Water hardness**

Water hardness is a measure of the mineral content of water. Minerals are substances such as calcite, quartz and mica that occur naturally as a result of geological processes.

**Hard water** is water that has a high mineral content. Water that has a low mineral content is known as **soft water**. If water has a high mineral content, it usually contains high levels of metal ions, mainly calcium (Ca) and magnesium (Mg). The calcium enters the water from either  $\text{CaCO}_3$  (limestone or chalk) or from mineral deposits of  $\text{CaSO}_4$ . The main source of magnesium is a sedimentary rock called dolomite,  $\text{CaMg}(\text{CO}_3)_2$ . Hard water may also contain other metals as well as bicarbonates and sulphates.



The simplest way to check whether water is hard or soft is to use the lather/froth test. If the water is very soft, soap will lather more easily when it is rubbed against the skin. With hard water this won't happen. Toothpaste will also not froth well in hard water.

A **water softener** works on the principle of **ion exchange**. Hard water passes through a media bed, usually made of resin beads that are supersaturated with sodium. As the water passes through the beads, the hardness minerals (e.g. calcium and magnesium) attach themselves to the beads. The sodium that was originally on the beads is released into the water. When the resin becomes saturated with calcium and magnesium, it must be recharged. A salt solution is passed through the resin. The sodium replaces the calcium and magnesium, and these ions are released into the waste water and discharged.

### 9.5.3 The pH scale

The concentration of specific ions in solution, affects whether the solution is acidic or basic. You will learn about acids and bases in Grade 11. Acids and bases can be described as substances that either increase or decrease the concentration of hydrogen ( $\text{H}^+$  or  $\text{H}_3\text{O}^+$ ) ions in a solution. An acid *increases* the hydrogen ion concentration in a solution, while a base *decreases* the hydrogen ion concentration. **pH** is used to measure whether a substance is acidic or basic (alkaline).


**Definition: pH**

pH is a measure of the acidity or alkalinity of a solution. The pH scale ranges from 0 to 14. Solutions with a pH less than seven are acidic, while those with a pH greater than seven are basic (alkaline). pH 7 is considered neutral.

pH can be calculated using the following equation:

$$\text{pH} = -\log[\text{H}^+]$$

or

$$\text{pH} = -\log[\text{H}_3\text{O}^+]$$

The brackets in the above equation are used to show *concentration* in  $\text{mol.dm}^{-3}$ .

**Worked Example 15: pH calculations**

**Question:** Calculate the pH of a solution where the concentration of hydrogen ions is  $1 \times 10^{-7} \text{ mol.dm}^{-3}$ .

**Answer****Step 1 : Determine the concentration of hydrogen ions in  $\text{mol.dm}^{-3}$** 

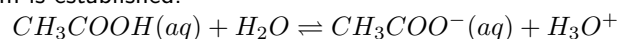
In this example, the concentration has been given and is  $1 \times 10^{-7} \text{ mol.dm}^{-3}$

**Step 2 : Substitute this value into the pH equation and calculate the pH value**

$$\begin{aligned}\text{pH} &= -\log[\text{H}^+] \\ &= -\log(1 \times 10^{-7}) \\ &= 7\end{aligned}$$

**Worked Example 16: pH calculations**

**Question:** In a solution of ethanoic acid (or acetic acid), the following equilibrium is established:



The concentration of  $\text{CH}_3\text{COO}^-$  ions is found to be  $0.003 \text{ mol.dm}^{-3}$ . Calculate the pH of the solution.

**Answer****Step 1 : Determine the concentration of hydrogen ions in the solution**

According to the balanced equation for this reaction, the mole ratio of  $\text{CH}_3\text{COO}^-$  ions to  $\text{H}_3\text{O}^+$  ions is the same, therefore the concentration of these two ions in the solution will also be the same. So,  $[\text{H}_3\text{O}^+] = 0.003 \text{ dm}^{-3}$ .

**Step 2 : Substitute this value into the pH equation and calculate the pH value**

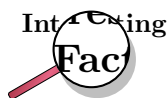
$$\begin{aligned}\text{pH} &= -\log[\text{H}_3\text{O}^+] \\ &= -\log(0.003) \\ &= 2.52\end{aligned}$$

Understanding pH is very important. In living organisms, it is necessary to maintain a constant pH so that chemical reactions can occur under optimal conditions.



**Important:** It may also be useful for calculations involving the pH scale, to know that the following equation can also be used:

$$[\text{H}_3\text{O}^+][\text{OH}^-] = 1 \times 10^{-14}$$



A build up of acid in the human body can be very dangerous. **Lactic acidosis** is a condition caused by the buildup of lactic acid in the body. It leads to acidification of the blood (acidosis) and can make a person very ill. Some of the symptoms of lactic acidosis are deep and rapid breathing, vomiting, and abdominal pain. In the fight against HIV, lactic acidosis is a problem. One of the antiretrovirals (ARV's) that is used in anti-HIV treatment is Stavudine (also known as Zerit or d4T). One of the side effects of Stavudine is lactic acidosis, particularly in overweight women. If it is not treated quickly, it can result in death.

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In agriculture, farmers need to know the pH of their soils so that they are able to plant the right kinds of crops. The pH of soils can vary depending on a number of factors such as rainwater, the kinds of rocks and materials from which the soil was formed and also human influences such as pollution and fertilisers. The pH of rain water can also vary and this too has an effect on agriculture, buildings, water courses, animals and plants. Rainwater is naturally acidic because carbon dioxide in the atmosphere combines with water to form carbonic acid. Unpolluted rainwater has a pH of approximately 5.6. However, human activities can alter the acidity of rain and this can cause serious problems such as acid rain.



### Exercise: Calculating pH

- Calculate the pH of each of the following solutions:
    - A  $0.2 \text{ mol.dm}^{-3}$  KOH solution
    - A  $0.5 \text{ mol.dm}^{-3}$  HCl solution
  - What is the concentration (in  $\text{mol.dm}^{-3}$ ) of  $\text{H}_3\text{O}^+$  ions in a NaOH solution which has a pH of 12?
  - The concentrations of hydronium ( $\text{H}_3\text{O}^+$ ) and hydroxyl ( $\text{OH}^-$ ) ions in a typical sample of seawater are  $10^{-8} \text{ mol.dm}^{-3}$  and  $10^{-6} \text{ mol.dm}^{-3}$  respectively.
    - Is the seawater acidic or basic?
    - What is the pH of the seawater?
    - Give a possible explanation for the pH of the seawater.
- (IEB Paper 2, 2002)

### 9.5.4 Acid rain

The acidity of rainwater comes from the natural presence of three substances ( $\text{CO}_2$ , NO, and  $\text{SO}_2$ ) in the lowest layer of the atmosphere. These gases are able to dissolve in water and therefore make rain more acidic than it would otherwise be. Of these gases, carbon dioxide ( $\text{CO}_2$ ) has the highest concentration and therefore contributes the most to the natural acidity of rainwater. We will look at each of these gases in turn.

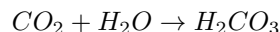


#### Definition: Acid rain

Acid rain refers to the deposition of acidic components in rain, snow and dew. Acid rain occurs when sulfur dioxide and nitrogen oxides are emitted into the atmosphere, undergo chemical transformations, and are absorbed by water droplets in clouds. The droplets then fall to earth as rain, snow, mist, dry dust, hail, or sleet. This increases the acidity of the soil, and affects the chemical balance of lakes and streams.

### 1. Carbon dioxide

Carbon dioxide reacts with water in the atmosphere to form **carbonic acid** ( $\text{H}_2\text{CO}_3$ ).

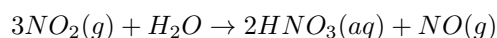


The carbonic acid dissociates to form hydrogen and hydrogen carbonate ions. It is the presence of hydrogen ions that lowers the pH of the solution, making the rain acidic.

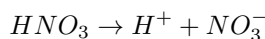


### 2. Nitric oxide

Nitric oxide (NO) also contributes to the natural acidity of rainwater and is formed during lightning storms when nitrogen and oxygen react. In air, NO is oxidised to form nitrogen dioxide ( $\text{NO}_2$ ). It is the nitrogen dioxide which then reacts with water in the atmosphere to form **nitric acid** ( $\text{HNO}_3$ ).

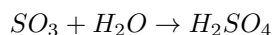
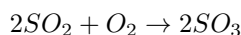


The nitric acid dissociates in water to produce hydrogen ions and nitrate ions. This again lowers the pH of the solution, making it acidic.



### 3. Sulfur dioxide

Sulfur dioxide in the atmosphere first reacts with oxygen to form sulfur trioxide, before reacting with water to form **sulfuric acid**.



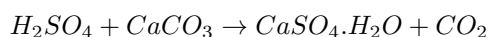
Sulfuric acid dissociates in a similar way to the previous reactions.



Although these reactions do take place naturally, human activities can greatly increase the concentration of these gases in the atmosphere, so that rain becomes far more acidic than it would otherwise be. The burning of fossil fuels in industries, vehicles etc is one of the biggest culprits. If the acidity of the rain drops below 5, it is referred to as **acid rain**.

Acid rain can have a very damaging effect on the environment. In rivers, dams and lakes, increased acidity can mean that some species of animals and plants will not survive. Acid rain can also degrade soil minerals, producing metal ions that are washed into water systems. Some of these ions may be toxic e.g.  $\text{Al}^{3+}$ . From an economic perspective, altered soil pH can drastically affect agricultural productivity.

Acid rain can also affect buildings and monuments, many of which are made from marble and limestone. A chemical reaction takes place between  $\text{CaCO}_3$  (limestone) and sulfuric acid to produce aqueous ions which can be easily washed away. The same reaction can occur in the lithosphere where limestone rocks are present e.g. limestone caves can be eroded by acidic rainwater.



**Activity :: Investigation : Acid rain**

You are going to test the effect of 'acid rain' on a number of substances.

*Materials needed:*

samples of chalk, marble, zinc, iron, lead, dilute sulfuric acid, test tubes, beaker, glass dropper

*Method:*

1. Place a small sample of each of the following substances in a separate test tube: chalk, marble, zinc, iron and lead
2. To each test tube, add a few drops of dilute sulfuric acid.
3. Observe what happens and record your results.

*Discussion questions:*

- In which of the test tubes did reactions take place? What happened to the sample substances?
  - What do your results tell you about the effect that acid rain could have on each of the following: buildings, soils, rocks and geology, water ecosystems?
  - What precautions could be taken to reduce the potential impact of acid rain?
- 

## 9.6 Electrolytes, ionisation and conductivity

**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.



**Definition: Conductivity**

Conductivity is a measure of a solution's ability to conduct an electric current.

### 9.6.1 Electrolytes

An **electrolyte** is a material that *increases* the conductivity of water when dissolved in it. Electrolytes can be further divided into **strong electrolytes** and **weak electrolytes**.



**Definition: Electrolyte**

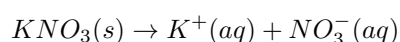
An electrolyte is a substance that contains free ions and behaves as an electrically conductive medium. Because they generally consist of ions in solution, electrolytes are also known as ionic solutions.

#### 1. Strong electrolytes

A strong electrolyte is a material that ionises completely when it is dissolved in water:

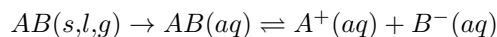


This is a **chemical change** because the original compound has been split into its component ions and bonds have been broken. In a strong electrolyte, we say that the *extent of ionisation* is high. In other words, the original material dissociates completely so that there is a high concentration of ions in the solution. An example is a solution of potassium nitrate:

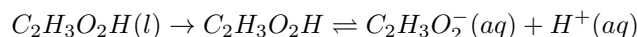


## 2. Weak electrolytes

A weak electrolyte is a material that goes into solution and will be surrounded by water molecules when it is added to water. However, not *all* of the molecules will dissociate into ions. The *extent of ionisation* of a weak electrolyte is low and therefore the concentration of ions in the solution is also low.

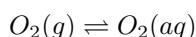
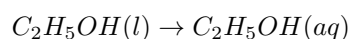


The following example shows that, in the final solution of a weak electrolyte, some of the original compound *plus* some dissolved ions are present.



### 9.6.2 Non-electrolytes

A **non-electrolyte** is a material that does not increase the conductivity of water when dissolved in it. The substance goes into solution and becomes surrounded by water molecules, so that the molecules of the chemical become separated from each other. However, although the substance does dissolve, it is not changed in any way and no chemical bonds are broken. The change is a **physical change**. In the oxygen example below, the reaction is shown to be reversible because oxygen is only partially soluble in water and comes out of solution very easily.



### 9.6.3 Factors that affect the conductivity of water

The conductivity of water is therefore affected by the following factors:

- The **type of substance** that dissolves in water

Whether a material is a strong electrolyte (e.g. potassium nitrate,  $KNO_3$ ), a weak electrolyte (e.g. acetate,  $C_2H_3O_2H$ ) or a non-electrolyte (e.g. sugar, alcohol, oil) will affect the conductivity of water because the concentration of ions in solution will be different in each case.

- The **concentration of ions** in solution

The higher the concentration of ions in solution, the higher its conductivity will be.

- **Temperature**

The warmer the solution the higher the solubility of the material being dissolved, and therefore the higher the conductivity as well.

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#### Activity :: Experiment : Electrical conductivity

##### Aim:

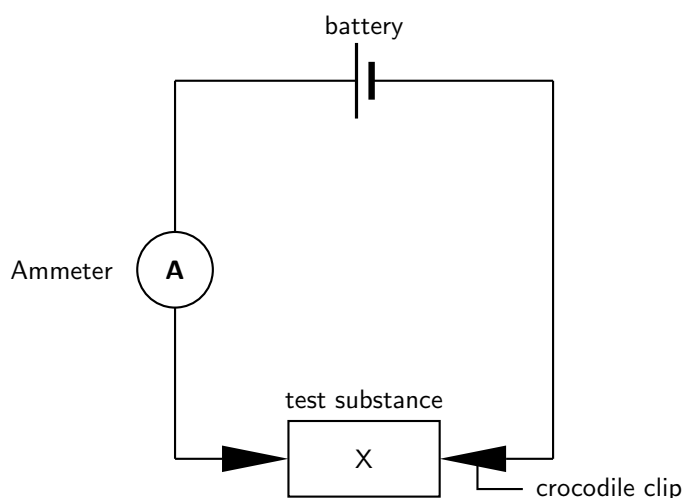
To investigate the electrical conductivities of different substances and solutions.

##### Apparatus:

solid salt (NaCl) crystals; different liquids such as distilled water, tap water, seawater, benzene and alcohol; solutions of salts e.g. NaCl, KBr; a solution of an acid (e.g. HCl) and a solution of a base (e.g. NaOH); torch cells; ammeter; conducting wire, crocodile clips and 2 carbon rods.

**Method:**

Set up the experiment by connecting the circuit as shown in the diagram below. In the diagram, 'X' represents the substance or solution that you will be testing. When you are using the solid crystals, the crocodile clips can be attached directly to each end of the crystal. When you are using solutions, two carbon rods are placed into the liquid, and the clips are attached to each of the rods. In each case, complete the circuit and allow the current to flow for about 30 seconds. Observe whether the ammeter shows a reading.

**Results:**

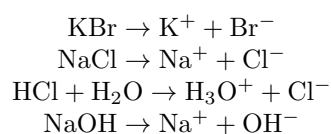
Record your observations in a table similar to the one below:

Test substance	Ammeter reading

What do you notice? Can you explain these observations?

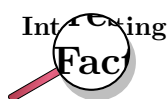
Remember that for electricity to flow, there needs to be a movement of charged particles e.g. ions. With the solid NaCl crystals, there was no flow of electricity recorded on the ammeter. Although the solid is made up of ions, they are held together very tightly within the crystal lattice, and therefore no current will flow. Distilled water, benzene and alcohol also don't conduct a current because they are *covalent compounds* and therefore do not contain ions.

The ammeter should have recorded a current when the salt solutions and the acid and base solutions were connected in the circuit. In solution, salts *dissociate* into their ions, so that these are free to move in the solution. Acids and bases behave in a similar way, and dissociate to form hydronium and oxonium ions. Look at the following examples:

**Conclusions:**

Solutions that contain free-moving ions are able to conduct electricity because of the movement of charged particles. Solutions that do not contain free-moving ions do not conduct electricity.





Conductivity in streams and rivers is affected by the geology of the area where the water is flowing through. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is made of materials that do not ionise when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity because the materials ionise when they are washed into the water. Pollution can also affect conductivity. A failing sewage system or an inflow of fertiliser runoff would raise the conductivity because of the presence of chloride, phosphate, and nitrate (ions) while an oil spill (non-ionic) would lower the conductivity. It is very important that conductivity is kept within a certain acceptable range so that the organisms living in these water systems are able to survive.

## 9.7 Precipitation reactions

Sometimes, ions in solution may react with each other to form a new substance that is *insoluble*. This is called a **precipitate**.



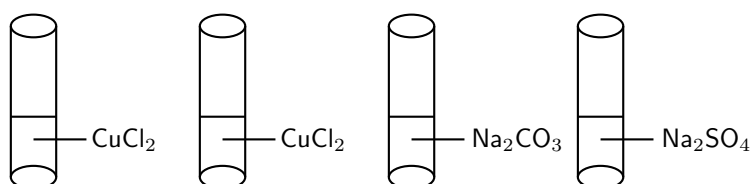
### Definition: Precipitate

A precipitate is the solid that forms in a solution during a chemical reaction.

### Activity :: Demonstration : The reaction of ions in solution

#### Apparatus and materials:

4 test tubes; copper(II) chloride solution; sodium carbonate solution; sodium sulphate solution



#### Method:

1. Prepare 2 test tubes with approximately 5 ml of dilute  $\text{Cu(II)}$ chloride solution in each
2. Prepare 1 test tube with 5 ml sodium carbonate solution
3. Prepare 1 test tube with 5 ml sodium sulphate solution
4. Carefully pour the sodium carbonate solution into one of the test tubes containing copper(II) chloride and observe what happens
5. Carefully pour the sodium sulphate solution into the second test tube containing copper(II) chloride and observe what happens

#### Results:

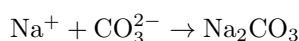
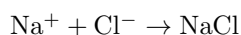
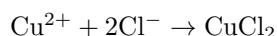
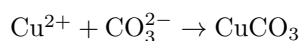
1. A light blue precipitate forms when sodium carbonate reacts with copper(II) chloride
  2. No precipitate forms when sodium sulphate reacts with copper(II) chloride
- 

It is important to understand what happened in the previous demonstration. We will look at what happens in each reaction, step by step.

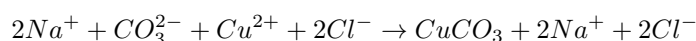
1. **Reaction 1:** Sodium carbonate reacts with copper(II) chloride

When these compounds react, a number of ions are present in solution:  $Cu^{2+}$ ,  $Cl^{-}$ ,  $Na^{+}$  and  $CO_3^{2-}$ .

Because there are lots of ions in solution, they will collide with each other and may recombine in different ways. The product that forms may be insoluble, in which case a precipitate will form, or the product will be soluble, in which case the ions will go back into solution. Let's see how the ions in this example could have combined with each other:



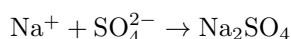
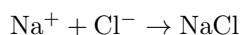
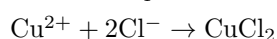
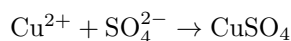
You can automatically exclude the reactions where sodium carbonate and copper(II) chloride are the products because these were the initial reactants. You also know that sodium chloride (NaCl) is soluble in water, so the remaining product (copper carbonate) must be the one that is insoluble. It is also possible to look up which salts are soluble and which are insoluble. If you do this, you will find that most carbonates are insoluble, therefore the precipitate that forms in this reaction must be  $CuCO_3$ . The reaction that has taken place between the ions in solution is as follows:



2. **Reaction 2:** Sodium sulphate reacts with copper(II) chloride

The ions that are present in solution are  $Cu^{2+}$ ,  $Cl^{-}$ ,  $Na^{+}$  and  $SO_4^{2-}$ .

The ions collide with each other and may recombine in different ways. The possible combinations of the ions are as follows:



If we look up which of these salts are soluble and which are insoluble, we see that most chlorides and most sulphates are soluble. This is why no precipitate forms in this second reaction. Even when the ions recombine, they immediately separate and go back into solution. The reaction that has taken place between the ions in solution is as follows:

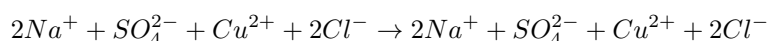


Table 9.1 shows some of the general rules about the solubility of different salts based on a number of investigations:

Table 9.1: General rules for the solubility of salts

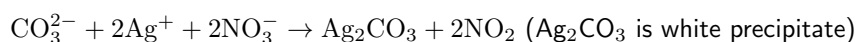
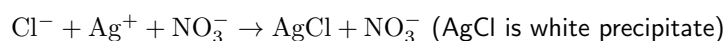
Salt	Solubility
Nitrates	All are soluble
Potassium, sodium and ammonium salts	All are soluble
Chlorides	All are soluble except silver chloride, lead(II)chloride and mercury(II)chloride
Sulphates	All are soluble except lead(II)sulphate, barium sulphate and calcium sulphate
Carbonates	All are insoluble except those of potassium, sodium and ammonium

## 9.8 Testing for common anions in solution

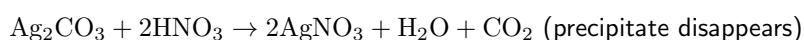
It is also possible to carry out tests to determine which ions are present in a solution.

### 9.8.1 Test for a chloride

Prepare a solution of the unknown salt using distilled water and add a small amount of **silver nitrate** solution. If a white precipitate forms, the salt is either a chloride or a carbonate.

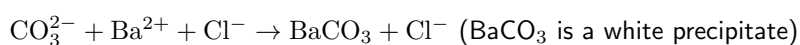
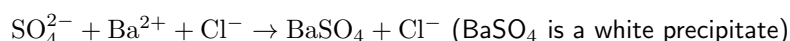


The next step is to treat the precipitate with a small amount of **concentrated nitric acid**. If the precipitate remains unchanged, then the salt is a chloride. If carbon dioxide is formed, and the precipitate disappears, the salt is a carbonate.

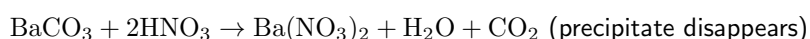
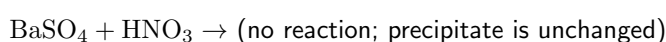


### 9.8.2 Test for a sulphate

Add a small amount of barium chloride solution to a solution of the test salt. If a white precipitate forms, the salt is either a sulphate or a carbonate.

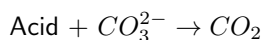


If the precipitate is treated with nitric acid, it is possible to distinguish whether the salt is a sulphate or a carbonate (as in the test for a chloride).

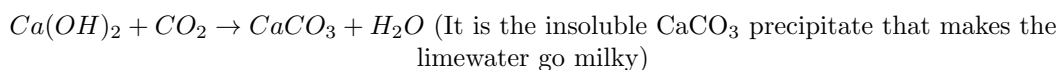


### 9.8.3 Test for a carbonate

If a sample of the dry salt is treated with a small amount of acid, the production of carbon dioxide is a positive test for a carbonate.



If the gas is passed through limewater and the solution becomes milky, the gas is carbon dioxide.



### 9.8.4 Test for bromides and iodides

As was the case with the chlorides, the bromides and iodides also form precipitates when they are reacted with silver nitrate. Silver chloride is a white precipitate, but the silver bromide and silver iodide precipitates are both pale yellow. To determine whether the precipitate is a bromide or an iodide, we use chlorine water and carbon tetrachloride ( $\text{CCl}_4$ ).

Chlorine water frees bromine gas from the bromide, and colours the carbon tetrachloride a red-dish brown.

Chlorine water frees iodine gas from an iodide, and colours the carbon tetrachloride is coloured purple.



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#### Exercise: Precipitation reactions and ions in solution

1. Silver nitrate ( $\text{AgNO}_3$ ) reacts with potassium chloride ( $\text{KCl}$ ) and a white precipitate is formed.
    - (a) Write a balanced equation for the reaction that takes place.
    - (b) What is the name of the insoluble salt that forms?
    - (c) Which of the salts in this reaction are soluble?
  2. Barium chloride reacts with sulfuric acid to produce barium sulphate and hydrochloric acid.
    - (a) Write a balanced equation for the reaction that takes place.
    - (b) Does a precipitate form during the reaction?
    - (c) Describe a test that could be used to test for the presence of barium sulphate in the products.
  3. A test tube contains a clear, colourless salt solution. A few drops of silver nitrate solution are added to the solution and a pale yellow precipitate forms. Which one of the following salts was dissolved in the original solution?
    - (a)  $\text{NaI}$
    - (b)  $\text{KCl}$
    - (c)  $\text{K}_2\text{CO}_3$
    - (d)  $\text{Na}_2\text{SO}_4$
- (IEB Paper 2, 2005)
-

## 9.9 Threats to the Hydrosphere

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 a number of factors that threaten our hydrosphere, and most of these threats are because of human activities. We are going to focus on two of these issues: **overuse** and **pollution** and look at ways in which these problems can possibly be overcome.

### 1. Overuse of water

We mentioned earlier that only a very small percentage of the hydrosphere's water is available as freshwater. However, despite this, 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 such as 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, but also because of the increasing needs of industries as they expand and develop. For each of us, this should be a very scary thought. Try to imagine a day without water...difficult isn't it? Water is so much a part of our lives, that we are hardly aware of the huge part that it plays in our daily lives.

---

#### Activity :: Discussion : Creative water conservation

As populations grow, so do the demands that are placed on dwindling water resources. While many people argue that building dams helps to solve this water-shortage problem, the reality is that dams are only a temporary solution, and that they often end up doing far more ecological damage than good. The only sustainable solution is to reduce the *demand* for water, so that water supplies are sufficient to meet this. The more important question then is how to do this.

#### Discussion:

Divide the class into groups, so that there are about five people in each. Each group is going to represent a different sector within society. Your teacher will tell you which sector you belong to from the following: Farming, industry, city management or civil society (i.e. you will represent the ordinary 'man on the street'). In your groups, discuss the following questions as they relate to the group of people you represent: (Remember to take notes during your discussions, and nominate a spokesperson to give feedback to the rest of the class on behalf of your group)

- What steps could be taken by your group to conserve water?
  - Why do you think these steps are *not* being taken?
  - What incentives do you think could be introduced to encourage this group to conserve water more efficiently?
- 

### 2. Pollution

Pollution of the hydrosphere is also a major problem. When we think of 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 hydrosphere 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, *nutrient pollution* e.g. fertiliser runoff which causes eutrophication (this was discussed in chapter ref 7) and toxic trace elements such as aluminium, mercury and copper to name a few. Most of these elements come from mines or from industries.

It is important to realise that our hydrosphere exists in a delicate balance with other systems, and that disturbing this balance can have serious consequences for life on this planet.

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**Activity :: Group Project : School Action Project**

There is a lot that can be done within a school to save water. As a class, discuss what actions could be taken by your class to make people more aware of how important it is to conserve water.

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## 9.10 Summary

- The **hydrosphere** includes all the water that is on Earth. Sources of water include fresh-water (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 use.
- The **polar** nature of water means that **ionic compounds** dissociate easily in aqueous solution into their component ions.
- **Ions** in solution play a number of roles. In the human body for example, ions help to regulate the internal environment (e.g. controlling muscle function, regulating blood pH). Ions in solution also determine water hardness and pH.
- **Water hardness** is a measure of the mineral content of water. Hard water has a high mineral concentration and generally also a high concentration of metal ions e.g. calcium and magnesium. The opposite is true for soft water.
- **pH** is a measure of the concentration of hydrogen ions in solution. The formula used to calculate pH is as follows:

$$\text{pH} = -\log[\text{H}_3\text{O}^+] \text{ or } \text{pH} = -\log[\text{H}^+]$$

A solution with a pH less than 7 is considered acidic and more than 7 is considered basic (or alkaline). A neutral solution has a pH of 7.

- Gases such as  $\text{CO}_2$ ,  $\text{NO}_2$  and  $\text{SO}_2$  dissolve in water to form weak acid solutions. Rain is naturally acidic because of the high concentrations of carbon dioxide in the atmosphere. Human activities such as burning fossil fuels, increase the concentration of these gases in the atmosphere, resulting in **acid rain**.
- **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 extent to which the substance ionises in 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 its conductivity.

- A **precipitate** is formed when ions in solution react with each other to form an insoluble product. Solubility 'rules' help to identify the precipitate that has been formed.
- A number of tests can be used to identify whether certain **anions** are present in a solution.
- Despite the importance of the hydrosphere, a number of factors threaten it. These include **overuse** of water, and **pollution**.



### Exercise: Summary Exercise

- Give one word for each of the following descriptions:
  - the change in phase of water from a gas to a liquid
  - a charged atom
  - a term used to describe the mineral content of water
  - a gas that forms sulfuric acid when it reacts with water
- Match the information in column A with the information in column B by writing only the letter (A to I) next to the question number (1 to 7)

#### Column A

- A polar molecule
- molecular solution
- Mineral that increases water hardness
- Substance that increases the hydrogen ion concentration
- A strong electrolyte
- A white precipitate
- A non-conductor of electricity

#### Column B

- $\text{H}_2\text{SO}_4$
- $\text{CaCO}_3$
- $\text{NaOH}$
- salt water
- calcium
- carbon dioxide
- potassium nitrate
- sugar water
- $\text{O}_2$

- For each of the following questions, choose the one correct answer from the list provided.
  - Which one of the following substances does not conduct electricity in the solid phase but is an electrical conductor when molten?
    - $\text{Cu}$
    - $\text{PbBr}_2$
    - $\text{H}_2\text{O}$
    - $\text{I}_2$
 (IEB Paper 2, 2003)
  - The following substances are dissolved in water. Which one of the solutions is basic?
    - sodium nitrate
    - calcium sulphate
    - ammonium chloride
    - potassium carbonate
 (IEB Paper 2, 2005)
- The concentration of hydronium and hydroxyl ions in a typical sample of seawater are  $10^{-8}$  and  $10^{-6}$  respectively.
  - Is the seawater acidic or basic?
  - Calculate the pH of this seawater.
- Three test tubes (X, Y and Z) each contain a solution of an unknown potassium salt. The following observations were made during a practical investigation to identify the solutions in the test tubes:  
A: A white precipitate formed when silver nitrate ( $\text{AgNO}_3$ ) was added to test tube Z.

B: A white precipitate formed in test tubes X and Y when barium chloride ( $\text{BaCl}_2$ ) was added.

C: The precipitate in test tube X dissolved in hydrochloric acid ( $\text{HCl}$ ) and a gas was released.

D: The precipitate in test tube Y was insoluble in hydrochloric acid.

(a) Use the above information to identify the solutions in each of the test tubes X, Y and Z.

(b) Write a chemical equation for the reaction that took place in test tube X before hydrochloric acid was added.

(DoE Exemplar Paper 2 2007)

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## **Part II**

# **Physics**



# Chapter 10

## Units

### 10.1 Introduction

Imagine you had to make curtains and needed to buy fabric. The shop assistant would need to know how much fabric you needed. Telling her you need fabric 2 wide and 6 long would be insufficient — you have to specify the **unit** (i.e. 2 *metres* wide and 6 *metres* long). Without the unit the information is incomplete and the shop assistant would have to guess. If you were making curtains for a doll's house the dimensions might be 2 centimetres wide and 6 centimetres long!

It is not just lengths that have units, all physical quantities have units (e.g. time, temperature, distance, etc.).

**Definition: Physical Quantity**

A physical quantity is anything that you can measure. For example, length, temperature, distance and time are physical quantities.

### 10.2 Unit Systems

#### 10.2.1 SI Units

We will be using the SI units in this course. SI units are the internationally agreed upon units. Historically these units are based on the metric system which was developed in France at the time of the French Revolution.

**Definition: SI Units**

The name *SI units* comes from the French *Système International d'Unités*, which means *international system of units*.

There are seven base SI units. These are listed in Table 10.1. All physical quantities have units which can be built from these seven base units. So, it is possible to create a different set of units by defining a different set of base units.

These seven units are called base units because none of them can be expressed as combinations of the other six. This is identical to bricks and concrete being the base units of a building. You can build different things using different combinations of bricks and concrete. The 26 letters of the alphabet are the base units for a language like English. Many different words can be formed by using these letters.

Base quantity	Name	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
amount of substance	mole	mol
luminous intensity	candela	cd

Table 10.1: SI Base Units

### 10.2.2 The Other Systems of Units

The SI Units are not the only units available, but they are most widely used. In Science there are three other sets of units that can also be used. These are mentioned here for interest only.

#### c.g.s. Units

In the c.g.s. system, the metre is replaced by the centimetre and the kilogram is replaced by the gram. This is a simple change but it means that all units derived from these two are changed. For example, the units of force and work are different. These units are used most often in astrophysics and atomic physics.

#### Imperial Units

Imperial units arose when kings and queens decided the measures that were to be used in the land. All the imperial base units, except for the measure of time, are different to those of SI units. This is the unit system you are most likely to encounter if SI units are not used. Examples of imperial units are pounds, miles, gallons and yards. These units are used by the Americans and British. As you can imagine, having different units in use from place to place makes scientific communication very difficult. This was the motivation for adopting a set of internationally agreed upon units.

#### Natural Units

This is the most sophisticated choice of units. Here the most fundamental discovered quantities (such as the speed of light) are set equal to 1. The argument for this choice is that all other quantities should be built from these fundamental units. This system of units is used in high energy physics and quantum mechanics.

## 10.3 Writing Units as Words or Symbols

Unit names are always written with a lowercase first letter, for example, we write metre and litre. The symbols or abbreviations of units are also written with lowercase initials, for example *m* for metre and *ℓ* for litre. The exception to this rule is if the unit is named after a person, then the symbol is a capital letter. For example, the kelvin was named after Lord Kelvin and its symbol is K. If the abbreviation of the unit that is named after a person has two letters, the second letter is lowercase, for example Hz for hertz.



#### Exercise: Naming of Units

For the following symbols of units that you will come across later in this book, write whether you think the unit is named after a person or not.

- |                   |                |
|-------------------|----------------|
| 1. J (joule)      | 5. C (coulomb) |
| 2. $\ell$ (litre) | 6. lm (lumen)  |
| 3. N (newton)     | 7. m (metre)   |
| 4. mol (mole)     | 8. bar (bar)   |
- 

## 10.4 Combinations of SI Base Units

To make working with units easier, some combinations of the base units are given special names, but it is always correct to reduce everything to the base units. Table 10.2 lists some examples of combinations of SI base units that are assigned special names. Do not be concerned if the formulae look unfamiliar at this stage - we will deal with each in detail in the chapters ahead (as well as many others)!

It is very important that you are able to recognise the units correctly. For instance, the **newton** (N) is another name for the **kilogram metre per second squared** ( $\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$ ), while the **kilogram metre squared per second squared** ( $\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$ ) is called the **joule** (J).

Quantity	Formula	Unit Expressed in Base Units	Name of Combination
Force	$ma$	$\text{kg}\cdot\text{m}\cdot\text{s}^{-2}$	N (newton)
Frequency	$\frac{1}{T}$	$\text{s}^{-1}$	Hz (hertz)
Work	$Fs$	$\text{kg}\cdot\text{m}^2\cdot\text{s}^{-2}$	J (joule)

Table 10.2: Some examples of combinations of SI base units assigned special names



**Important:** When writing combinations of base SI units, place a dot ( $\cdot$ ) between the units to indicate that different base units are used. For example, the symbol for metres per second is correctly written as  $\text{m}\cdot\text{s}^{-1}$ , and not as  $\text{ms}^{-1}$  or  $\text{m/s}$ .

## 10.5 Rounding, Scientific Notation and Significant Figures

### 10.5.1 Rounding Off

Certain numbers may take an infinite amount of paper and ink to write out. Not only is that impossible, but writing numbers out to a high precision (many decimal places) is very inconvenient and rarely gives better answers. For this reason we often estimate the number to a certain number of decimal places. Rounding off or approximating a decimal number to a given number of decimal places is the quickest way to approximate a number. For example, if you wanted to round-off 2,6525272 to three decimal places then you would first count three places after the decimal.

$$2,652|5272$$

All numbers to the right of  $|$  are ignored after you determine whether the number in the third decimal place must be rounded up or rounded down. You *round up* the final digit (make the digit one more) if the first digit after the  $|$  was greater or equal to 5 and *round down* (leave the digit alone) otherwise. So, since the first digit after the  $|$  is a 5, we must round up the digit in the third decimal place to a 3 and the final answer of 2,6525272 rounded to three decimal places is 2,653.

**Worked Example 17: Rounding-off**

**Question:** Round off  $\pi = 3,141592654\dots$  to 4 decimal places.

**Answer**

**Step 3 : Determine the last digit that is kept and mark the cut-off with |.**

$$\pi = 3,1415|92654\dots$$

**Step 4 : Determine whether the last digit is rounded up or down.**

The last digit of  $\pi = 3,1415|92654\dots$  must be rounded up because there is a 9 after the |.

**Step 5 : Write the final answer.**

$$\pi = 3,1416 \text{ rounded to 4 decimal places.}$$

**Worked Example 18: Rounding-off**

**Question:** Round off  $9,191919\dots$  to 2 decimal places

**Answer**

**Step 1 : Determine the last digit that is kept and mark the cut-off with |.**

$$9,19|1919\dots$$

**Step 2 : Determine whether the last digit is rounded up or down.**

The last digit of  $9,19|1919\dots$  must be rounded down because there is a 1 after the |.

**Step 3 : Write the final answer.**

$$\text{Answer} = 9,19 \text{ rounded to 2 decimal places.}$$

## 10.5.2 Error Margins

In a calculation that has many steps, it is best to leave the rounding off right until the end. For example, Jack and Jill walk to school. They walk 0,9 kilometers to get to school and it takes them 17 minutes. We can calculate their speed in the following two ways.

Method 1	Method 2
Change 17 minutes to hours:	Change 17 minutes to hours:
$\begin{aligned} \text{time in hours} &= \frac{17 \text{ min}}{60 \text{ min}} \\ &= 0,28333333 \text{ hr} \end{aligned}$	$\begin{aligned} \text{time in hours} &= \frac{17 \text{ min}}{60 \text{ min}} \\ &= 0,28 \text{ hr} \end{aligned}$
$\begin{aligned} \text{speed} &= \frac{\text{Distance}}{\text{Time}} \\ &= \frac{0,9 \text{ km}}{0,28333333 \text{ hr}} \\ &= 3,176470588 \text{ km}\cdot\text{hr}^{-1} \\ &= 3,18 \text{ km}\cdot\text{hr}^{-1} \end{aligned}$	$\begin{aligned} \text{speed} &= \frac{\text{Distance}}{\text{Time}} \\ &= \frac{0,9 \text{ km}}{0,28 \text{ hr}} \\ &= 3,214285714 \text{ km}\cdot\text{hr}^{-1} \\ &= 3,21 \text{ km}\cdot\text{hr}^{-1} \end{aligned}$

Table 10.3: Rounding numbers

You will see that we get two different answers. In Method 1 no rounding was done, but in Method 2, the time was rounded to 2 decimal places. This made a big difference to the answer. The answer in Method 1 is more accurate because rounded numbers were not used in the calculation. Always only round off your final answer.

### 10.5.3 Scientific Notation

In Science one often needs to work with very large or very small numbers. These can be written more easily in scientific notation, in the general form

$$d \times 10^e$$

where  $d$  is a decimal number between 0 and 10 that is rounded off to a few decimal places.  $e$  is known as the *exponent* and is an integer. If  $e > 0$  it represents how many times the decimal place in  $d$  should be moved to the right. If  $e < 0$ , then it represents how many times the decimal place in  $d$  should be moved to the left. For example  $3,24 \times 10^3$  represents 3240 (the decimal moved three places to the right) and  $3,24 \times 10^{-3}$  represents 0,00324 (the decimal moved three places to the left).

If a number must be converted into scientific notation, we need to work out how many times the number must be multiplied or divided by 10 to make it into a number between 1 and 10 (i.e. the value of  $e$ ) and what this number between 1 and 10 is (the value of  $d$ ). We do this by counting the number of decimal places the decimal comma must move.

For example, write the speed of light in scientific notation, to two decimal places. The speed of light is  $299\,792\,458 \text{ m}\cdot\text{s}^{-1}$ . First, find where the decimal comma must go for two decimal places (to find  $d$ ) and then count how many places there are after the decimal comma to determine  $e$ .

In this example, the decimal comma must go after the first 2, but since the number after the 9 is 7,  $d = 3,00$ .  $e = 8$  because there are 8 digits left after the decimal comma. So the speed of light in scientific notation, to two decimal places is  $3,00 \times 10^8 \text{ m}\cdot\text{s}^{-1}$ .

### 10.5.4 Significant Figures

In a number, each non-zero digit is a significant figure. Zeroes are only counted if they are between two non-zero digits or are at the end of the decimal part. For example, the number 2000 has 1 significant figure (the 2), but 2000,0 has 5 significant figures. You estimate a number like this by removing significant figures from the number (starting from the right) until you have the desired number of significant figures, rounding as you go. For example 6,827 has 4 significant figures, but if you wish to write it to 3 significant figures it would mean removing the 7 and rounding up, so it would be 6,83.



#### Exercise: Using Significant Figures

1. Round the following numbers:
  - (a)  $123,517 \ell$  to 2 decimal places
  - (b)  $14,328 \text{ km}\cdot\text{h}^{-1}$  to one decimal place
  - (c)  $0,00954 \text{ m}$  to 3 decimal places
2. Write the following quantities in scientific notation:
  - (a)  $10130 \text{ Pa}$  to 2 decimal places
  - (b)  $978,15 \text{ m}\cdot\text{s}^{-2}$  to one decimal place
  - (c)  $0,000001256 \text{ A}$  to 3 decimal places
3. Count how many significant figures each of the quantities below has:
  - (a)  $2,590 \text{ km}$
  - (b)  $12,305 \text{ mL}$
  - (c)  $7800 \text{ kg}$

## 10.6 Prefixes of Base Units

Now that you know how to write numbers in scientific notation, another important aspect of units is the prefixes that are used with the units.



### Definition: Prefix

A prefix is a group of letters that are placed in front of a word. The effect of the prefix is to change meaning of the word. For example, the prefix *un* is often added to a word to mean *not*, as in *unnecessary* which means *not necessary*.

In the case of units, the prefixes have a special use. The kilogram (kg) is a simple example. 1 kg is equal to 1 000 g or  $1 \times 10^3$  g. Grouping the  $10^3$  and the g together we can replace the  $10^3$  with the prefix k (kilo). Therefore the k takes the place of the  $10^3$ .

The kilogram is unique in that it is the only SI base unit containing a prefix.

In Science, all the prefixes used with units are some power of 10. Table 10.4 lists some of these prefixes. You will not use most of these prefixes, but those prefixes listed in **bold** should be learnt. The case of the prefix symbol is very important. Where a letter features twice in the table, it is written in uppercase for exponents bigger than one and in lowercase for exponents less than one. For example M means mega ( $10^6$ ) and m means milli ( $10^{-3}$ ).

Prefix	Symbol	Exponent	Prefix	Symbol	Exponent
yotta	Y	$10^{24}$	yocto	y	$10^{-24}$
zetta	Z	$10^{21}$	zepto	z	$10^{-21}$
exa	E	$10^{18}$	atto	a	$10^{-18}$
peta	P	$10^{15}$	femto	f	$10^{-15}$
tera	T	$10^{12}$	pico	p	$10^{-12}$
<b>giga</b>	G	$10^9$	<b>nano</b>	n	$10^{-9}$
<b>mega</b>	M	$10^6$	<b>micro</b>	$\mu$	$10^{-6}$
<b>kilo</b>	k	$10^3$	<b>milli</b>	m	$10^{-3}$
<b>hecto</b>	h	$10^2$	<b>centi</b>	c	$10^{-2}$
<b>deca</b>	da	$10^1$	<b>deci</b>	d	$10^{-1}$

Table 10.4: Unit Prefixes



**Important:** There is no space and no dot between the prefix and the symbol for the unit.

Here are some examples of the use of prefixes:

- 40000 m can be written as 40 km (kilometre)
- 0,001 g is the same as  $1 \times 10^{-3}$  g and can be written as 1 mg (milligram)
- $2,5 \times 10^6$  N can be written as 2,5 MN (meganewton)
- 250000 A can be written as 250 kA (kiloampere) or 0,250 MA (megaampere)
- 0,000000075 s can be written as 75 ns (nanoseconds)
- $3 \times 10^{-7}$  mol can be rewritten as  $0,3 \times 10^{-6}$  mol, which is the same as 0,3  $\mu$ mol (micromol)





### Exercise: Using Scientific Notation

1. Write the following in scientific notation using Table 10.4 as a reference.
    - (a) 0,511 MV
    - (b) 10 cℓ
    - (c) 0,5 μm
    - (d) 250 nm
    - (e) 0,00035 hg
  2. Write the following using the prefixes in Table 10.4.
    - (a)  $1,602 \times 10^{-19}$  C
    - (b)  $1,992 \times 10^6$  J
    - (c)  $5,98 \times 10^4$  N
    - (d)  $25 \times 10^{-4}$  A
    - (e)  $0,0075 \times 10^6$  m
- 

## 10.7 The Importance of Units

Without units much of our work as scientists would be meaningless. We need to express our thoughts clearly and units give meaning to the numbers we measure and calculate. Depending on which units we use, the numbers are different. For example if you have 12 water, it means nothing. You could have 12 ml of water, 12 litres of water, or even 12 bottles of water. Units are an essential part of the language we use. Units must be specified when expressing physical quantities. Imagine that you are baking a cake, but the units, like grams and millilitres, for the flour, milk, sugar and baking powder are not specified!

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### Activity :: Investigation : Importance of Units

Work in groups of 5 to discuss other possible situations where using the incorrect set of units can be to your disadvantage or even dangerous. Look for examples at home, at school, at a hospital, when travelling and in a shop.

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### Activity :: Case Study : The importance of units

Read the following extract from CNN News 30 September 1999 and answer the questions below.

#### NASA: Human error caused loss of Mars orbiter November 10, 1999

Failure to convert English measures to metric values caused the loss of the Mars Climate Orbiter, a spacecraft that smashed into the planet instead of reaching a safe orbit, a NASA investigation concluded Wednesday.

The Mars Climate Orbiter, a key craft in the space agency's exploration of the red planet, vanished on 23 September after a 10 month journey. It is believed that the craft came dangerously close to the atmosphere of Mars, where it presumably burned and broke into pieces.

An investigation board concluded that NASA engineers failed to convert English measures of rocket thrusts to newton, a metric system measuring rocket force. One English pound of force equals 4,45 newtons. A small difference between the two

values caused the spacecraft to approach Mars at too low an altitude and the craft is thought to have smashed into the planet's atmosphere and was destroyed.

The spacecraft was to be a key part of the exploration of the planet. From its station about the red planet, the Mars Climate Orbiter was to relay signals from the Mars Polar Lander, which is scheduled to touch down on Mars next month.

"The root cause of the loss of the spacecraft was a failed translation of English units into metric units and a segment of ground-based, navigation-related mission software," said Arthus Stephenson, chairman of the investigation board.

**Questions:**

1. Why did the Mars Climate Orbiter crash? Answer in your own words.
  2. How could this have been avoided?
  3. Why was the Mars Orbiter sent to Mars?
  4. Do you think space exploration is important? Explain your answer.
- 

## 10.8 How to Change Units

It is very important that you are aware that different systems of units exist. Furthermore, you must be able to convert between units. Being able to change between units (for example, converting from millimetres to metres) is a useful skill in Science.

The following conversion diagrams will help you change from one unit to another.

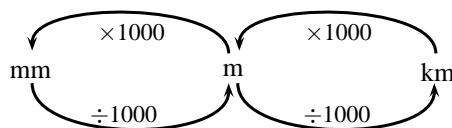


Figure 10.1: The distance conversion table

If you want to change millimetre to metre, you divide by 1000 (follow the arrow from mm to m); or if you want to change kilometre to millimetre, you multiply by  $1000 \times 1000$ .

The same method can be used to change millilitre to litre or kilolitre. Use figure 10.2 to change volumes:

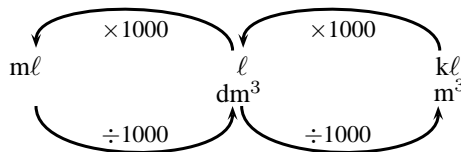


Figure 10.2: The volume conversion table



### Worked Example 19: Conversion 1

**Question:** Express 3 800 mm in metres.

**Answer**

**Step 1 : Find the two units on the conversion diagram.**

Use Figure 10.1 . Millimetre is on the left and metre in the middle.

**Step 2 : Decide whether you are moving to the left or to the right.**

You need to go from mm to m, so you are moving from left to right.

**Step 3 : Read from the diagram what you must do and find the answer.**

$$3\,800\text{ mm} \div 1000 = 3,8\text{ m}$$



**Worked Example 20: Conversion 2**

**Question:** Convert 4,56 kg to g.

**Answer**

**Step 1 : Find the two units on the conversion diagram.**

Use Figure 10.1. Kilogram is the same as kilometre and gram the same as metre.

**Step 2 : Decide whether you are moving to the left or to the right.**

You need to go from kg to g, so it is from right to left.

**Step 3 : Read from the diagram what you must do and find the answer.**

$$4,56\text{ kg} \times 1000 = 4560\text{ g}$$

### 10.8.1 Two other useful conversions

Very often in Science you need to convert speed and temperature. The following two rules will help you do this:

#### Converting speed

When converting  $\text{km}\cdot\text{h}^{-1}$  to  $\text{m}\cdot\text{s}^{-1}$  you divide by 3,6. For example  $72\text{ km}\cdot\text{h}^{-1} \div 3,6 = 20\text{ m}\cdot\text{s}^{-1}$ .

When converting  $\text{m}\cdot\text{s}^{-1}$  to  $\text{km}\cdot\text{h}^{-1}$ , you multiply by 3,6. For example  $30\text{ m}\cdot\text{s}^{-1} \times 3,6 = 108\text{ km}\cdot\text{h}^{-1}$ .

#### Converting temperature

Converting between the kelvin and celsius temperature scales is easy. To convert from celsius to kelvin add 273. To convert from kelvin to celsius subtract 273. Representing the kelvin temperature by  $T_K$  and the celsius temperature by  $T_{\circ C}$ ,

$$T_K = T_{\circ C} + 273$$

## 10.9 A sanity test

A sanity test is a method of checking whether an answer makes sense. All we have to do is to take a careful look at our answer and ask the question *Does the answer make sense?*

Imagine you were calculating the number of people in a classroom. If the answer you got was 1 000 000 people you would know it was wrong — it is not possible to have that many people in a classroom. That is all a sanity test is — is your answer insane or not?

It is useful to have an idea of some numbers before we start. For example, let us consider masses. An average person has a mass around 70 kg, while the heaviest person in medical history had a mass of 635 kg. If you ever have to calculate a person's mass and you get 7 000 kg, this should

fail your sanity check — your answer is insane and you must have made a mistake somewhere. In the same way an answer of 0.01 kg should fail your sanity test.

The only problem with a sanity check is that you must know what typical values for things are. For example, finding the number of learners in a classroom you need to know that there are usually 20–50 people in a classroom. If you get an answer of 2500, you should realise that it is wrong.

---

**Activity :: The scale of the matter... : Try to get an idea of the typical values for the following physical quantities and write your answers into the table:**

Category	Quantity	Minimum	Maximum
People	mass		
	height		
Transport	speed of cars on freeways		
	speed of trains		
	speed of aeroplanes		
	distance between home and school		
General	thickness of a sheet of paper		
	height of a doorway		

---

## 10.10 Summary

1. You need to know the seven base SI Units as listed in table 10.1. Combinations of SI Units can have different names.
2. Unit names and abbreviations are written with lowercase letter unless it is named after a person.
3. Rounding numbers and using scientific notation is important.
4. Table 10.4 summarises the prefixes used in Science.
5. Use figures 10.1 and 10.2 to convert between units.

## 10.11 End of Chapter Exercises

1. Write down the SI unit for each of the following quantities:
  - (a) length
  - (b) time
  - (c) mass
  - (d) quantity of matter
2. For each of the following units, write down the symbol and what power of 10 it represents:
  - (a) millimetre
  - (b) centimetre
  - (c) metre
  - (d) kilometre

(4)

(4)

3. For each of the following symbols, write out the unit in full and write what power of 10 it represents:

- (a)  $\mu\text{g}$
- (b)  $\text{mg}$
- (c)  $\text{kg}$
- (d)  $\text{Mg}$

(4)

4. Write each of the following in scientific notation, correct to 2 decimal places:

- (a) 0,00000123 N
- (b) 417 000 000 kg
- (c) 246800 A
- (d) 0,00088 mm

(4)

5. Rewrite each of the following, accurate to two decimal places, using the correct prefix where applicable:

- (a) 0,00000123 N
- (b) 417 000 000 kg
- (c) 246800 A
- (d) 0,00088 mm

(4)

6. For each of the following, write the measurement using the correct symbol for the prefix and the base unit:

- (a) 1,01 microseconds
- (b) 1 000 milligrams
- (c) 7,2 megameters
- (d) 11 nanolitre

(4)

7. The Concorde is a type of aeroplane that flies very fast. The top speed of the Concorde is  $2\,172\text{ km}\cdot\text{hr}^{-1}$ . Convert the Concorde's top speed to  $\text{m}\cdot\text{s}^{-1}$ .

(3)

8. The boiling point of water is  $100\text{ }^{\circ}\text{C}$ . What is the boiling point of water in kelvin?

(3)

Total = 30



## Chapter 11

# Motion in One Dimension - Grade 10

### 11.1 Introduction

This chapter is about how things move in a straight line or more scientifically how things move *in one dimension*. This is useful for learning how to describe the movement of cars along a straight road or of trains along straight railway tracks. If you want to understand how any object moves, for example a car on the freeway, a soccer ball being kicked towards the goal or your dog chasing the neighbour's cat, then you have to understand three basic ideas about what it means when something *is moving*. These three ideas describe different parts of exactly how an object moves. They are:

1. position or displacement which tells us exactly where the object is,
2. speed or velocity which tells us exactly how fast the object's position is changing or more familiarly, how fast the object is moving, and
3. acceleration which tells us exactly how fast the object's velocity is changing.

You will also learn how to use position, displacement, speed, velocity and acceleration to describe the motion of simple objects. You will learn how to read and draw graphs that summarise the motion of a moving object. You will also learn about the equations that can be used to describe motion and how to apply these equations to objects moving in one dimension.

### 11.2 Reference Point, Frame of Reference and Position

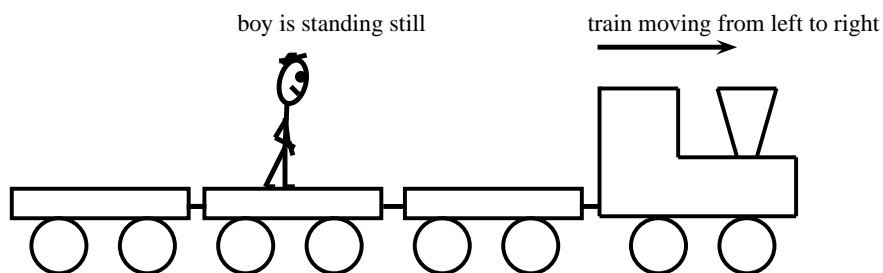
The most important idea when studying motion, is you have to know where you are. The word *position* describes your location (where you are). However, saying that you are *here* is meaningless, and you have to specify your position *relative* to a known reference point. For example, if you are 2 m from the doorway, inside your classroom then your reference point is the doorway. This defines your position inside the classroom. Notice that you need a reference point (the doorway) and a direction (inside) to define your location.

#### 11.2.1 Frames of Reference

**Definition: Frame of Reference**

A frame of reference is a reference point combined with a set of directions.

A *frame of reference* is similar to the idea of a reference point. A frame of reference is defined as a reference point combined with a set of directions. For example, a boy is standing still inside



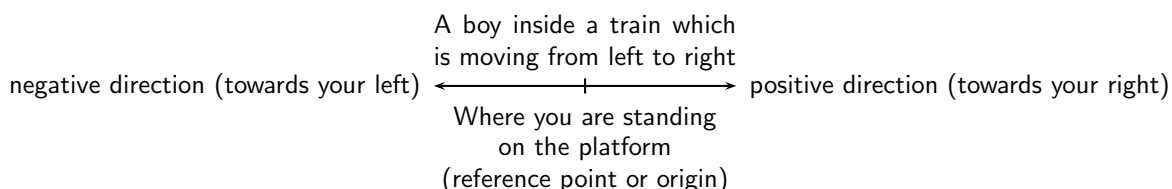
From your frame of reference the boy is moving from left to right.

Figure 11.1: Frames of Reference

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.

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

For this chapter, we will only use frames of reference in the  $x$ -direction. Frames of reference will be covered in more detail in Grade 12.



## 11.2.2 Position



### Definition: Position

Position is a measurement of a location, with reference to an origin.

A position is a measurement of a location, with reference to an origin. Positions can therefore be negative or positive. The symbol  $x$  is used to indicate position.  $x$  has units of length for example cm, m or km. Figure 11.2.2 shows the position of a school. Depending on what reference point we choose, we can say that the school is 300 m from Joan's house (with Joan's house as the reference point or origin) or 500 m from Joel's house (with Joel's house as the reference point or origin).

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



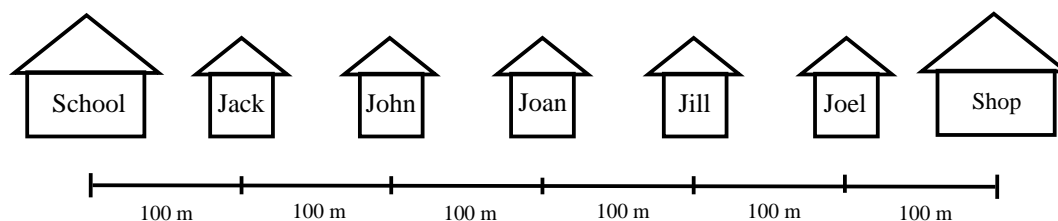


Figure 11.2: Illustration of position

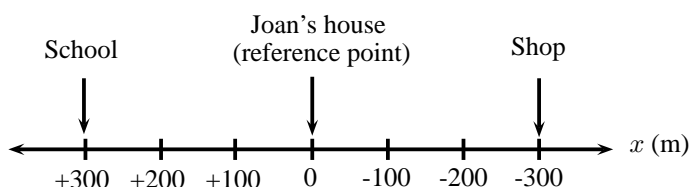


Figure 11.3: The origin is at Joan's house and the position of the school is +300 m. Positions towards the left are defined as positive and positions towards the right are defined as negative.

**Activity :: Discussion : Reference Points**

Divide into groups of 5 for this activity. On a straight line, choose a reference point. Since position can have both positive and negative values, discuss the advantages and disadvantages of choosing

1. either end of the line,
2. the middle of the line.

This reference point can also be called "the origin".

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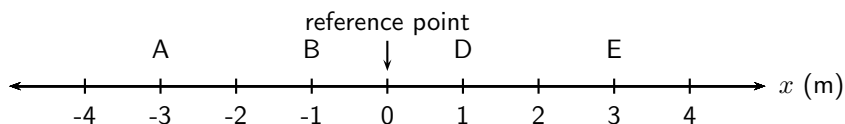


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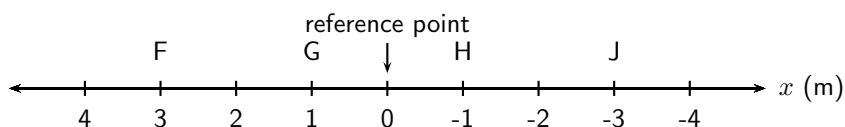
?

**Exercise: Position**

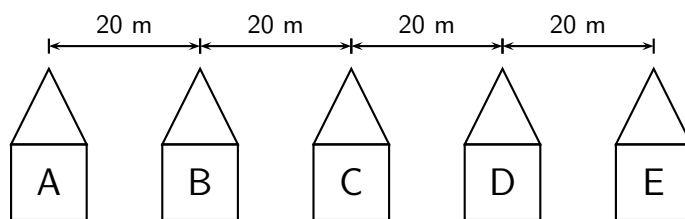
1. Write down the positions for objects at A, B, D and E. Do not forget the units.



2. Write down the positions for objects at F, G, H and J. Do not forget the units.



3. There are 5 houses on Newton Street, A, B, C, D and E. For all cases, assume that positions to the right are positive.



- Draw a frame of reference with house A as the origin and write down the positions of houses B, C, D and E.
- You live in house C. What is your position relative to house E?
- What are the positions of houses A, B and D, if house B is taken as the reference point?

---

## 11.3 Displacement and Distance



### Definition: Displacement

Displacement is the change in an object's position.

The displacement of an object is defined as its change in position (final position minus initial position). Displacement has a magnitude and direction and is therefore a vector. For example, if the initial position of a car is  $x_i$  and it moves to a final position of  $x_f$ , then the displacement is:

$$x_f - x_i$$

However, subtracting an initial quantity from a final quantity happens often in Physics, so we use the shortcut  $\Delta$  to mean *final - initial*. Therefore, displacement can be written:

$$\Delta x = x_f - x_i$$



**Important:** The symbol  $\Delta$  is read out as *delta*.  $\Delta$  is a letter of the Greek alphabet and is used in Mathematics and Science to indicate a change in a certain quantity, or a final value minus an initial value. For example,  $\Delta x$  means change in  $x$  while  $\Delta t$  means change in  $t$ .



**Important:** The words *initial* and *final* will be used very often in Physics. *Initial* will always refer to something that happened earlier in time and *final* will always refer to something that happened later in time. It will often happen that the final value is smaller than the initial value, such that the difference is negative. This is ok!

Displacement does not depend on the path travelled, but only on the initial and final positions (Figure 11.4). We use the word *distance* to describe how far an object travels along a particular path. Distance is the actual distance that was covered. Distance (symbol  $d$ ) does not have a direction, so it is a scalar. Displacement is the shortest distance from the starting point to the endpoint – from the school to the shop in the figure. Displacement has direction and is therefore a vector.

Figure 11.2.2 shows the five houses we discussed earlier. Jack walks to school, but instead of walking straight to school, he decided to walk to his friend Joel's house first to fetch him so that they can walk to school together. Jack covers a distance of 400 m to Joel's house and another 500 m to school. He covers a distance of 900 m. His displacement, however, is only 100 m

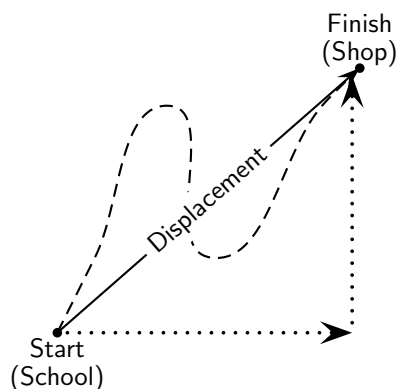


Figure 11.4: Illustration of displacement

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.

To calculate his distance and displacement, we need to choose a reference point and a direction. Let's choose Jack's house as the reference point, and towards Joel's house as the positive direction (which means that towards the school is negative). We would do the calculations as follows:

$\begin{aligned}\text{Distance}(d) &= \text{path travelled} \\ &= 400 \text{ m} + 500 \text{ m} \\ &= 900 \text{ m}\end{aligned}$	$\begin{aligned}\text{Displacement}(\Delta x) &= x_f - x_i \\ &= -100 \text{ m} + 0 \text{ m} \\ &= -100 \text{ m}\end{aligned}$
---	--

Joel walks to school with Jack and after school walks back home. What is Joel's displacement and what distance did he cover? For this calculation we use Joel's house as the reference point. Let's take towards the school as the positive direction.

$\begin{aligned}\text{Distance}(d) &= \text{path travelled} \\ &= 500 \text{ m} + 500 \text{ m} \\ &= 1000 \text{ m}\end{aligned}$	$\begin{aligned}\text{Displacement}(\Delta x) &= x_f - x_i \\ &= 0 \text{ m} + 0 \text{ m} \\ &= 0 \text{ m}\end{aligned}$
--	--

It is possible to have a displacement of 0 m and a distance that is not 0 m. This happens when an object completes a round trip back to its original position, like an athlete running around a track.

### 11.3.1 Interpreting Direction

Very often in calculations you will get a negative answer. For example, Jack's displacement in the example above, is calculated as -100 m. The minus sign in front of the answer means that his displacement is 100 m in the opposite direction (opposite to the direction chosen as positive in the beginning of the question). When we start a calculation we choose a frame of reference and a positive direction. In the first example above, the reference point is Jack's house and the positive direction is towards Joel's house. Therefore Jack's displacement is 100 m towards the school. Notice that distance has no direction, but displacement has.

### 11.3.2 Differences between Distance and Displacement

#### Definition: Vectors and Scalars

A vector is a physical quantity with magnitude (size) and direction. A scalar is a physical quantity with magnitude (size) only.



The differences between distance and displacement can be summarised as:

Distance	Displacement
1. depends on the path	1. independent of path taken
2. always positive	2. can be positive or negative
3. is a scalar	3. is a vector



### Exercise: Point of Reference

- Use Figure 11.2.2 to answer the following questions.
  - Jill walks to Joan's house and then to school, what is her distance and displacement?
  - John walks to Joan's house and then to school, what is his distance and displacement?
  - Jack walks to the shop and then to school, what is his distance and displacement?
  - What reference point did you use for each of the above questions?
- You stand at the front door of your house (displacement,  $\Delta x = 0$  m). The street is 10 m away from the front door. You walk to the street and back again.
  - What is the distance you have walked?
  - What is your final displacement?
  - Is displacement a vector or a scalar? Give a reason for your answer.

## 11.4 Speed, Average Velocity and Instantaneous Velocity



### Definition: Velocity

Velocity is the rate of change of displacement.



### Definition: Instantaneous velocity

Instantaneous velocity is the velocity of a body at a specific instant in time.



### Definition: Average velocity

Average velocity is the total displacement of a body over a time interval.

Velocity is the rate of change of position. It tells us how much an object's position changes in time. This is the same as the displacement divided by the time taken. Since displacement is a vector and time taken is a scalar, velocity is also a vector. We use the symbol  $v$  for velocity. If we have a displacement of  $\Delta x$  and a time taken of  $\Delta t$ ,  $v$  is then defined as:

$$\text{velocity (in m} \cdot \text{s}^{-1}\text{)} = \frac{\text{change in displacement (in m)}}{\text{change in time (in s)}}$$

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

Velocity can be positive or negative. Positive values of velocity mean that the object is moving away from the reference point or origin and negative values mean that the object is moving towards the reference point or origin.



**Important:** An instant in time is different from the time taken or the time interval. It is therefore useful to use the symbol  $t$  for an instant in time (for example during the 4<sup>th</sup> second) and the symbol  $\Delta t$  for the time taken (for example during the first 5 seconds of the motion).

Average velocity (symbol  $v$ ) is the displacement for the whole motion divided by the time taken for the whole motion. Instantaneous velocity is the velocity at a specific instant in time.

(Average) Speed (symbol  $s$ ) is the distance travelled ( $d$ ) divided by the time taken ( $\Delta t$ ) for the journey. Distance and time are scalars and therefore speed will also be a scalar. Speed is calculated as follows:

$$\text{speed (in m} \cdot \text{s}^{-1}\text{)} = \frac{\text{distance (in m)}}{\text{time (in s)}}$$

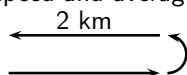
$$s = \frac{d}{\Delta t}$$

Instantaneous speed is the magnitude of instantaneous velocity. It has the same value, but no direction.



### Worked Example 21: Average speed and average velocity

**Question:** James walks 2 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.



#### Answer

##### Step 1 : Identify what information is given and what is asked for

The question explicitly gives

- the distance and time out (2 km in 30 minutes)
- the distance and time back (2 km in 30 minutes)

##### Step 2 : Check that all units are SI units.

The information is not in SI units and must therefore be converted.

To convert km to m, we know that:

$$1 \text{ km} = 1\,000 \text{ m}$$

$$\therefore 2 \text{ km} = 2\,000 \text{ m} \quad (\text{multiply both sides by 2, because we want to convert 2 km to m.})$$

Similarly, to convert 30 minutes to seconds,

$$1 \text{ min} = 60 \text{ s}$$

$$\therefore 30 \text{ min} = 1\,800 \text{ s} \quad (\text{multiply both sides by 30})$$

##### Step 3 : Determine James' displacement and distance.

James started at home and returned home, so his displacement is 0 m.

$$\Delta x = 0 \text{ m}$$

James walked a total distance of 4 000 m (2 000 m out and 2 000 m back).

$$d = 4\,000\text{ m}$$

**Step 4 : Determine his total time.**

James took 1 800 s to walk out and 1 800 s to walk back.

$$\Delta t = 3\,600\text{ s}$$

**Step 5 : Determine his average speed**

$$\begin{aligned}s &= \frac{d}{\Delta t} \\&= \frac{4\,000\text{ m}}{3\,600\text{ s}} \\&= 1,11\text{ m} \cdot \text{s}^{-1}\end{aligned}$$

**Step 6 : Determine his average velocity**

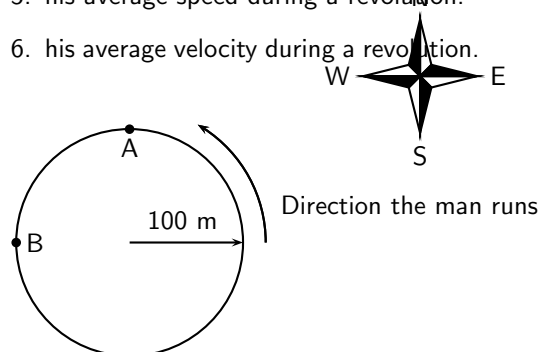
$$\begin{aligned}v &= \frac{\Delta x}{\Delta t} \\&= \frac{0\text{ m}}{3\,600\text{ s}} \\&= 0\text{ m} \cdot \text{s}^{-1}\end{aligned}$$



**Worked Example 22: Instantaneous Speed and Velocity**

**Question:** A man runs around a circular track of radius 100 m. It takes him 120 s to complete a revolution of the track. If he runs at constant speed, calculate:

1. his speed,
2. his instantaneous velocity at point A,
3. his instantaneous velocity at point B,
4. his average velocity between points A and B,
5. his average speed during a revolution.
6. his average velocity during a revolution.



**Answer**

**Step 1 : Decide how to approach the problem**

To determine the man's speed we need to know the distance he travels and

how long it takes. We know it takes 120 s to complete one revolution of the track. (A revolution is to go around the track once.)

### Step 2 : Determine the distance travelled

What distance is one revolution of the track? We know the track is a circle and we know its radius, so we can determine the distance around the circle. We start with the equation for the circumference of a circle

$$\begin{aligned} C &= 2\pi r \\ &= 2\pi(100 \text{ m}) \\ &= 628,32 \text{ m} \end{aligned}$$

Therefore, the distance the man covers in one revolution is 628,32 m.

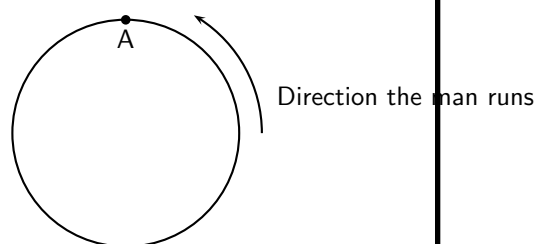
### Step 3 : Determine the speed

We know that speed is distance covered per unit time. So if we divide the distance covered by the time it took we will know how much distance was covered for every unit of time. No direction is used here because speed is a scalar.

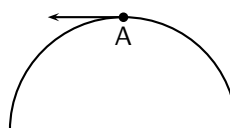
$$\begin{aligned} s &= \frac{d}{\Delta t} \\ &= \frac{628,32 \text{ m}}{120 \text{ s}} \\ &= 5,24 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

### Step 4 : Determine the instantaneous velocity at A

Consider the point A in the diagram. We know which way the man is running around the track and we know his speed. His velocity at point A will be his speed (the magnitude of the velocity) plus his direction of motion (the direction of his velocity). The instant that he arrives at A he is moving as indicated in the diagram.

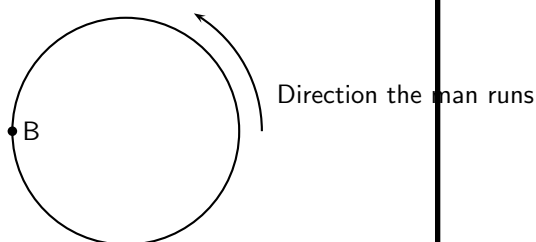


His velocity will be  $5,24 \text{ m} \cdot \text{s}^{-1}$  West.

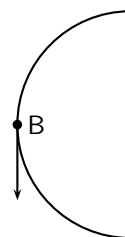


### Step 5 : Determine the instantaneous velocity at B

Consider the point B in the diagram. We know which way the man is running around the track and we know his speed. His velocity at point B will be his speed (the magnitude of the velocity) plus his direction of motion (the direction of his velocity). The instant that he arrives at B he is moving as indicated in the diagram.



His velocity will be  $5,24 \text{ m} \cdot \text{s}^{-1}$  South.



### Step 6 : Determine the average velocity between A and B

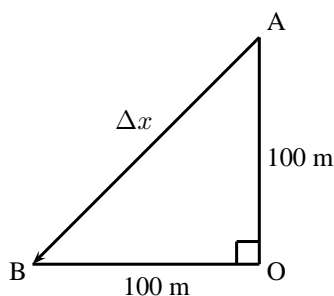
To determine the average velocity between A and B, we need the change in displacement between A and B and the change in time between A and B.

The displacement from A and B can be calculated by using the Theorem of Pythagoras:

$$\begin{aligned}(\Delta x)^2 &= (100 \text{ m})^2 + (100 \text{ m})^2 \\&= 20000 \text{ m}^2 \\ \Delta x &= 141,42135... \text{ m}\end{aligned}$$

The time for a full revolution is 120 s, therefore the time for a  $\frac{1}{4}$  of a revolution is 30 s.

$$\begin{aligned}v_{AB} &= \frac{\Delta x}{\Delta t} \\&= \frac{141,42... \text{ m}}{30 \text{ s}} \\&= 4.71 \text{ m} \cdot \text{s}^{-1}\end{aligned}$$



Velocity is a vector and needs a direction.

Triangle AOB is isosceles and therefore angle BAO = 45°.

The direction is between west and south and is therefore southwest.

The final answer is:  $v = 4.71 \text{ m} \cdot \text{s}^{-1}$ , southwest.

#### Step 7 : Determine his average speed during a revolution

Because he runs at a constant rate, we know that his speed anywhere around the track will be the same. His average speed is  $5,24 \text{ m} \cdot \text{s}^{-1}$ .

#### Step 8 : Determine his average velocity over a complete revolution

**Important:** Remember - displacement can be zero even when distance travelled is not!

To calculate average velocity we need his total displacement and his total time. His displacement is zero because he ends up where he started. His time is 120 s. Using these we can calculate his average velocity:

$$\begin{aligned}v &= \frac{\Delta x}{\Delta t} \\&= \frac{0 \text{ m}}{120 \text{ s}} \\&= 0 \text{ m} \cdot \text{s}^{-1}\end{aligned}$$

### 11.4.1 Differences between Speed and Velocity

The differences between speed and velocity can be summarised as:

Speed	Velocity
1. depends on the path taken	1. independent of path taken
2. always positive	2. can be positive or negative
3. is a scalar	3. is a vector
4. no dependence on direction and so is only positive	4. direction can be guessed from the sign (i.e. positive or negative)

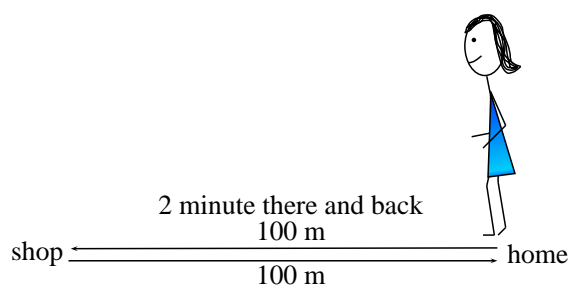


Additionally, an object that makes a round trip, i.e. travels away from its starting point and then returns to the same point has zero velocity but travels a non-zero speed.

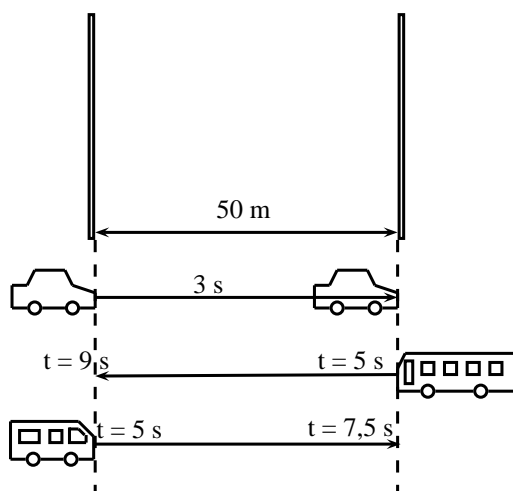


### Exercise: Displacement and related quantities

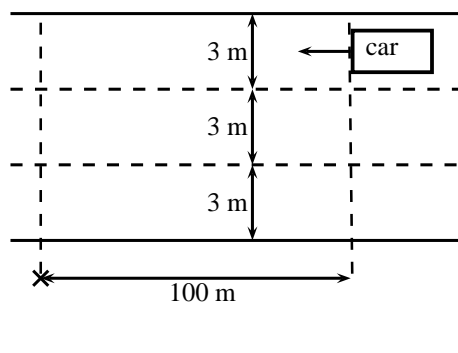
1. Theresa has to walk to the shop to buy some milk. After walking 100 m, she realises that she does not have enough money, and goes back home. If it took her two minutes to leave and come back, calculate the following:
  - (a) How long was she out of the house (the time interval  $\Delta t$  in seconds)?
  - (b) How far did she walk (distance (d))?
  - (c) What was her displacement ( $\Delta x$ )?
  - (d) What was her average velocity (in  $\text{m}\cdot\text{s}^{-1}$ )?
  - (e) What was her average speed (in  $\text{m}\cdot\text{s}^{-1}$ )?



2. Desmond is watching a straight stretch of road from his classroom window. He can see two poles which he earlier measured to be 50 m apart. Using his stopwatch, Desmond notices that it takes 3 s for most cars to travel from the one pole to the other.
  - (a) Using the equation for velocity ( $v = \frac{\Delta x}{\Delta t}$ ), show all the working needed to calculate the velocity of a car travelling from the left to the right.
  - (b) If Desmond measures the velocity of a red Golf to be  $-16,67 \text{ m}\cdot\text{s}^{-1}$ , in which direction was the Gold travelling?  
Desmond leaves his stopwatch running, and notices that at  $t = 5,0 \text{ s}$ , a taxi passes the left pole at the same time as a bus passes the right pole. At time  $t = 7,5 \text{ s}$  the taxi passes the right pole. At time  $t = 9,0 \text{ s}$ , the bus passes the left pole.
  - (c) How long did it take the taxi and the bus to travel the distance between the poles? (Calculate the time interval ( $\Delta t$ ) for both the taxi and the bus).
  - (d) What was the velocity of the taxi and the bus?
  - (e) What was the speed of the taxi and the bus?
  - (f) What was the speed of taxi and the bus in  $\text{km}\cdot\text{h}^{-1}$ ?



3. After a long day, a tired man decides not to use the pedestrian bridge to cross over a freeway, and decides instead to run across. He sees a car 100 m away travelling towards him, and is confident that he can cross in time.
- If the car is travelling at  $120 \text{ km}\cdot\text{h}^{-1}$ , what is the car's speed in  $\text{m}\cdot\text{s}^{-1}$ .
  - How long will it take the a car to travel 100 m?
  - If the man is running at  $10 \text{ km}\cdot\text{h}^{-1}$ , what is his speed in  $\text{m}\cdot\text{s}^{-1}$ ?
  - If the freeway has 3 lanes, and each lane is 3 m wide, how long will it take for the man to cross all three lanes?
  - If the car is travelling in the furthestmost lane from the man, will he be able to cross all 3 lanes of the freeway safely?



#### Activity :: Investigation : An Exercise in Safety

Divide into groups of 4 and perform the following investigation. Each group will be performing the same investigation, but the aim for each group will be different.

- Choose an aim for your investigation from the following list and formulate a hypothesis:
  - Do cars travel at the correct speed limit?
  - Is it safe to cross the road outside of a pedestrian crossing?
  - Does the colour of your car determine the speed you are travelling at?
  - Any other relevant question that you would like to investigate.
- On a road that you often cross, measure out 50 m along a straight section, far away from traffic lights or intersections.
- Use a stopwatch to record the time each of 20 cars take to travel the 50 m section you measured.
- Design a table to represent your results. Use the results to answer the question posed in the aim of the investigation. You might need to do some more measurements for your investigation. Plan in your group what else needs to be done.
- Complete any additional measurements and write up your investigation under the following headings:
  - Aim and Hypothesis
  - Apparatus
  - Method
  - Results
  - Discussion
  - Conclusion
- Answer the following questions:
  - How many cars took less than 3 seconds to travel 50 m?
  - What was the shortest time a car took to travel 50 m?

- (c) What was the average time taken by the 20 cars?
- (d) What was the average speed of the 20 cars?
- (e) Convert the average speed to  $\text{km}\cdot\text{h}^{-1}$ .

## 11.5 Acceleration



### Definition: Acceleration

Acceleration is the rate of change of velocity.

Acceleration (symbol  $a$ ) is the rate of change of velocity. It is a measure of how fast the velocity of an object changes in time. If we have a change in velocity ( $\Delta v$ ) over a time interval ( $\Delta t$ ), then the acceleration ( $a$ ) is defined as:

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

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

Since velocity is a vector, acceleration is also a vector. Acceleration does not provide any information about a motion, but only about how the motion changes. It is not possible to tell how fast an object is moving or in which direction from the acceleration.

Like velocity, acceleration can be negative or positive. We see that 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. Similarly, if the velocity is negative and the acceleration is positive the object is slowing down. This is illustrated in the following worked example.



### Worked Example 23: Acceleration

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

#### Answer

#### Step 9 : Identify what information is given and what is asked for:

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

For the first 8 seconds:

$$\begin{aligned} v_i &= 2 \text{ m}\cdot\text{s}^{-1} \\ v_f &= 10 \text{ m}\cdot\text{s}^{-1} \\ t_i &= 0 \text{ s} \\ t_f &= 8 \text{ s} \end{aligned}$$

For the last 6 seconds:

$$\begin{aligned} v_i &= 10 \text{ m}\cdot\text{s}^{-1} \\ v_f &= 4 \text{ m}\cdot\text{s}^{-1} \\ t_i &= 8 \text{ s} \\ t_f &= 14 \text{ s} \end{aligned}$$

#### Step 10 : Calculate the acceleration.

For the first 8 seconds:

$$\begin{aligned} a &= \frac{\Delta v}{\Delta t} \\ &= \frac{10 \text{ m}\cdot\text{s}^{-1} - 2 \text{ m}\cdot\text{s}^{-1}}{8 \text{ s} - 0 \text{ s}} \\ &= 1 \text{ m}\cdot\text{s}^{-2} \end{aligned}$$

For the next 6 seconds:

$$\begin{aligned} a &= \frac{\Delta v}{\Delta t} \\ &= \frac{4 \text{ m}\cdot\text{s}^{-1} - 10 \text{ m}\cdot\text{s}^{-1}}{14 \text{ s} - 8 \text{ s}} \\ &= -1 \text{ m}\cdot\text{s}^{-2} \end{aligned}$$

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.



**Important:** Acceleration does not tell us about the direction of the motion. Acceleration only tells us how the velocity changes.



**Important:** Deceleration

Avoid the use of the word *deceleration* to refer to a negative acceleration. This word usually means *slowing down* and it is possible for an object to slow down with both a positive and negative acceleration, because the sign of the velocity of the object must also be taken into account to determine whether the body is slowing down or not.



### Exercise: Acceleration

1. An athlete is accelerating uniformly from an initial velocity of  $0 \text{ m}\cdot\text{s}^{-1}$  to a final velocity of  $4 \text{ m}\cdot\text{s}^{-1}$  in 2 seconds. 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  $15 \text{ m}\cdot\text{s}^{-1}$  to a final velocity of  $7 \text{ m}\cdot\text{s}^{-1}$  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  $200 \text{ m}\cdot\text{s}^{-1}$  to a velocity of  $100 \text{ m}\cdot\text{s}^{-1}$  in 10 seconds. It then accelerates uniformly to a final velocity of  $240 \text{ m}\cdot\text{s}^{-1}$  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 14 seconds of its motion.
  - (c) Calculate the acceleration of the aeroplane during the whole 24 seconds of its motion.

## 11.6 Description of Motion

The purpose of this chapter is to describe motion, and now that we understand the definitions of displacement, distance, velocity, speed and acceleration, we are ready to start using these ideas to describe how an object is moving. There are many ways of describing motion:

1. words
2. diagrams
3. graphs

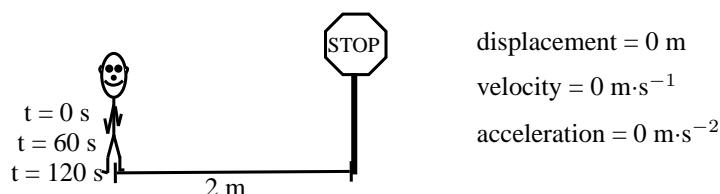
These methods will be described in this section.

We will consider three types of motion: when the object is not moving (stationary object), when the object is moving at a constant velocity (uniform motion) and when the object is moving at a constant acceleration (motion at constant acceleration).

### 11.6.1 Stationary Object

The simplest motion that we can come across is that of a stationary object. A stationary object does not move and so its position does not change, for as long as it is standing still. An example of this situation is when someone is waiting for something without moving. The person remains in the same position.

Lesedi is waiting for a taxi. He is standing two metres from a stop street at  $t = 0$  s. After one minute, at  $t = 60$  s, he is still 2 metres from the stop street and after two minutes, at  $t = 120$  s, also 2 metres from the stop street. His position has not changed. His displacement is zero (because his position is the same), his velocity is zero (because his displacement is zero) and his acceleration is also zero (because his velocity is not changing).



We can now draw graphs of position vs. time ( $x$  vs.  $t$ ), velocity vs. time ( $v$  vs.  $t$ ) and acceleration vs. time ( $a$  vs.  $t$ ) for a stationary object. The graphs are shown in Figure 11.5. Lesedi's position is 2 metres from the stop street. If the stop street is taken as the reference point, his position remains at 2 metres for 120 seconds. The graph is a horizontal line at 2 m. The velocity and acceleration graphs are also shown. They are both horizontal lines on the  $x$ -axis. Since his position is not changing, his velocity is  $0 \text{ m}\cdot\text{s}^{-1}$  and since velocity is not changing, acceleration is  $0 \text{ m}\cdot\text{s}^{-2}$ .



#### Definition: Gradient

The gradient of a line can be calculated by dividing the change in the  $y$ -value by the change in the  $x$ -value.

$$m = \frac{\Delta y}{\Delta x}$$

Since we know that velocity is the rate of change of position, we can confirm the value for the velocity vs. time graph, by calculating the gradient of the  $x$  vs.  $t$  graph.

**Important:** The gradient of a position vs. time graph gives the velocity.

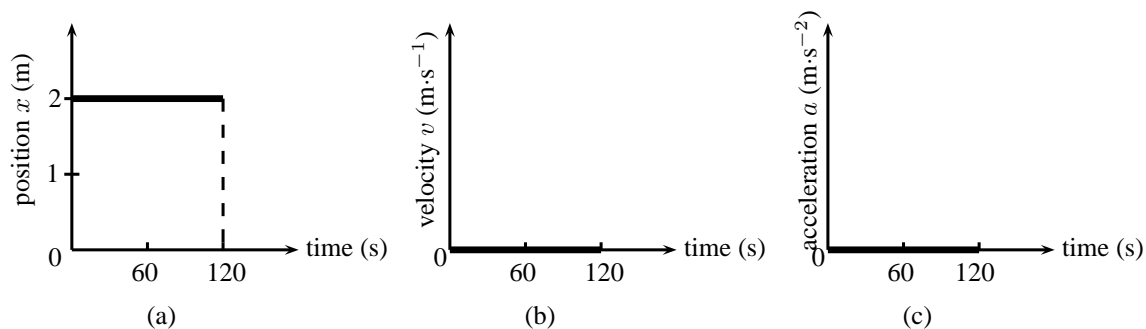


Figure 11.5: Graphs for a stationary object (a) position vs. time (b) velocity vs. time (c) acceleration vs. time.

If we calculate the gradient of the  $x$  vs.  $t$  graph for a stationary object we get:

$$\begin{aligned}
 v &= \frac{\Delta x}{\Delta t} \\
 &= \frac{x_f - x_i}{t_f - t_i} \\
 &= \frac{2 \text{ m} - 2 \text{ m}}{120 \text{ s} - 60 \text{ s}} \quad (\text{initial position} = \text{final position}) \\
 &= 0 \text{ m} \cdot \text{s}^{-1} \quad (\text{for the time that Lesedi is stationary})
 \end{aligned}$$

Similarly, we can confirm the value of the acceleration by calculating the gradient of the velocity vs. time graph.

**Important:** The gradient of a velocity vs. time graph gives the acceleration.

If we calculate the gradient of the  $v$  vs.  $t$  graph for a stationary object we get:

$$\begin{aligned}
 a &= \frac{\Delta v}{\Delta t} \\
 &= \frac{v_f - v_i}{t_f - t_i} \\
 &= \frac{0 \text{ m} \cdot \text{s}^{-1} - 0 \text{ m} \cdot \text{s}^{-1}}{120 \text{ s} - 60 \text{ s}} \\
 &= 0 \text{ m} \cdot \text{s}^{-2}
 \end{aligned}$$

Additionally, because the velocity vs. time graph is related to the position vs. time graph, we can use the area under the velocity vs. time graph to calculate the displacement of an object.

**Important:** The area under the velocity vs. time graph gives the displacement.

The displacement of the object is given by the area under the graph, which is 0 m. This is obvious, because the object is not moving.

### 11.6.2 Motion at Constant Velocity

Motion at a constant velocity or *uniform motion* means that the position of the object is changing at the same rate.

Assume that Lesedi takes 100 s to walk the 100 m to the taxi-stop every morning. If we assume that Lesedi's house is the origin, then Lesedi's velocity is:

$$\begin{aligned}
 v &= \frac{\Delta x}{\Delta t} \\
 &= \frac{x_f - x_i}{t_f - t_i} \\
 &= \frac{100 \text{ m} - 0 \text{ m}}{100 \text{ s} - 0 \text{ s}} \\
 &= 1 \text{ m} \cdot \text{s}^{-1}
 \end{aligned}$$

Lesedi's velocity is  $1 \text{ m} \cdot \text{s}^{-1}$ . This means that he walked 1 m in the first second, another metre in the second second, and another in the third second, and so on. For example, after 50 s he will be 50 m from home. His position increases by 1 m every 1 s. A diagram of Lesedi's position is shown in Figure 11.6.

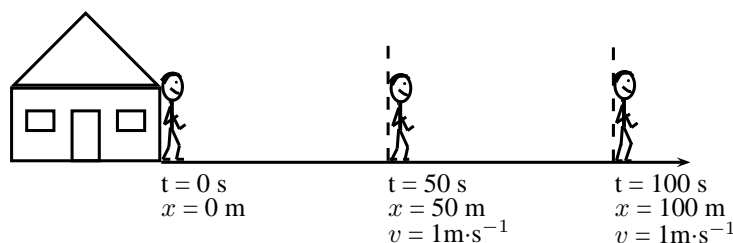


Figure 11.6: Diagram showing Lesedi's motion at a constant velocity of  $1 \text{ m} \cdot \text{s}^{-1}$

We can now draw graphs of position vs.time ( $x$  vs.  $t$ ), velocity vs.time ( $v$  vs.  $t$ ) and acceleration vs.time ( $a$  vs.  $t$ ) for Lesedi moving at a constant velocity. The graphs are shown in Figure 11.7.

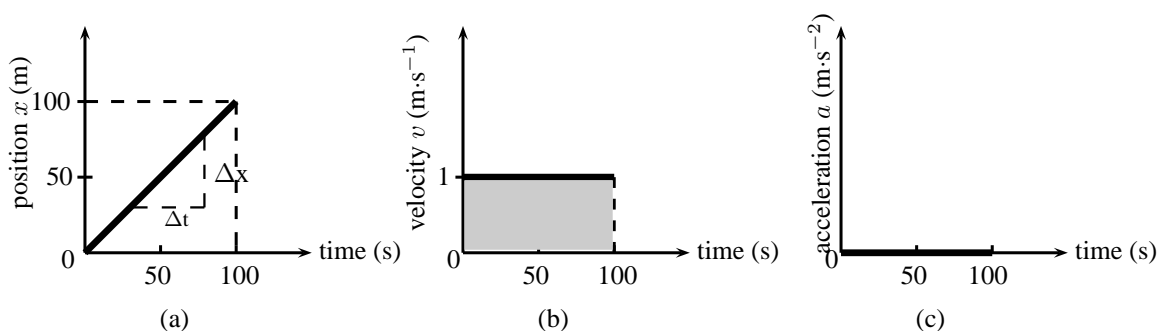


Figure 11.7: Graphs for motion at constant velocity (a) position vs. time (b) velocity vs. time (c) acceleration vs. time. The area of the shaded portion in the  $v$  vs.  $t$  graph corresponds to the object's displacement.

In the evening Lesedi walks 100 m from the bus stop to his house in 100 s. Assume that Lesedi's house is the origin. The following graphs can be drawn to describe the motion.

We see that the  $v$  vs.  $t$  graph is a horizontal line. If the velocity vs. time graph is a horizontal line, it means that the velocity is *constant* (not changing). Motion at a constant velocity is known as *uniform motion*.

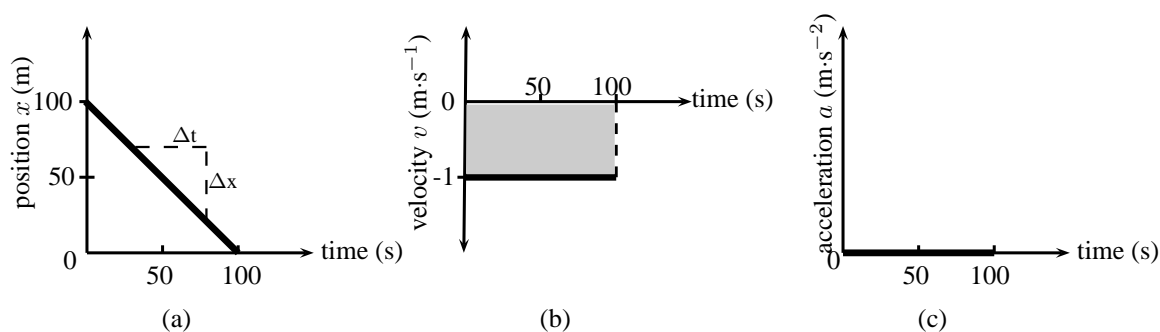


Figure 11.8: Graphs for motion with a constant negative velocity (a) position vs. time (b) velocity vs. time (c) acceleration vs. time. The area of the shaded portion in the  $v$  vs.  $t$  graph corresponds to the object's displacement.

We can use the  $x$  vs.  $t$  to calculate the velocity by finding the gradient of the line.

$$\begin{aligned}
 v &= \frac{\Delta x}{\Delta t} \\
 &= \frac{x_f - x_i}{t_f - t_i} \\
 &= \frac{0 \text{ m} - 100 \text{ m}}{100 \text{ s} - 0 \text{ s}} \\
 &= -1 \text{ m} \cdot \text{s}^{-1}
 \end{aligned}$$

Lesedi has a velocity of  $-1 \text{ m} \cdot \text{s}^{-1}$ , or  $1 \text{ m} \cdot \text{s}^{-1}$  towards his house. You will notice that the  $v$  vs.  $t$  graph is a horizontal line corresponding to a velocity of  $-1 \text{ m} \cdot \text{s}^{-1}$ . The horizontal line means that the velocity stays the same (remains constant) during the motion. This is uniform velocity.

We can use the  $v$  vs.  $t$  to calculate the acceleration by finding the gradient of the line.

$$\begin{aligned}
 a &= \frac{\Delta v}{\Delta t} \\
 &= \frac{v_f - v_i}{t_f - t_i} \\
 &= \frac{1 \text{ m} \cdot \text{s}^{-1} - 1 \text{ m} \cdot \text{s}^{-1}}{100 \text{ s} - 0 \text{ s}} \\
 &= 0 \text{ m} \cdot \text{s}^{-2}
 \end{aligned}$$

Lesedi has an acceleration of  $0 \text{ m} \cdot \text{s}^{-2}$ . You will notice that the graph of  $a$  vs.  $t$  is a horizontal line corresponding to an acceleration value of  $0 \text{ m} \cdot \text{s}^{-2}$ . There is no acceleration during the motion because his velocity does not change.

We can use the  $v$  vs.  $t$  to calculate the displacement by finding the area under the graph.

$$\begin{aligned}
 v &= \text{Area under graph} \\
 &= \ell \times b \\
 &= 100 \times (-1) \\
 &= -100 \text{ m}
 \end{aligned}$$

This means that Lesedi has a displacement of 100 m towards his house.



### Exercise: Velocity and acceleration

1. Use the graphs in Figure 11.7 to calculate each of the following:



- (a) Calculate Lesedi's velocity between 50 s and 100 s using the  $x$  vs.  $t$  graph.  
Hint: Find the gradient of the line.
  - (b) Calculate Lesedi's acceleration during the whole motion using the  $v$  vs.  $t$  graph.
  - (c) Calculate Lesedi's displacement during the whole motion using the  $v$  vs.  $t$  graph.
2. Thandi takes 200 s to walk 100 m to the bus stop every morning. Draw a graph of Thandi's position as a function of time (assuming that Thandi's home is the reference point). Use the gradient of the  $x$  vs.  $t$  graph to draw the graph of velocity vs. time. Use the gradient of the  $v$  vs.  $t$  graph to draw the graph of acceleration vs. time.
  3. In the evening Thandi takes 200 s to walk 100 m from the bus stop to her home. Draw a graph of Thandi's position as a function of time (assuming that Thandi's home is the origin). Use the gradient of the  $x$  vs.  $t$  graph to draw the graph of velocity vs. time. Use the gradient of the  $v$  vs.  $t$  graph to draw the graph of acceleration vs. time.
  4. Discuss the differences between the two sets of graphs in questions 2 and 3.
- 
- 

### Activity :: Experiment : Motion at constant velocity

#### Aim:

To measure the position and time during motion at constant velocity and determine the average velocity as the gradient of a "Position vs. Time" graph.

#### Apparatus:

A battery operated toy car, stopwatch, meter stick or measuring tape.

#### Method:

1. Work with a friend. Copy the table below into your workbook.
2. Complete the table by timing the car as it travels each distance.
3. Time the car twice for each distance and take the average value as your accepted time.
4. Use the distance and average time values to plot a graph of "Distance vs. Time" **onto graph paper**. Stick the graph paper into your workbook. (Remember that "A vs. B" always means "y vs. x").
5. Insert all axis labels and units onto your graph.
6. Draw the best straight line through your data points.
7. Find the gradient of the straight line. This is the average velocity.

#### Results:

Distance (m)	Time (s)		
	1	2	Ave.
0			
0,5			
1,0			
1,5			
2,0			
2,5			
3,0			

#### Conclusions:

Answer the following questions in your workbook.

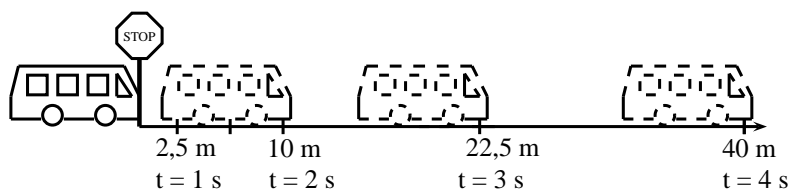
#### Questions:

1. Did the car travel with a constant velocity?
  2. How can you tell by looking at the "Distance vs. Time" graph if the velocity is constant?
  3. How would the "Distance vs. Time" look for a car with a faster velocity?
  4. How would the "Distance vs. Time" look for a car with a slower velocity?
- 

### 11.6.3 Motion at Constant Acceleration

The final situation we will be studying is motion at constant acceleration. We know that acceleration is the rate of change of velocity. So, if we have a constant acceleration, this means that the velocity changes at a constant rate.

Let's look at our first example of Lesedi waiting at the taxi stop again. A taxi arrived and Lesedi got in. The taxi stopped at the stop street and then accelerated as follows: After 1 s the taxi covered a distance of 2,5 m, after 2 s it covered 10 m, after 3 seconds it covered 22,5 m and after 4 s it covered 40 m. The taxi is covering a larger distance every second. This means that it is accelerating.



To calculate the velocity of the taxi you need to calculate the gradient of the line at each second:

$$\begin{aligned}
 v_{1s} &= \frac{\Delta x}{\Delta t} & v_{2s} &= \frac{\Delta x}{\Delta t} & v_{3s} &= \frac{\Delta x}{\Delta t} \\
 &= \frac{x_f - x_i}{t_f - t_i} & &= \frac{x_f - x_i}{t_f - t_i} & &= \frac{x_f - x_i}{t_f - t_i} \\
 &= \frac{5 \text{ m} - 0 \text{ m}}{1,5 \text{ s} - 0,5 \text{ s}} & &= \frac{15 \text{ m} - 5 \text{ m}}{2,5 \text{ s} - 1,5 \text{ s}} & &= \frac{30 \text{ m} - 15 \text{ m}}{3,5 \text{ s} - 2,5 \text{ s}} \\
 &= 5 \text{ m} \cdot \text{s}^{-1} & &= 10 \text{ m} \cdot \text{s}^{-1} & &= 15 \text{ m} \cdot \text{s}^{-1}
 \end{aligned}$$

From these velocities, we can draw the velocity-time graph which forms a straight line.

The acceleration is the gradient of the  $v$  vs.  $t$  graph and can be calculated as follows:

$$\begin{aligned}
 a &= \frac{\Delta v}{\Delta t} \\
 &= \frac{v_f - v_i}{t_f - t_i} \\
 &= \frac{15 \text{ m} \cdot \text{s}^{-1} - 5 \text{ m} \cdot \text{s}^{-1}}{3 \text{ s} - 1 \text{ s}} \\
 &= 5 \text{ m} \cdot \text{s}^{-2}
 \end{aligned}$$

The acceleration does not change during the motion (the gradient stays constant). This is motion at constant or uniform acceleration.

The graphs for this situation are shown in Figure 11.9.

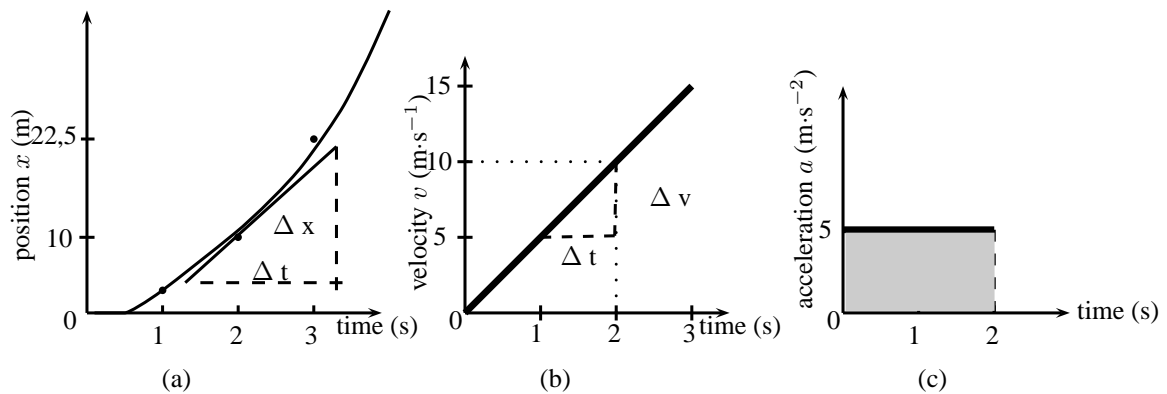


Figure 11.9: Graphs for motion with a constant acceleration (a) position vs. time (b) velocity vs. time (c) acceleration vs. time.

### Velocity from Acceleration vs. Time Graphs

Just as we used velocity vs. time graphs to find displacement, we can use acceleration vs. time graphs to find the velocity of an object at a given moment in time. We simply calculate the area under the acceleration vs. time graph, at a given time. In the graph below, showing an object at a constant positive acceleration, the increase in velocity of the object after 2 seconds corresponds to the shaded portion.

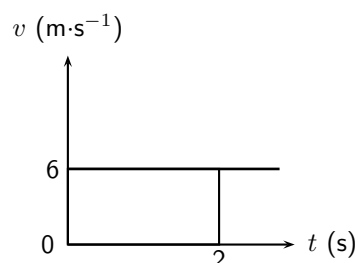
$$\begin{aligned}
 v &= \text{area of rectangle} = a \times \Delta t \\
 &= 5 \text{ m} \cdot \text{s}^{-2} \times 2 \text{ s} \\
 &= 10 \text{ m} \cdot \text{s}^{-1}
 \end{aligned}$$

The velocity of the object at  $t = 2 \text{ s}$  is therefore  $10 \text{ m} \cdot \text{s}^{-1}$ . This corresponds with the values obtained in Figure 11.9.

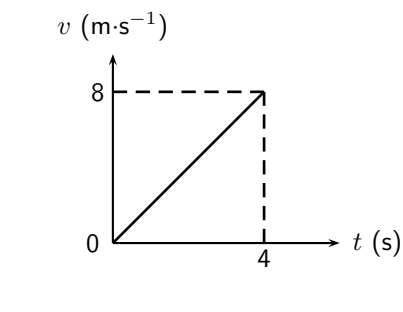


### Exercise: Graphs

1. A car is parked 10 m from home for 10 minutes. Draw a displacement-time, velocity-time and acceleration-time graphs for the motion. Label all the axes.
2. A bus travels at a constant velocity of  $12 \text{ m} \cdot \text{s}^{-1}$  for 6 seconds. Draw the displacement-time, velocity-time and acceleration-time graph for the motion. Label all the axes.
3. An athlete runs with a constant acceleration of  $1 \text{ m} \cdot \text{s}^{-2}$  for 4 s. Draw the acceleration-time, velocity-time and displacement time graphs for the motion. Accurate values are only needed for the acceleration-time and velocity-time graphs.
4. The following velocity-time graph describes the motion of a car. Draw the displacement-time graph and the acceleration-time graph and explain the motion of the car according to the three graphs.



5. The following velocity-time graph describes the motion of a truck. Draw the displacement-time graph and the acceleration-time graph and explain the motion of the truck according to the three graphs.



## 11.7 Summary of Graphs

The relation between graphs of position, velocity and acceleration as functions of time is summarised in Figure 11.10.

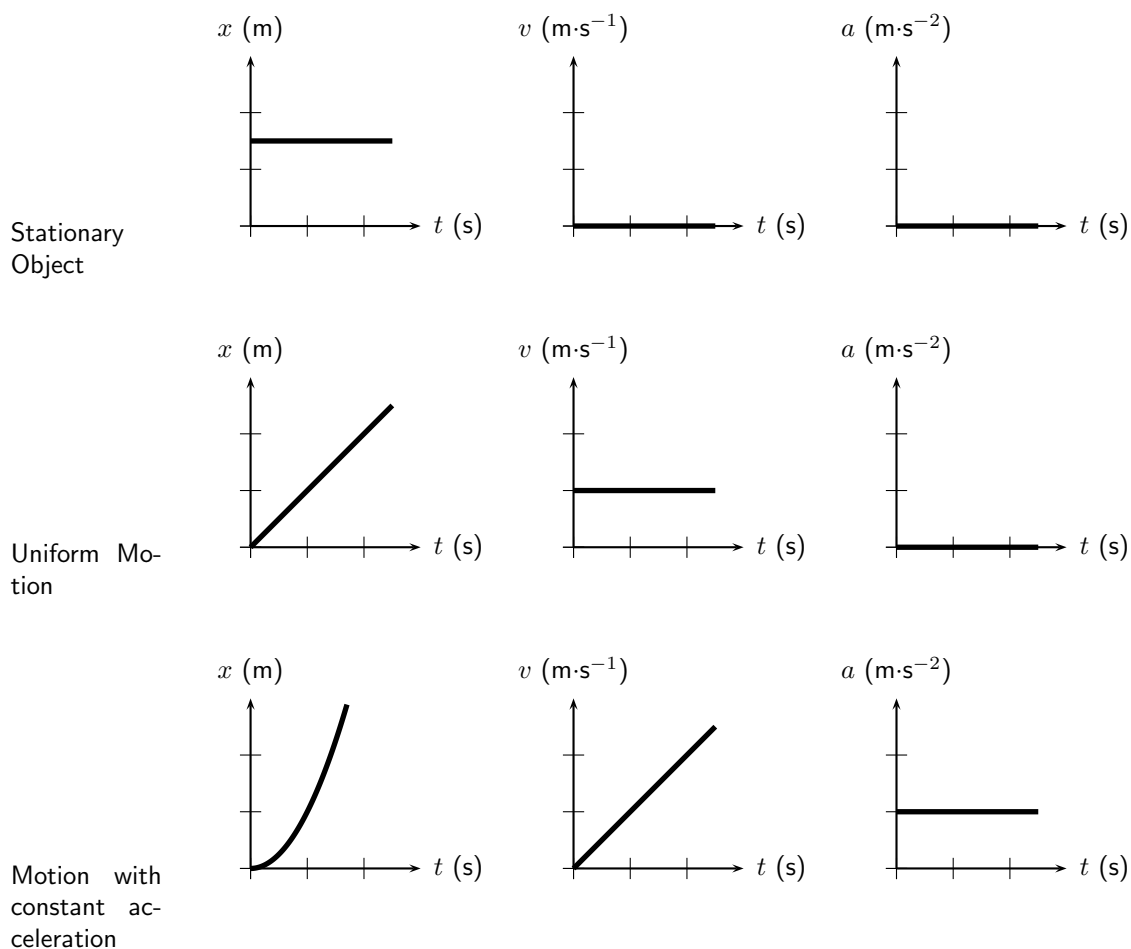


Figure 11.10: Position-time, velocity-time and acceleration-time graphs.



**Important:** Often you will be required to describe the motion of an object that is presented as a graph of either position, velocity or acceleration as functions of time. The description of the motion represented by a graph should include the following (where possible):

1. whether the object is moving in the positive or negative direction
2. whether the object is at rest, moving at constant velocity or moving at constant positive acceleration (speeding up) or constant negative acceleration (slowing down)

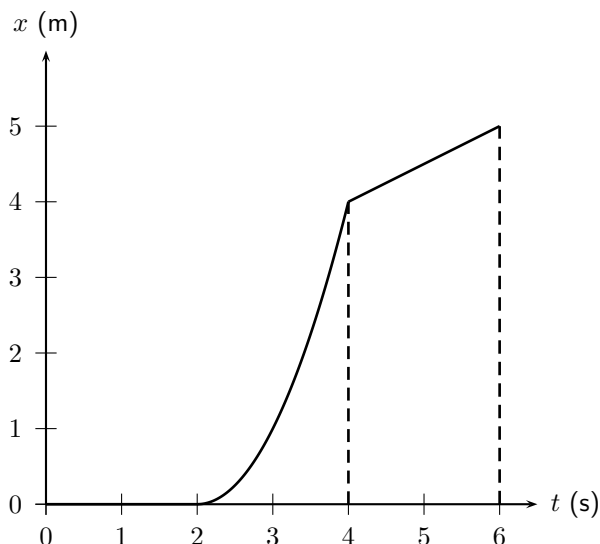
You will also often be required to draw graphs based on a description of the motion in words or from a diagram. Remember that these are just different methods of presenting the same information. If you keep in mind the general shapes of the graphs for the different types of motion, there should not be any difficulty with explaining what is happening.

## 11.8 Worked Examples

The worked examples in this section demonstrate the types of questions that can be asked about graphs.


**Worked Example 24: Description of motion based on a position-time graph**

**Question:** The position vs. time graph for the motion of a car is given below. Draw the corresponding velocity vs. time and acceleration vs. time graphs, and then describe the motion of the car.


**Answer**
**Step 1 : Identify what information is given and what is asked for**

The question gives a position vs. time graph and the following three things are required:

1. Draw a  $v$  vs.  $t$  graph.
2. Draw an  $a$  vs.  $t$  graph.
3. Describe the motion of the car.

To answer these questions, break the motion up into three sections: 0 – 2 seconds, 2 – 4 seconds and 4 – 6 seconds.

**Step 2 : Velocity vs. time graph for 0 – 2 seconds**

For the first 2 seconds we can see that the displacement remains constant - so the object is not moving, thus it has zero velocity during this time. We can reach this conclusion by another path too: remember that the gradient of a displacement vs. time graph is the velocity. For the first 2 seconds we can see that the displacement vs. time graph is a horizontal line, ie. it has a gradient of zero. Thus the velocity during this time is zero and the object is stationary.

**Step 3 : Velocity vs. time graph for 2 – 4 seconds**

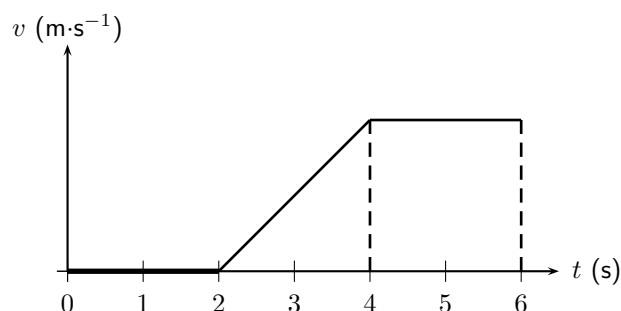
For the next 2 seconds, displacement is increasing with time so the object is moving. Looking at the gradient of the displacement graph we can see that it is not constant. In fact, the slope is getting steeper (the gradient is increasing) as time goes on. Thus, remembering that the gradient of a displacement vs. time graph is the velocity, the velocity must be increasing with time during this phase.

**Step 4 : Velocity vs. time graph for 4 – 6 seconds**

For the final 2 seconds we see that displacement is still increasing with time, but this time the gradient is constant, so we know that the object is now travelling at a constant velocity, thus the velocity vs. time graph will be a horizontal line during this stage. We can now draw the graphs:

So our velocity vs. time graph looks like this one below. Because we haven't been given any values on the vertical axis of the displacement vs. time graph,

we cannot figure out what the exact gradients are and therefore what the values of the velocities are. In this type of question it is just important to show whether velocities are positive or negative, increasing, decreasing or constant.



Once we have the velocity vs. time graph its much easier to get the acceleration vs. time graph as we know that the gradient of a velocity vs. time graph is the just the acceleration.

**Step 5 : Acceleration vs. time graph for 0 – 2 seconds**

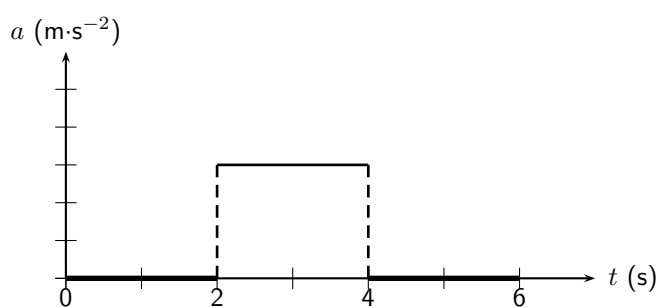
For the first 2 seconds the velocity vs. time graph is horizontal and has a value of zero, thus it has a gradient of zero and there is no acceleration during this time. (This makes sense because we know from the displacement time graph that the object is stationary during this time, so it can't be accelerating).

**Step 6 : Acceleration vs. time graph for 2 – 4 seconds**

For the next 2 seconds the velocity vs. time graph has a positive gradient. This gradient is not changing (i.e. its constant) throughout these 2 seconds so there must be a constant positive acceleration.

**Step 7 : Acceleration vs. time graph for 4 – 6 seconds**

For the final 2 seconds the object is traveling with a constant velocity. During this time the gradient of the velocity vs. time graph is once again zero, and thus the object is not accelerating. The acceleration vs. time graph looks like this:



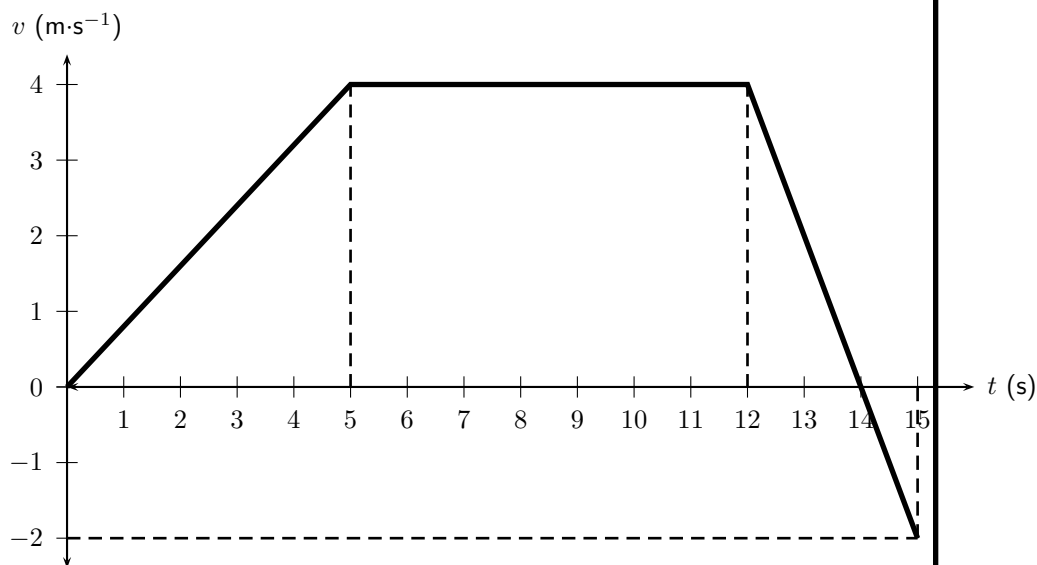
**Step 8 : A description of the object's motion**

A brief description of the motion of the object could read something like this: At  $t = 0$  s and object is stationary at some position and remains stationary until  $t = 2$  s when it begins accelerating. It accelerates in a positive direction for 2 seconds until  $t = 4$  s and then travels at a constant velocity for a further 2 seconds.



**Worked Example 25: Calculations from a velocity vs. time graph**

**Question:** The velocity vs. time graph of a truck is plotted below. Calculate the distance and displacement of the truck after 15 seconds.

**Answer****Step 1 : Decide how to tackle the problem**

We are asked to calculate the distance and displacement of the car. All we need to remember here is that we can use the area between the velocity vs. time graph and the time axis to determine the distance and displacement.

**Step 2 : Determine the area under the velocity vs. time graph**

Break the motion up: 0 – 5 seconds, 5 – 12 seconds, 12 – 14 seconds and 14 – 15 seconds.

For 0 – 5 seconds: The displacement is equal to the area of the triangle on the left:

$$\begin{aligned}\text{Area}_{\triangle} &= \frac{1}{2} b \times h \\ &= \frac{1}{2} \times 5 \text{ s} \times 4 \text{ m} \cdot \text{s}^{-1} \\ &= 10 \text{ m}\end{aligned}$$

For 5 – 12 seconds: The displacement is equal to the area of the rectangle:

$$\begin{aligned}\text{Area}_{\square} &= \ell \times b \\ &= 7 \text{ s} \times 4 \text{ m} \cdot \text{s}^{-1} \\ &= 28 \text{ m}^2\end{aligned}$$

For 12 – 14 seconds the displacement is equal to the area of the triangle above the time axis on the right:

$$\begin{aligned}\text{Area}_{\triangle} &= \frac{1}{2} b \times h \\ &= \frac{1}{2} \times 2 \text{ s} \times 4 \text{ m} \cdot \text{s}^{-1} \\ &= 4 \text{ m}\end{aligned}$$

For 14 – 15 seconds the displacement is equal to the area of the triangle below the time axis:

$$\begin{aligned}\text{Area}_{\triangle} &= \frac{1}{2} b \times h \\ &= \frac{1}{2} \times 1 \text{ s} \times 2 \text{ m} \cdot \text{s}^{-1} \\ &= 1 \text{ m}\end{aligned}$$

**Step 3 : Determine the total distance of the car**

Now the total distance of the car is the sum of all of these areas:

$$\begin{aligned}\Delta x &= 10 \text{ m} + 28 \text{ m} + 4 \text{ m} + 1 \text{ m} \\ &= 43 \text{ m}\end{aligned}$$



**Step 4 : Determine the total displacement of the car**

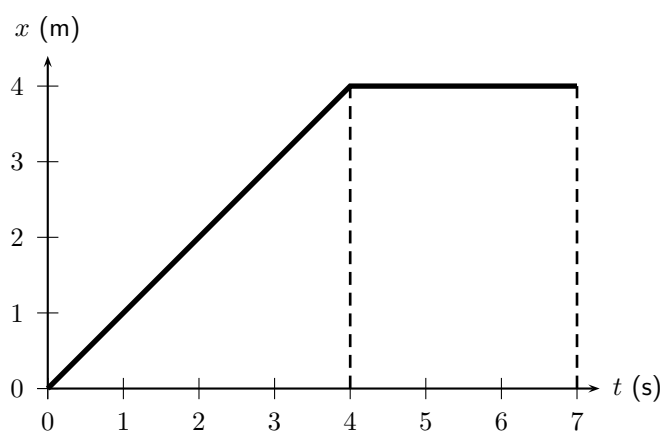
Now the total displacement of the car is just the sum of all of these areas. HOWEVER, because in the last second (from  $t = 14$  s to  $t = 15$  s) the velocity of the car is negative, it means that the car was going in the opposite direction, i.e. back where it came from! So, to find the total displacement, we have to add the first 3 areas (those with positive displacements) and subtract the last one (because it is a displacement in the opposite direction).

$$\begin{aligned}\Delta x &= 10 \text{ m} + 28 \text{ m} + 4 \text{ m} - 1 \text{ m} \\ &= 41 \text{ m in the positive direction}\end{aligned}$$

**Worked Example 26: Velocity from a position vs. time graph**

**Question:** The position vs. time graph below describes the motion of an athlete.

1. What is the velocity of the athlete during the first 4 seconds?
2. What is the velocity of the athlete from  $t = 4$  s to  $t = 7$  s?

**Answer****Step 1 : The velocity during the first 4 seconds**

The velocity is given by the gradient of a position vs. time graph. During the first 4 seconds, this is

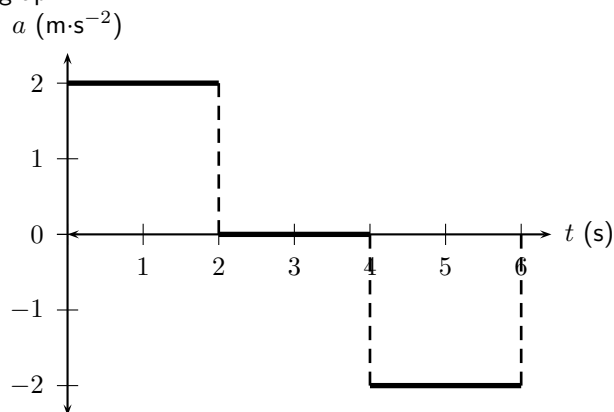
$$\begin{aligned}v &= \frac{\Delta x}{\Delta t} \\ &= \frac{4 \text{ m} - 0 \text{ m}}{4 \text{ s} - 0 \text{ s}} \\ &= 1 \text{ m} \cdot \text{s}^{-1}\end{aligned}$$

**Step 2 : The velocity during the last 3 seconds**

For the last 3 seconds we can see that the displacement stays constant. The graph shows a horizontal line and therefore the gradient is zero. Thus  $v = 0 \text{ m} \cdot \text{s}^{-1}$ .


**Worked Example 27: Drawing a  $v$  vs.  $t$  graph from an  $a$  vs.  $t$  graph**

**Question:** The acceleration vs. time graph for a car starting from rest, is given below. Calculate the velocity of the car and hence draw the velocity vs. time graph.


**Answer**

**Step 1 : Calculate the velocity values by using the area under each part of the graph.**

The motion of the car can be divided into three time sections: 0 – 2 seconds; 2 – 4 seconds and 4 – 6 seconds. To be able to draw the velocity vs. time graph, the velocity for each time section needs to be calculated. The velocity is equal to the area of the square under the graph:

For 0 – 2 seconds:

$$\begin{aligned} \text{Area}_{\square} &= \ell \times b \\ &= 2 \text{ s} \times 2 \text{ m} \cdot \text{s}^{-2} \\ &= 4 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

For 2 – 4 seconds:

$$\begin{aligned} \text{Area}_{\square} &= \ell \times b \\ &= 2 \text{ s} \times 0 \text{ m} \cdot \text{s}^{-2} \\ &= 0 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

For 4 – 6 seconds:

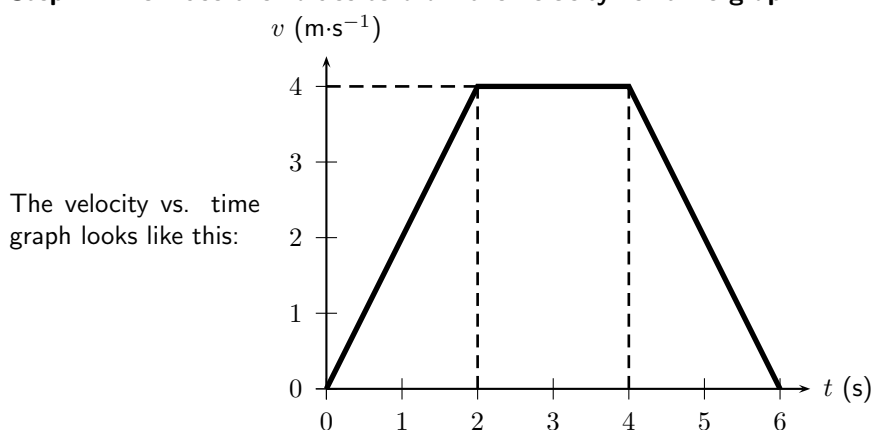
$$\begin{aligned} \text{Area}_{\square} &= \ell \times b \\ &= 2 \text{ s} \times -2 \text{ m} \cdot \text{s}^{-2} \\ &= -4 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

The velocity of the car is  $4 \text{ m} \cdot \text{s}^{-1}$  at  $t = 2 \text{ s}$ .

The velocity of the car is  $0 \text{ m} \cdot \text{s}^{-1}$  from  $t = 2 \text{ s}$  to  $t = 4 \text{ s}$ .

The acceleration had a negative value, which means that the velocity is decreasing. It starts at a velocity of  $4 \text{ m} \cdot \text{s}^{-1}$  and decreases to  $0 \text{ m} \cdot \text{s}^{-1}$ .

**Step 2 : Now use the values to draw the velocity vs. time graph.**



## 11.9 Equations of Motion

In this chapter we will look at the third way to describe motion. We have looked at describing motion in terms of graphs and words. In this section we examine equations that can be used to describe motion.

This section is about solving problems relating to uniformly accelerated motion. In other words, motion at constant acceleration.

The following are the variables that will be used in this section:

$v_i$	=	initial velocity ( $\text{m}\cdot\text{s}^{-1}$ ) at $t = 0$ s
$v_f$	=	final velocity ( $\text{m}\cdot\text{s}^{-1}$ ) at time $t$
$\Delta x$	=	displacement (m)
$t$	=	time (s)
$\Delta t$	=	time interval (s)
$a$	=	acceleration ( $\text{m}\cdot\text{s}^{-2}$ )

$$v_f = v_i + at \quad (11.1)$$

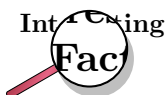
$$\Delta x = \frac{(v_i + v_f)}{2}t \quad (11.2)$$

$$\Delta x = v_i t + \frac{1}{2}at^2 \quad (11.3)$$

$$v_f^2 = v_i^2 + 2a\Delta x \quad (11.4)$$

The questions can vary a lot, but the following method for answering them will always work. Use this when attempting a question that involves motion with constant acceleration. You need any three known quantities ( $v_i$ ,  $v_f$ ,  $\Delta x$ ,  $t$  or  $a$ ) to be able to calculate the fourth one.

1. Read the question carefully to identify the quantities that are given. Write them down.
2. Identify the equation to use. *Write it down!!!*
3. Ensure that all the values are in the correct unit and fill them in your equation.
4. Calculate the answer and fill in its unit.



Galileo Galilei of Pisa, Italy, was the first to determine the correct mathematical law for acceleration: the total distance covered, starting from rest, is proportional to the square of the time. He also concluded that objects retain their velocity unless a force – often friction – acts upon them, refuting the accepted Aristotelian hypothesis that objects "naturally" slow down and stop unless a force acts upon them. This principle was incorporated into Newton's laws of motion (1st law).

### 11.9.1 Finding the Equations of Motion

The following does not form part of the syllabus and can be considered additional information.

### Derivation of Equation 11.1

According to the definition of acceleration:

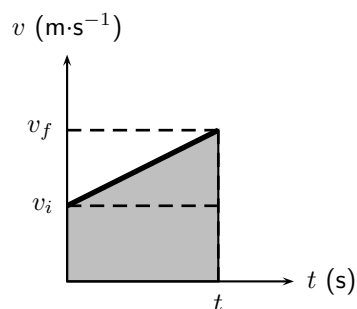
$$a = \frac{\Delta v}{t}$$

where  $\Delta v$  is the change in velocity, i.e.  $\Delta v = v_f - v_i$ . Thus we have

$$\begin{aligned} a &= \frac{v_f - v_i}{t} \\ v_f &= v_i + at \end{aligned}$$

### Derivation of Equation 11.2

We have seen that displacement can be calculated from the area under a velocity vs. time graph. For *uniformly accelerated motion* the most complicated velocity vs. time graph we can have is a straight line. Look at the graph below - it represents an object with a starting velocity of  $v_i$ , accelerating to a final velocity  $v_f$  over a total time  $t$ .



To calculate the final displacement we must calculate the area under the graph - this is just the area of the rectangle added to the area of the triangle. This portion of the graph has been shaded for clarity.

$$\begin{aligned} \text{Area}_{\triangle} &= \frac{1}{2}b \times h \\ &= \frac{1}{2}t \times (v_f - v_i) \\ &= \frac{1}{2}v_f t - \frac{1}{2}v_i t \end{aligned}$$

$$\begin{aligned} \text{Area}_{\square} &= \ell \times b \\ &= t \times v_i \\ &= v_i t \end{aligned}$$

$$\begin{aligned} \text{Displacement} &= \text{Area}_{\square} + \text{Area}_{\triangle} \\ \Delta x &= v_i t + \frac{1}{2}v_f t - \frac{1}{2}v_i t \\ \Delta x &= \frac{(v_i + v_f)}{2}t \end{aligned}$$

**Derivation of Equation 11.3**

This equation is simply derived by eliminating the final velocity  $v_f$  in equation 11.2. Remembering from equation 11.1 that

$$v_f = v_i + at$$

then equation 11.2 becomes

$$\begin{aligned}\Delta x &= \frac{v_i + v_i + at}{2}t \\ &= \frac{2v_it + at^2}{2} \\ \Delta x &= v_it + \frac{1}{2}at^2\end{aligned}$$

**Derivation of Equation 11.4**

This equation is just derived by eliminating the time variable in the above equation. From Equation 11.1 we know

$$t = \frac{v_f - v_i}{a}$$

Substituting this into Equation 11.3 gives

$$\begin{aligned}\Delta x &= v_i\left(\frac{v_f - v_i}{a}\right) + \frac{1}{2}a\left(\frac{v_f - v_i}{a}\right)^2 \\ &= \frac{v_iv_f}{a} - \frac{v_i^2}{a} + \frac{1}{2}a\left(\frac{v_f^2 - 2v_iv_f + v_i^2}{a^2}\right) \\ &= \frac{v_iv_f}{a} - \frac{v_i^2}{a} + \frac{v_f^2}{2a} - \frac{v_iv_f}{a} + \frac{v_i^2}{2a} \\ 2a\Delta x &= -2v_i^2 + v_f^2 + v_i^2 \\ v_f^2 &= v_i^2 + 2a\Delta x\end{aligned}\tag{11.5}$$

This gives us the final velocity in terms of the initial velocity, acceleration and displacement and is independent of the time variable.

**Worked Example 28: Equations of motion**

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

**Answer**

**Step 1 : Identify what information is given and what is asked for**

We are given:

$$\begin{aligned}v_i &= 10 \text{ m}\cdot\text{s}^{-1} \\ \Delta x &= 725 \text{ m} \\ t &= 10 \text{ s} \\ a &= ?\end{aligned}$$

**Step 2 : Find an equation of motion relating the given information to the acceleration**

If you struggle to find the correct equation, find the quantity that is not given and then look for an equation that has this quantity in it.

We can use equation 11.3

$$\Delta x = v_it + \frac{1}{2}at^2$$

**Step 3 : Substitute your values in and find the answer**

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

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

$$725 \text{ m} - 100 \text{ m} = (50 \text{ s}^2) a$$

$$a = 12,5 \text{ m} \cdot \text{s}^{-2}$$

**Step 4 : Quote the final answer**

The racing car is accelerating at  $12,5 \text{ m} \cdot \text{s}^{-2}$  north.

**Worked Example 29: Equations of motion**

**Question:** 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

- its acceleration
- its final velocity
- at what time the motorcycle had covered half the total distance
- what distance the motorcycle had covered in half the total time.

**Answer**

**Step 1 : Identify what information is given and what is asked for**

We are given:

$$\begin{aligned}v_i &= 0 \text{ m} \cdot \text{s}^{-1} \text{ (because the object starts from rest.)} \\ \Delta x &= 64 \text{ m} \\ t &= 4 \text{ s} \\ a &= ? \\ v_f &= ? \\ t &= ? \text{ at half the distance } \Delta x = 32 \text{ m.} \\ \Delta x &= ? \text{ at half the time } t = 2 \text{ s.}\end{aligned}$$

All quantities are in SI units.

**Step 2 : Acceleration:** Find a suitable equation to calculate the acceleration

We can use equations 11.3

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

**Step 3 : Substitute the values and calculate the acceleration**

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

**Step 4 : Final velocity:** Find a suitable equation to calculate the final velocity

We can use equation 11.1 - remember we now also know the acceleration of the object.

$$v_f = v_i + at$$

**Step 5 : Substitute the values and calculate the final velocity**

$$\begin{aligned}v_f &= v_i + at \\ v_f &= 0 \text{ m} \cdot \text{s}^{-1} + (8 \text{ m} \cdot \text{s}^{-2})(4 \text{ s}) \\ &= 32 \text{ m} \cdot \text{s}^{-1} \text{ east}\end{aligned}$$

**Step 6 : Time at half the distance:** Find an equation to calculate the time

We can use equation 11.3:

$$\begin{aligned}\Delta x &= v_i t + \frac{1}{2}at^2 \\ 32 \text{ m} &= (0 \text{ m} \cdot \text{s}^{-1})t + \frac{1}{2}(8 \text{ m} \cdot \text{s}^{-2})(t)^2 \\ 32 \text{ m} &= 0 + (4 \text{ m} \cdot \text{s}^{-2})t^2 \\ 8 \text{ s}^2 &= t^2 \\ t &= 2,83 \text{ s}\end{aligned}$$

**Step 7 : Distance at half the time: Find an equation to relate the distance and time**

Half the time is 2 s, thus we have  $v_i$ ,  $a$  and  $t$  - all in the correct units. We can use equation 11.3 to get the distance:

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



**Exercise: Acceleration**

1. A car starts off at  $10 \text{ m} \cdot \text{s}^{-1}$  and accelerates at  $1 \text{ m} \cdot \text{s}^{-2}$  for 10 s. What is its final velocity?
2. A train starts from rest, and accelerates at  $1 \text{ m} \cdot \text{s}^{-2}$  for 10 s. How far does it move?
3. A bus is going  $30 \text{ m} \cdot \text{s}^{-1}$  and stops in 5 s. What is its stopping distance for this speed?
4. A racing car going at  $20 \text{ m} \cdot \text{s}^{-1}$  stops in a distance of 20 m. What is its acceleration?
5. A ball has a uniform acceleration of  $4 \text{ m} \cdot \text{s}^{-1}$ . Assume the ball starts from rest. Determine the velocity and displacement at the end of 10 s.
6. A motorcycle has a uniform acceleration of  $4 \text{ m} \cdot \text{s}^{-1}$ . Assume the motorcycle has an initial velocity of  $20 \text{ m} \cdot \text{s}^{-1}$ . Determine the velocity and displacement at the end of 12 s.
7. An aeroplane accelerates uniformly such that it goes from rest to  $144 \text{ km} \cdot \text{hr}^{-1}$  in 8 s. Calculate the acceleration required and the total distance that it has traveled in this time.

## 11.10 Applications in the Real-World

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 worked example illustrates this application.







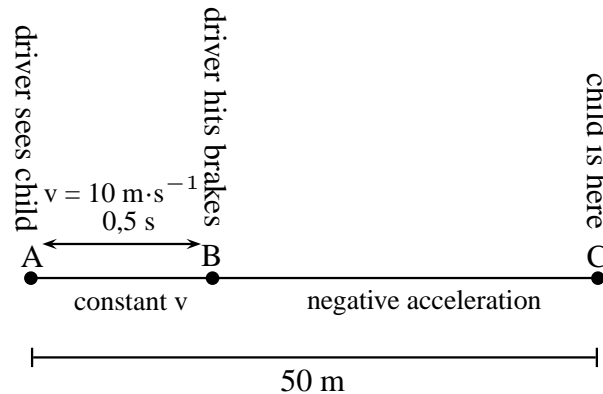
**Worked Example 30: Stopping distance**

**Question:** A truck is travelling at a constant velocity of  $10 \text{ m}\cdot\text{s}^{-1}$  when the driver sees a child 50 m in front of him in the road. He hits the brakes to stop the truck. The truck accelerates at a rate of  $-1.25 \text{ m}\cdot\text{s}^{-2}$ . His reaction time to hit the brakes is 0,5 seconds. Will the truck hit the child?

**Answer**

**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.
- How long 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 traveled, we use:

$$\begin{aligned} v &= \frac{d}{t} \\ 10 &= \frac{d}{0,5} \\ d &= 5 \text{ m} \end{aligned}$$

The truck covers 5 m before the driver hits the brakes.

**Step 3 : Calculate the time BC**

We have the following for the motion between B and C:

$$\begin{aligned} v_i &= 10 \text{ m}\cdot\text{s}^{-1} \\ v_f &= 0 \text{ m}\cdot\text{s}^{-1} \\ a &= -1,25 \text{ m}\cdot\text{s}^{-2} \\ t &= ? \end{aligned}$$

We can use equation 11.1

$$\begin{aligned} v_f &= v_i + at \\ 0 &= 10 + (-1,25)t \\ -10 &= -1,25t \\ t &= 8 \text{ s} \end{aligned}$$

**Step 4 : Calculate the distance BC**

For the distance we can use equation 11.2 or equation 11.3. We will use equation 11.2:

$$\begin{aligned} \Delta x &= \frac{(v_i + v_f)t}{2} \\ \Delta x &= \frac{10 + 0}{2}(8) \\ \Delta x &= 40 \text{ m} \end{aligned}$$

## 11.11 Summary

- 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 distance between the object and the reference point. It has magnitude and direction because it is a vector.
- The distance of an object is the length of the path travelled from the starting point to the end point. It has magnitude only because it is a scalar.
- A vector is a physical quantity with magnitude and direction.
- A scalar is a physical quantity with magnitude only.
- Speed ( $s$ ) is the distance covered ( $d$ ) divided by the time taken ( $\Delta t$ ):

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

- Average velocity ( $v$ ) is the displacement ( $\Delta x$ ) divided by the time taken ( $\Delta t$ ):

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

- Instantaneous speed is the speed at a specific instant in time.
- Instantaneous velocity is the velocity at a specific instant in time.
- Acceleration ( $a$ ) is the change in velocity ( $\Delta v$ ) over a time interval ( $\Delta t$ ):

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

- The gradient of a position - time graph ( $x$  vs.  $t$ ) give the velocity.
- The gradient of a velocity - time graph ( $v$  vs.  $t$ ) give the acceleration.
- The area under a velocity - time graph ( $v$  vs.  $t$ ) give the displacement.
- The area under an acceleration - time graph ( $a$  vs.  $t$ ) gives the velocity.
- The graphs of motion are summarised in figure 11.10.
- The equations of motion are used where constant acceleration takes place:

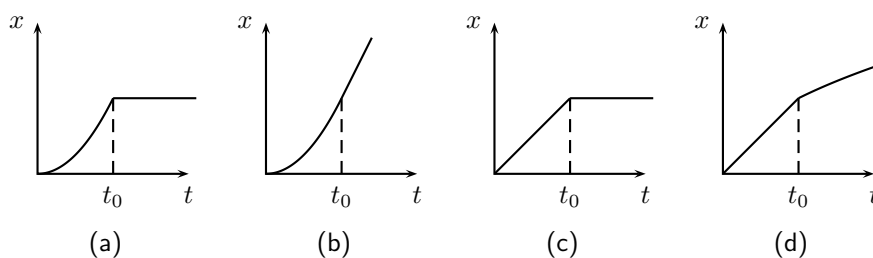
$$\begin{aligned} v_f &= v_i + at \\ \Delta x &= \frac{(v_i + v_f)}{2}t \\ \Delta x &= v_i t + \frac{1}{2}at^2 \\ v_f^2 &= v_i^2 + 2a\Delta x \end{aligned}$$

## 11.12 End of Chapter Exercises: Motion in One Dimension

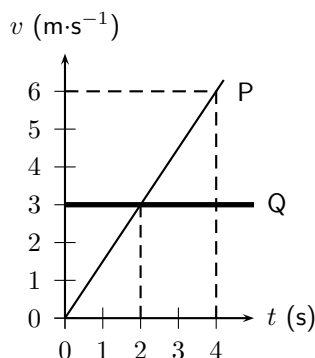
- Give one word/term for the following descriptions.
  - The shortest path from start to finish.
  - A physical quantity with magnitude and direction.
  - The quantity defined as a change in velocity over a time period.
  - The point from where you take measurements.
  - The distance covered in a time interval.
  - The velocity at a specific instant in time.
- Choose an item from column B that match the description in column A. Write down only the letter next to the question number. You may use an item from column B more than once.

Column A	Column B
a. The area under a velocity - time graph	gradient
b. The gradient of a velocity - time graph	area
c. The area under an acceleration - time graph	velocity
d. The gradient of a displacement - time graph	displacement
	acceleration
	slope

- Indicate whether the following statements are TRUE or FALSE. Write only 'true' or 'false'. If the statement is false, write down the correct statement.
  - A scalar is the displacement of an object over a time interval.
  - The position of an object is where it is located.
  - The sign of the velocity of an object tells us in which direction it is travelling.
  - The acceleration of an object is the change of its displacement over a period in time.
- [SC 2003/11] A body accelerates uniformly from rest for  $t_0$  seconds after which it continues with a constant velocity. Which graph is the correct representation of the body's motion?



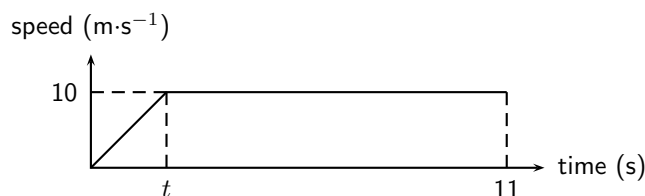
- [SC 2003/11] The velocity-time graphs of two cars are represented by P and Q as shown



The difference in the distance travelled by the two cars (in m) after 4 s is ...

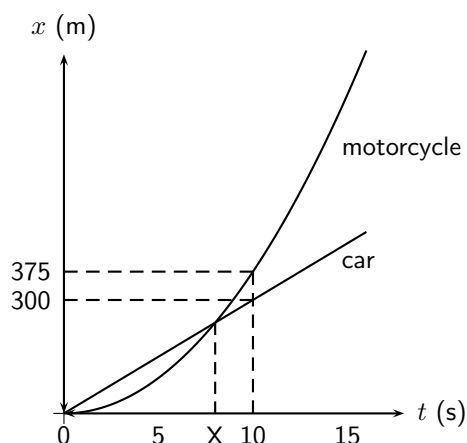
- (a) 12
- (b) 6
- (c) 2
- (d) 0

6. [IEB 2005/11 HG] The graph that follows shows how the speed of an athlete varies with time as he sprints for 100 m.



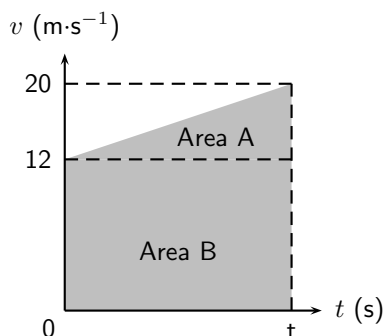
Which of the following equations can be used to correctly determine the time  $t$  for which he accelerates?

- (a)  $100 = (10)(11) - \frac{1}{2}(10)t$
  - (b)  $100 = (10)(11) + \frac{1}{2}(10)t$
  - (c)  $100 = 10t + \frac{1}{2}(10)t^2$
  - (d)  $100 = \frac{1}{2}(0)t + \frac{1}{2}(10)t^2$
7. [SC 2002/03 HG1] In which one of the following cases will the distance covered and the magnitude of the displacement be the same?
- (a) A girl climbs a spiral staircase.
  - (b) An athlete completes one lap in a race.
  - (c) A raindrop falls in still air.
  - (d) A passenger in a train travels from Cape Town to Johannesburg.
8. [SC 2003/11] A car, travelling at constant velocity, passes a stationary motor cycle at a traffic light. As the car overtakes the motorcycle, the motorcycle accelerates uniformly from rest for 10 s. The following displacement-time graph represents the motions of both vehicles from the traffic light onwards.



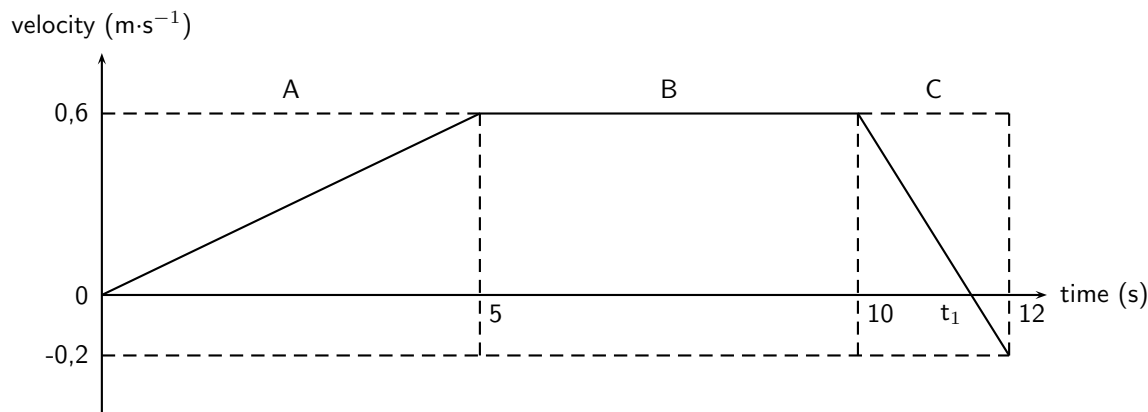
- (a) Use the graph to find the magnitude of the constant velocity of the car.
- (b) Use the information from the graph to show by means of calculation that the magnitude of the acceleration of the motorcycle, for the first 10 s of its motion is  $7,5 \text{ m}\cdot\text{s}^{-2}$ .
- (c) Calculate how long (in seconds) it will take the motorcycle to catch up with the car (point X on the time axis).
- (d) How far behind the motorcycle will the car be after 15 seconds?

9. [IEB 2005/11 HG] Which of the following statements is **true** of a body that accelerates uniformly?
- Its rate of change of position with time remains constant.
  - Its position changes by the same amount in equal time intervals.
  - Its velocity increases by increasing amounts in equal time intervals.
  - Its rate of change of velocity with time remains constant.
10. [IEB 2003/11 HG1] The velocity-time graph for a car moving along a straight horizontal road is shown below.



Which of the following expressions gives the magnitude of the average velocity of the car?

- $\frac{\text{Area A}}{t}$
  - $\frac{\text{Area A} + \text{Area B}}{t}$
  - $\frac{\text{Area B}}{t}$
  - $\frac{\text{Area A} - \text{Area B}}{t}$
11. [SC 2002/11 SG] A car is driven at  $25 \text{ m}\cdot\text{s}^{-1}$  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 m away from the speed trap.
- Calculate the magnitude of the minimum acceleration which the car must have to avoid exceeding the speed limit, if the municipal speed limit is  $16.6 \text{ m}\cdot\text{s}^{-1}$ .
  - 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  $16.6 \text{ m}\cdot\text{s}^{-1}$ .
12. A traffic officer is watching his speed trap equipment at the bottom of a valley. He can see cars as they enter the valley 1 km to his left until they leave the valley 1 km to his right. Nelson is recording the times of cars entering and leaving the valley for a school project. Nelson notices a white Toyota enter the valley at 11:01:30 and leave the valley at 11:02:42. Afterwards, Nelson hears that the traffic officer recorded the Toyota doing  $140 \text{ km}\cdot\text{hr}^{-1}$ .
- What was the time interval ( $\Delta t$ ) for the Toyota to travel through the valley?
  - What was the average speed of the Toyota?
  - Convert this speed to  $\text{km}\cdot\text{hr}^{-1}$ .
  - Discuss whether the Toyota could have been travelling at  $140 \text{ km}\cdot\text{hr}^{-1}$  at the bottom of the valley.
  - Discuss the differences between the instantaneous speed (as measured by the speed trap) and average speed (as measured by Nelson).
13. [IEB 2003/11HG] A velocity-time graph for a ball rolling along a track is shown below. The graph has been divided up into 3 sections, A, B and C for easy reference. (Disregard any effects of friction.)



- (a) Use the graph to determine the following:
- the speed 5 s after the start
  - the distance travelled in Section A
  - the acceleration in Section C
- (b) At time  $t_1$  the velocity-time graph intersects the time axis. Use an appropriate equation of motion to calculate the value of time  $t_1$  (in s).
- (c) Sketch a displacement-time graph for the motion of the ball for these 12 s. (You do not need to calculate the actual values of the displacement for each time interval, but do pay attention to the general shape of this graph during each time interval.)
14. In towns and cities, the speed limit is  $60 \text{ km}\cdot\text{hr}^{-1}$ . The length of the average car is 3.5 m, and the width of the average car is 2 m. In order to cross the road, you need to be able to walk further than the width of a car, before that car reaches you. To cross safely, you should be able to walk at least 2 m further than the width of the car (4 m in total), before the car reaches you.
- If your walking speed is  $4 \text{ km}\cdot\text{hr}^{-1}$ , what is your walking speed in  $\text{m}\cdot\text{s}^{-1}$ ?
  - How long does it take you to walk a distance equal to the width of the average car?
  - What is the speed in  $\text{m}\cdot\text{s}^{-1}$  of a car travelling at the speed limit in a town?
  - How many metres does a car travelling at the speed limit travel, in the same time that it takes you to walk a distance equal to the width of car?
  - Why is the answer to the previous question important?
  - If you see a car driving toward you, and it is 28 m away (the same as the length of 8 cars), is it safe to walk across the road?
  - How far away must a car be, before you think it might be safe to cross? How many car-lengths is this distance?
15. A bus on a straight road starts from rest at a bus stop and accelerates at  $2 \text{ m}\cdot\text{s}^{-2}$  until it reaches a speed of  $20 \text{ m}\cdot\text{s}^{-1}$ . Then the bus travels for 20 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 s.
- How long does the bus take to travel from the first bus stop to the second bus stop?
  - What is the average velocity of the bus during the trip?





## Chapter 12

# Gravity and Mechanical Energy - Grade 10

### 12.1 Weight

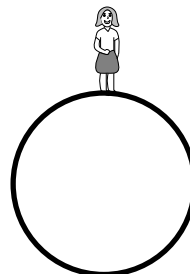
Weight is the gravitational force that the Earth exerts on any object. The weight of an object gives you an indication of how strongly the Earth attracts that body towards its centre. Weight is calculated as follows:

$$\text{Weight} = mg$$

where  $m$  = mass of the object (in kg)  
and  $g$  = the acceleration due to gravity ( $9,8 \text{ m} \cdot \text{s}^{-2}$ )

For example, what is Sarah's weight if her mass is 50 kg. Sarah's weight is calculated according to:

$$\begin{aligned}\text{Weight} &= mg \\ &= (50 \text{ kg})(9,8 \text{ m} \cdot \text{s}^{-2}) \\ &= 490 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2} \\ &= 490 \text{ N}\end{aligned}$$



**Important:** Weight is sometimes abbreviated as  $F_g$  which refers to the force of gravity. Do not use the abbreviation  $W$  for weight as it refers to 'Work'.

Now, we have said that the value of  $g$  is approximately  $9,8 \text{ m} \cdot \text{s}^{-2}$  on the surface of the Earth. The actual value varies slightly over the surface of the Earth. Each planet in our Solar System has its own value for  $g$ . These values are listed as multiples of  $g$  on Earth in Table 12.1



#### Worked Example 31: Determining mass and weight on other planets

**Question:** Sarah's mass on Earth is 50 kg. What is her mass and weight on Mars?

**Answer**

**Step 1 :** Determine what information is given and what is asked

$m$  (on Earth) = 50 kg

$m$  (on Mars) = ?

Planet	Gravitational Acceleration (multiples of $g$ on Earth)
Mercury	0,376
Venus	0,903
Earth	1
Mars	0,38
Jupiter	2,34
Saturn	1,16
Uranus	1,15
Neptune	1,19
Pluto	0,066

Table 12.1: A list of the gravitational accelerations at the surfaces of each of the planets in our solar system. Values are listed as multiples of  $g$  on Earth. **Note:** The "surface" is taken to mean the cloud tops of the gas giants (Jupiter, Saturn, Uranus and Neptune).

Weight (on Mars) = ?

**Step 2 : Calculate her mass on Mars**

Sarah's mass does not change because she is still made up of the same amount of matter. Her mass on Mars is therefore 50 kg.

**Step 3 : Calculate her weight on Mars**

$$\begin{aligned}\text{Sarah's weight} &= 50 \times 0,38 \times 9,8 \\ &= 186,2 \text{ N}\end{aligned}$$

### 12.1.1 Differences between Mass and Weight

Mass is measured in kilograms (kg) and is the amount of matter in an object. An object's mass does not change unless matter is added or removed from the object.

The differences between mass and weight can be summarised in the following table:

Mass	Weight
1. is a measure of how much matter there is in an object.	1. is the force with which the Earth attracts an object.
2. is measured in kilograms.	2. is measured in newtons
3. is the same on any planet.	3. is different on different planets.
4. is a scalar.	4. is a vector.



**Exercise: Weight**

- A bag of sugar has a mass of 1 kg. How much does it weigh:
  - on Earth?
  - on Jupiter?
  - on Pluto?

2. Neil Armstrong was the first man to walk on the surface of the Moon. The gravitational acceleration on the Moon is  $\frac{1}{6}$  of the gravitational acceleration on Earth, and there is negligible gravitational acceleration in outer space. If Neil's mass was 90 kg, what was his weight:
    - (a) on Earth?
    - (b) on the Moon?
    - (c) in outer space?
  3. A monkey has a mass of 15 kg on Earth. The monkey travels to Mars. What is his mass and weight on Mars?
  4. Determine your mass by using a bathroom scale and calculate your weight for each planet in the Solar System, using the values given in Table 12.1
- 

## 12.2 Acceleration due to Gravity

### 12.2.1 Gravitational Fields

A *field* is a region of space in which a mass experiences a force. Therefore, a *gravitational* field is a region of space in which a mass experiences a gravitational force.

### 12.2.2 Free fall



**Important:** Free fall is motion in the Earth's gravitational field when no other forces act on the object.

Free fall is the term used to describe a special kind of motion in the Earth's gravitational field. Free fall is motion in the Earth's gravitational field when no other forces act on the object. It is basically an ideal situation, since in reality, there is always some air friction which slows down the motion.

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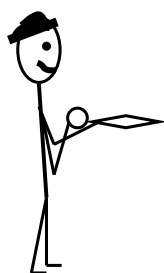
#### Activity :: Experiment : Acceleration due to Gravity

**Aim:** Investigating the acceleration of two different objects during free fall.

**Apparatus:** Tennis ball and a sheet of A4 paper.

**Method:**

1. Hold the tennis ball and sheet of paper (horizontally) the same distance from the ground. Which one would strike the ground first if both were dropped?



2. Drop both objects and observe. Explain your observations.
3. Now crumple the paper into a ball, more or less the same size as the tennis ball. Drop the paper and tennis ball again and observe. Explain your observations.

4. Why do you think the two situations are different?
  5. Compare the value for the acceleration due to gravity of the tennis ball to the crumpled piece of paper.
  6. Predict what will happen if an iron ball and a tennis ball of the same size are dropped from the same height. What will the values for their acceleration due to gravity be?
- 

If a metal ball and tennis ball (of the same size) were dropped from the same height, both would reach the ground at the same time. It does not matter that the one ball is heavier than the other. The acceleration of an object due to gravity is independent of the mass of the object. It does not matter what the mass of the object is.

The shape of the object, however, is important. The sheet of paper took much longer to reach the ground than the tennis ball. This is because the effect of air friction on the paper was much greater than the air friction on the tennis ball.

If we lived in a world where there was no air resistance, the A4 sheet of paper and the tennis ball would reach the ground at the same time. This happens in outer space or in a vacuum.

Galileo Galilei, an Italian scientist, studied the motion of objects. The following case study will tell you more about one of his investigations.

---

#### **Activity :: Case Study : Galileo Galilei**

In the late sixteenth century, it was generally believed that heavier objects would fall faster than lighter objects. The Italian scientist Galileo Galilei thought differently. Galileo hypothesized that two objects would fall at the same rate regardless of their mass. Legend has it that in 1590, Galileo planned out an experiment. He climbed to the top of the Leaning Tower of Pisa and dropped several large objects to test his theory. He wanted to show that two different objects fall at the same rate (as long as we ignore air resistance). Galileo's experiment proved his hypothesis correct; the acceleration of a falling object is independent of the object's mass.

A few decades after Galileo, Sir Isaac Newton would show that acceleration depends upon both force and mass. While there is greater force acting on a larger object, this force is canceled out by the object's greater mass. Thus two objects will fall (actually they are pulled) to the earth at exactly the same rate.

**Questions:** Read the case study above and answer the following questions.

1. Divide into pairs and explain Galileo's experiment to your friend.
  2. Write down an aim and a hypothesis for Galileo's experiment.
  3. Write down the result and conclusion for Galileo's experiment.
- 
- 

#### **Activity :: Research Project : Experimental Design**

Design an experiment similar to the one done by Galileo to prove that the acceleration due to gravity of an object is independent of the object's mass. The investigation must be such that you can perform it at home or at school. Bring your apparatus to school and perform the experiment. Write it up and hand it in for assessment.

**Activity :: Case Study : Determining the acceleration due to gravity 1**

Study the set of photographs alongside showing the position of a ball being dropped from a height at constant time intervals. The distance of the ball from the starting point in each consecutive image is observed to be:  $x_1 = 0$  cm,  $x_2 = 4,9$  cm,  $x_3 = 19,6$  cm,  $x_4 = 44,1$  cm,  $x_5 = 78,4$  cm and  $x_6 = 122,5$  cm. Answer the following questions:

1. Determine the time between each picture if the frequency of the exposures were 10 Hz.

2. Calculate the velocity,  $v_2$ , of the ball between positions 1 and 3.

$$v_2 = \frac{x_3 - x_1}{t_3 - t_1}$$

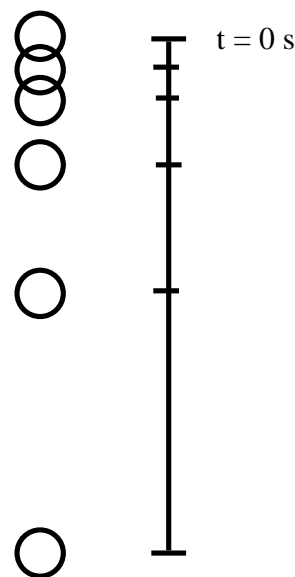
3. Calculate the velocity,  $v_5$ , of the ball between positions 4 and 6.

$$v_5 = \frac{x_6 - x_4}{t_6 - t_4}$$

4. Calculate the acceleration the ball between positions 2 and 5.

$$a = \frac{v_5 - v_2}{t_5 - t_2}$$

5. Compare your answer to the value for the acceleration due to gravity ( $9,8 \text{ m}\cdot\text{s}^{-2}$ ).



The acceleration due to gravity is constant. This means we can use the equations of motion under constant acceleration that we derived in Chapter 11 (on Page 155) to describe the motion of an object in free fall. The equations are repeated here for ease of use.

- $v_i$  = initial velocity ( $\text{m}\cdot\text{s}^{-1}$ ) at  $t = 0$  s  
 $v_f$  = final velocity ( $\text{m}\cdot\text{s}^{-1}$ ) at time  $t$   
 $\Delta x$  = displacement (m)  
 $t$  = time (s)  
 $\Delta t$  = time interval (s)  
 $g$  = acceleration ( $\text{m}\cdot\text{s}^{-2}$ )

$$v_f = v_i + gt \quad (12.1)$$

$$\Delta x = \frac{(v_i + v_f)}{2} t \quad (12.2)$$

$$\Delta x = v_i t + \frac{1}{2} gt^2 \quad (12.3)$$

$$v_f^2 = v_i^2 + 2g\Delta x \quad (12.4)$$

**Activity :: Experiment : Determining the acceleration due to gravity 2**

Work in groups of at least two people.

**Aim:** To determine the acceleration of an object in freefall.

**Apparatus:** Large marble, two stopwatches, measuring tape.

**Method:**

1. Measure the height of a door, from the top of the door to the floor, exactly. Write down the measurement.
2. One person must hold the marble at the top of the door. Drop the marble to the floor at the same time as he/she starts the first stopwatch.
3. The second person watches the floor and starts his stopwatch when the marble hits the floor.
4. The two stopwatches are stopped together and the two times subtracted. The difference in time will give the time taken for the marble to fall from the top of the door to the floor.
5. Design a table to show the results of your experiment. Choose appropriate headings and units.
6. Choose an appropriate equation of motion to calculate the acceleration of the marble. Remember that the marble starts from rest and that its displacement was determined in the first step.
7. Write a conclusion for your investigation.
8. Answer the following questions:
  - (a) Why do you think two stopwatches were used in this investigation?
  - (b) Compare the value for acceleration obtained in your investigation with the value of acceleration due to gravity ( $9,8 \text{ m}\cdot\text{s}^{-2}$ ). Explain your answer.

**Worked Example 32: A freely falling ball**

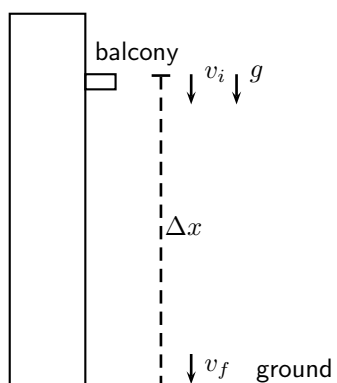
**Question:** A ball is dropped from the balcony of a tall building. The balcony is 15 m above the ground. Assuming gravitational acceleration is  $9,8 \text{ m}\cdot\text{s}^{-2}$ , find:

1. the time required for the ball to hit the ground, and
2. the velocity with which it hits the ground.

**Answer**

**Step 1 : Draw a rough sketch of the problem**

It always helps to understand the problem if we draw a picture like the one below:



**Step 2 : Identify what information is given and what is asked for**

We have these quantities:

$$\begin{aligned}\Delta x &= 15 \text{ m} \\ v_i &= 0 \text{ m} \cdot \text{s}^{-1} \\ g &= 9,8 \text{ m} \cdot \text{s}^{-2}\end{aligned}$$

**Step 3 : Choose up or down as the positive direction.**

Since the ball is falling, we choose down as positive. This means that the values for  $v_i$ ,  $\Delta x$  and  $a$  will be positive.

**Step 4 : Choose the most appropriate equation.**

We can use equation 12.3 to find the time:  $\Delta x = v_i t + \frac{1}{2} g t^2$

**Step 5 : Use the equation to find  $t$ .**

$$\begin{aligned}\Delta x &= v_i t + \frac{1}{2} g t^2 \\ 15 &= (0)t + \frac{1}{2} (9,8)(t)^2 \\ 15 &= 4,9 t^2 \\ t^2 &= 3,0612... \\ t &= 1,7496... \\ t &= 1,75 \text{ s}\end{aligned}$$

**Step 6 : Find the final velocity  $v_f$ .**

Using equation 12.1 to find  $v_f$ :

$$\begin{aligned}v_f &= v_i + g t \\ v_f &= 0 + (9,8)(1,7496...) \\ v_f &= 17,1464...\end{aligned}$$

Remember to add the direction:  $v_f = 17,15 \text{ m} \cdot \text{s}^{-1}$  downwards.

By now you should have seen that free fall motion is just a special case of motion with constant acceleration, and we use the same equations as before. The only difference is that the value for the acceleration,  $a$ , is always equal to the value of gravitational acceleration,  $g$ . In the equations of motion we can replace  $a$  with  $g$ .

**Exercise: Gravitational Acceleration**

1. A brick falls from the top of a 5 m high building. Calculate the velocity with which the brick reaches the ground. How long does it take the brick to reach the ground?
2. A stone is dropped from a window. It takes the stone 1,5 seconds to reach the ground. How high above the ground is the window?
3. An apple falls from a tree from a height of 1,8 m. What is the velocity of the apple when it reaches the ground?

## 12.3 Potential Energy

The potential energy of an object is generally defined as the energy an object has because of its position relative to other objects that it interacts with. There are different kinds of potential energy such as gravitational potential energy, chemical potential energy, electrical potential energy, to name a few. In this section we will be looking at gravitational potential energy.



### Definition: Potential energy

Potential energy is the energy an object has due to its position or state.

*Gravitational* potential energy is the energy of an object due to its position above the surface of the Earth. The symbol  $PE$  is used to refer to gravitational potential energy. You will often find that the words potential energy are used where *gravitational* potential energy is meant. We can define potential energy (or gravitational potential energy, if you like) as:

$$PE = mgh \quad (12.5)$$

where  $PE$  = potential energy measured in joules (J)

$m$  = mass of the object (measured in kg)

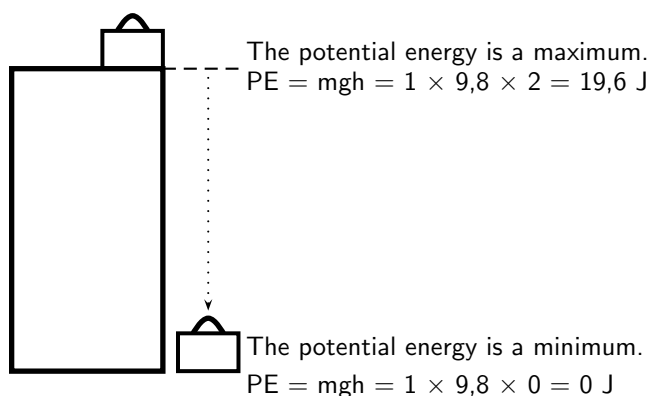
$g$  = gravitational acceleration ( $9,8 \text{ m}\cdot\text{s}^{-2}$ )

$h$  = perpendicular height from the reference point (measured in m)

A suitcase, with a mass of 1 kg, is placed at the top of a 2 m high cupboard. By lifting the suitcase against the force of gravity, we give the suitcase potential energy. This potential energy can be calculated using equation 12.5.

If the suitcase falls off the cupboard, it will lose its potential energy. Halfway down the cupboard, the suitcase will have lost half its potential energy and will have only 9,8 J left. At the bottom of the cupboard the suitcase will have lost all its potential energy and its potential energy will be equal to zero.

Objects have maximum potential energy at a maximum height and will lose their potential energy as they fall.



### Worked Example 33: Gravitational potential energy

**Question:** A brick with a mass of 1 kg is lifted to the top of a 4 m high roof. It slips off the roof and falls to the ground. Calculate the potential



energy of the brick at the top of the roof and on the ground once it has fallen.

**Answer**

**Step 1 : Analyse the question to determine what information is provided**

- The mass of the brick is  $m = 1 \text{ kg}$
- The height lifted is  $h = 4 \text{ m}$

All quantities are in SI units.

**Step 2 : Analyse the question to determine what is being asked**

- We are asked to find the gain in potential energy of the brick as it is lifted onto the roof.
- We also need to calculate the potential energy once the brick is on the ground again.

**Step 3 : Identify the type of potential energy involved**

Since the block is being lifted we are dealing with gravitational potential energy. To work out  $PE$ , we need to know the mass of the object and the height lifted. As both of these are given, we just substitute them into the equation for  $PE$ .

**Step 4 : Substitute and calculate**

$$\begin{aligned} PE &= mgh \\ &= (1)(9,8)(4) \\ &= 39,2 \text{ J} \end{aligned}$$



**Exercise: Gravitational Potential Energy**

- Describe the relationship between an object's gravitational potential energy and its:
  - mass and
  - height above a reference point.
- A boy, of mass 30 kg, climbs onto the roof of their garage. The roof is 2,5 m from the ground. He now jumps off the roof and lands on the ground.
  - How much potential energy has the boy gained by climbing on the roof?
  - The boy now jumps down. What is the potential energy of the boy when he is 1 m from the ground?
  - What is the potential energy of the boy when he lands on the ground?
- A hiker walks up a mountain, 800 m above sea level, to spend the night at the top in the first overnight hut. The second day he walks to the second overnight hut, 500 m above sea level. The third day he returns to his starting point, 200 m above sea level.
  - What is the potential energy of the hiker at the first hut (relative to sea level)?
  - How much potential energy has the hiker lost during the second day?
  - How much potential energy did the hiker have when he started his journey (relative to sea level)?
  - How much potential energy did the hiker have at the end of his journey?

## 12.4 Kinetic Energy



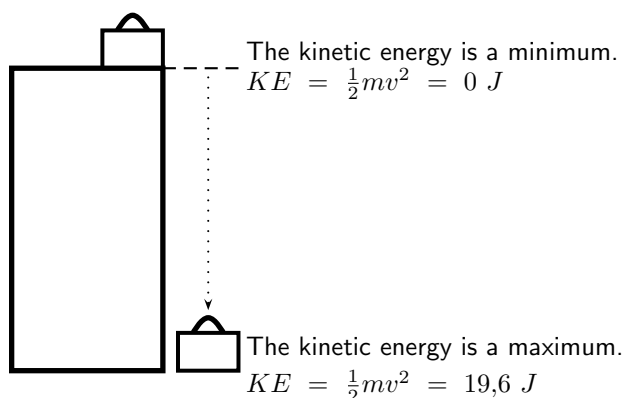
### Definition: Kinetic Energy

Kinetic energy is the energy an object has due to its motion.

Kinetic energy is the energy an object has because of its motion. This means that any moving object has kinetic energy. The faster it moves, the more kinetic energy it has. Kinetic energy ( $KE$ ) is therefore dependent on the velocity of the object. The mass of the object also plays a role. A truck of 2000 kg, moving at  $100 \text{ km}\cdot\text{hr}^{-1}$ , will have more kinetic energy than a car of 500 kg, also moving at  $100 \text{ km}\cdot\text{hr}^{-1}$ . Kinetic energy is defined as:

$$KE = \frac{1}{2}mv^2 \quad (12.6)$$

Consider the 1 kg suitcase on the cupboard that was discussed earlier. When the suitcase falls, it will gain velocity (fall faster), until it reaches the ground with a maximum velocity. The suitcase will not have any kinetic energy when it is on top of the cupboard because it is not moving. Once it starts to fall it will gain kinetic energy, because it gains velocity. Its kinetic energy will increase until it is a maximum when the suitcase reaches the ground.



### Worked Example 34: Calculation of Kinetic Energy

**Question:** A 1 kg brick falls off a 4 m high roof. It reaches the ground with a velocity of  $8,85 \text{ m}\cdot\text{s}^{-1}$ . What is the kinetic energy of the brick when it starts to fall and when it reaches the ground?

**Answer**

**Step 1 : Analyse the question to determine what information is provided**

- The mass of the rock  $m = 1 \text{ kg}$
- The velocity of the rock at the bottom  $v_{\text{bottom}} = 8,85 \text{ m}\cdot\text{s}^{-1}$

These are both in the correct units so we do not have to worry about unit conversions.

**Step 2 : Analyse the question to determine what is being asked**

We are asked to find the kinetic energy of the brick at the top and the bottom. From the definition we know that to work out  $KE$ , we need to know the mass and the velocity of the object and we are given both of these values.

**Step 3 : Calculate the kinetic energy at the top**

Since the brick is not moving at the top, its kinetic energy is zero.

**Step 4 : Substitute and calculate the kinetic energy**

$$\begin{aligned}
 KE &= \frac{1}{2}mv^2 \\
 &= \frac{1}{2}(1 \text{ kg})(8,85 \text{ m} \cdot \text{s}^{-1})^2 \\
 &= 39,2 \text{ J}
 \end{aligned}$$

### 12.4.1 Checking units

According to the equation for kinetic energy, the unit should be  $\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2}$ . We can prove that this unit is equal to the joule, the unit for energy.

$$\begin{aligned}
 (\text{kg})(\text{m} \cdot \text{s}^{-1})^2 &= (\text{kg} \cdot \text{m} \cdot \text{s}^{-2}) \cdot \text{m} \\
 &= \text{N} \cdot \text{m} \quad (\text{because Force (N)} = \text{mass (kg)} \times \text{acceleration (m} \cdot \text{s}^{-2})) \\
 &= \text{J} \quad (\text{Work (J)} = \text{Force (N)} \times \text{distance (m)})
 \end{aligned}$$

We can do the same to prove that the unit for potential energy is equal to the joule:

$$\begin{aligned}
 (\text{kg})(\text{m} \cdot \text{s}^{-2})(\text{m}) &= \text{N} \cdot \text{m} \\
 &= \text{J}
 \end{aligned}$$



#### Worked Example 35: Mixing Units & Energy Calculations

**Question:** A bullet, having a mass of 150 g, is shot with a muzzle velocity of  $960 \text{ m} \cdot \text{s}^{-1}$ . Calculate its kinetic energy.

**Answer**

**Step 1 : Analyse the question to determine what information is provided**

- We are given the mass of the bullet  $m = 150 \text{ g}$ . This is not the unit we want mass to be in. We need to convert to kg.

$$\begin{aligned}
 \text{Mass in grams} \div 1000 &= \text{Mass in kg} \\
 150 \text{ g} \div 1000 &= 0,150 \text{ kg}
 \end{aligned}$$

- We are given the initial velocity with which the bullet leaves the barrel, called the muzzle velocity, and it is  $v = 960 \text{ m} \cdot \text{s}^{-1}$ .

**Step 2 : Analyse the question to determine what is being asked**

- We are asked to find the kinetic energy.

**Step 3 : Substitute and calculate**

We just substitute the mass and velocity (which are known) into the equation for kinetic energy:

$$\begin{aligned}
 KE &= \frac{1}{2}mv^2 \\
 &= \frac{1}{2}(0,150)(960)^2 \\
 &= 69\,120 \text{ J}
 \end{aligned}$$



### Exercise: Kinetic Energy

- Describe the relationship between an object's kinetic energy and its:
  - mass and
  - velocity
- A stone with a mass of 100 g is thrown up into the air. It has an initial velocity of  $3 \text{ m}\cdot\text{s}^{-1}$ . Calculate its kinetic energy
  - as it leaves the thrower's hand.
  - when it reaches its turning point.
- A car with a mass of 700 kg is travelling at a constant velocity of  $100 \text{ km}\cdot\text{hr}^{-1}$ . Calculate the kinetic energy of the car.

## 12.5 Mechanical Energy



**Important:** Mechanical energy is the sum of the gravitational potential energy and the kinetic energy.

Mechanical energy,  $U$ , is simply the sum of gravitational potential energy ( $PE$ ) and the kinetic energy ( $KE$ ). Mechanical energy is defined as:

$$U = PE + KE \quad (12.7)$$

$$\begin{aligned} U &= PE + KE \\ U &= mgh + \frac{1}{2}mv^2 \end{aligned} \quad (12.8)$$

### 12.5.1 Conservation of Mechanical Energy

The Law of Conservation of Energy states:

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



#### Definition: Conservation of Energy

The Law of Conservation of Energy: Energy cannot be created or destroyed, but is merely changed from one form into another.

So far we have looked at two types of energy: gravitational potential energy and kinetic energy. The sum of the gravitational potential energy and kinetic energy is called the mechanical energy. In a closed system, one where there are no external forces acting, the mechanical energy will remain constant. In other words, it will not change (become more or less). This is called the Law of Conservation of Mechanical Energy and it states:

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



**Definition: Conservation of Mechanical Energy**

Law of Conservation of Mechanical Energy: The total amount of mechanical energy in a closed system remains constant.

This means that potential energy can become kinetic energy, or vice versa, but energy cannot 'disappear'. The mechanical energy of an object moving in the Earth's gravitational field (or accelerating as a result of gravity) is constant or conserved, unless external forces, like air resistance, acts on the object.

We can now use the conservation of mechanical energy to calculate the velocity of a body in freefall and show that the velocity is independent of mass.



**Important:** In problems involving the use of conservation of energy, the path taken by the object can be ignored. The only important quantities are the object's velocity (which gives its kinetic energy) and height above the reference point (which gives its gravitational potential energy).



**Important:** In the absence of friction, mechanical energy is conserved and

$$U_{\text{before}} = U_{\text{after}}$$

In the presence of friction, mechanical energy is **not** conserved. The mechanical energy lost is equal to the work done against friction.

$$\Delta U = U_{\text{before}} - U_{\text{after}} = \text{work done against friction}$$

In general, mechanical energy is conserved in the absence of external forces. Examples of external forces are: applied forces, frictional forces and air resistance.

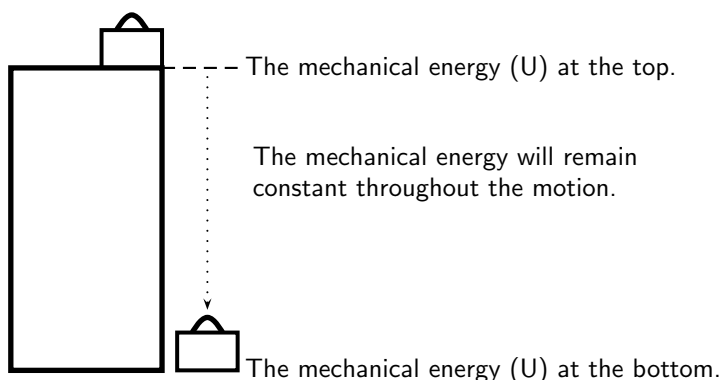
In the presence of internal forces like the force due to gravity or the force in a spring, mechanical energy is conserved.

## 12.5.2 Using the Law of Conservation of Energy

Mechanical energy is conserved (in the absence of friction). Therefore we can say that the sum of the  $PE$  and the  $KE$  anywhere during the motion must be equal to the sum of the  $PE$  and the  $KE$  anywhere else in the motion.

We can now apply this to the example of the suitcase on the cupboard. Consider the mechanical energy of the suitcase at the top and at the bottom. We can say:

$$\begin{aligned} U_{\text{top}} &= U_{\text{bottom}} \\ PE_{\text{top}} + KE_{\text{top}} &= PE_{\text{bottom}} + KE_{\text{bottom}} \\ mgh + \frac{1}{2}mv^2 &= mgh + \frac{1}{2}mv^2 \\ (1)(9,8)(2) + 0 &= 0 + \frac{1}{2}(1)(v^2) \\ 19,6 \text{ J} &= \frac{1}{2}v^2 \\ 39,2 &= v^2 \\ v &= 6,26 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$



The suitcase will strike the ground with a velocity of  $6,26 \text{ m}\cdot\text{s}^{-1}$ .

From this we see that when an object is lifted, like the suitcase in our example, 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 changed from one form into another. In our example, the potential energy that the suitcase loses is changed to kinetic energy.

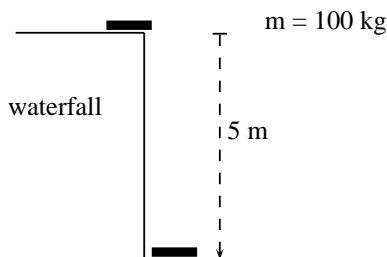
The suitcase will have maximum potential energy at the top of the cupboard and maximum kinetic energy at the bottom of the cupboard. Halfway down it will have half kinetic energy and half potential energy. As it moves down, the potential energy will be converted (changed) into kinetic energy until all the potential energy is gone and only kinetic energy is left. The  $19,6 \text{ J}$  of potential energy at the top will become  $19,6 \text{ J}$  of kinetic energy at the bottom.



### Worked Example 36: Using the Law of Conservation of Mechanical Energy

**Question:** During a flood a tree trunk of mass  $100 \text{ kg}$  falls down a waterfall. The waterfall is  $5 \text{ m}$  high. If air resistance is ignored, calculate

1. the potential energy of the tree trunk at the top of the waterfall.
2. the kinetic energy of the tree trunk at the bottom of the waterfall.
3. the magnitude of the velocity of the tree trunk at the bottom of the waterfall.



**Answer**

**Step 1 :** Analyse the question to determine what information is provided

- The mass of the tree trunk  $m = 100 \text{ kg}$
  - The height of the waterfall  $h = 5 \text{ m}$ .
- These are all in SI units so we do not have to convert.

**Step 2 :** Analyse the question to determine what is being asked

- Potential energy at the top

- Kinetic energy at the bottom
- Velocity at the bottom

**Step 3 : Calculate the potential energy.**

$$\begin{aligned} PE &= mgh \\ PE &= (100)(9,8)(5) \\ PE &= 4900 \text{ J} \end{aligned}$$

**Step 4 : Calculate the kinetic energy.**

The kinetic energy of the tree trunk at the bottom of the waterfall is equal to the potential energy it had at the top of the waterfall. Therefore  $KE = 4900 \text{ J}$ .

**Step 5 : Calculate the velocity.**

To calculate the velocity of the tree trunk we need to use the equation for kinetic energy.

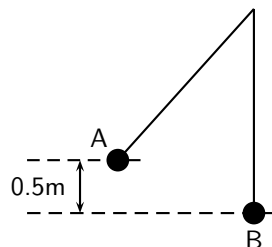
$$\begin{aligned} KE &= \frac{1}{2}mv^2 \\ 4900 &= \frac{1}{2}(100)(v^2) \\ 98 &= v^2 \\ v &= 9,899... \\ v &= 9,90 \text{ m} \cdot \text{s}^{-1} \text{ downwards} \end{aligned}$$



### Worked Example 37: Pendulum

**Question:** A 2 kg metal ball is suspended from a rope. If it is released from point *A* and swings down to the point *B* (the bottom of its arc):

1. Show that the velocity of the ball is independent of its mass.
2. Calculate the velocity of the ball at point *B*.



**Answer**

**Step 1 : Analyse the question to determine what information is provided**

- The mass of the metal ball is  $m = 2 \text{ kg}$
- The change in height going from point *A* to point *B* is  $h = 0,5 \text{ m}$
- The ball is released from point *A* so the velocity at point,  $v_A = 0 \text{ m} \cdot \text{s}^{-1}$ .

All quantities are in SI units.

**Step 2 : Analyse the question to determine what is being asked**

- Prove that the velocity is independent of mass.
- Find the velocity of the metal ball at point  $B$ .

**Step 3 : Apply the Law of Conservation of Mechanical Energy to the situation**

As there is no friction, mechanical energy is conserved. Therefore:

$$\begin{aligned} U_A &= U_B \\ PE_A + KE_A &= PE_B + KE_B \\ mgh_A + \frac{1}{2}m(v_A)^2 &= mgh_B + \frac{1}{2}m(v_B)^2 \\ mgh_A + 0 &= 0 + \frac{1}{2}m(v_B)^2 \\ mgh_A &= \frac{1}{2}m(v_B)^2 \end{aligned}$$

As the mass of the ball  $m$  appears on both sides of the equation, it can be eliminated so that the equation becomes:

$$\begin{aligned} gh_A &= \frac{1}{2}(v_B)^2 \\ 2gh_A &= (v_B)^2 \end{aligned}$$

This proves that the velocity of the ball 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.

**Step 4 : Calculate the velocity of the ball**

We can use the equation above, or do the calculation from 'first principles':

$$\begin{aligned} (v_B)^2 &= 2gh_A \\ (v_B)^2 &= (2)(9.8)(0.5) \\ (v_B)^2 &= 9.8 \\ v_B &= \sqrt{9.8} \text{ m} \cdot \text{s}^{-1} \end{aligned}$$



**Exercise: Potential Energy**

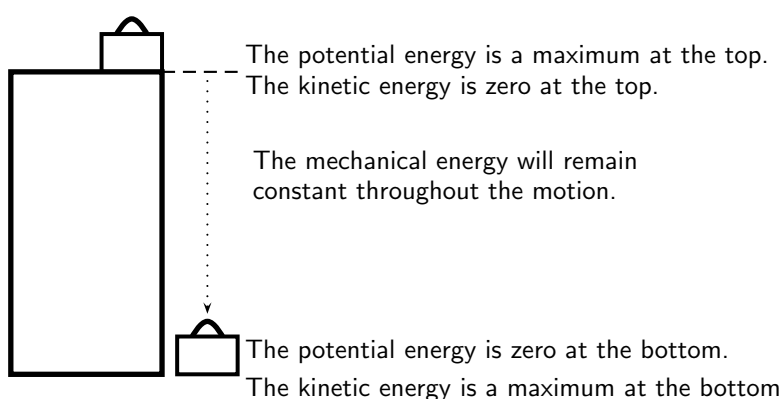
1. A tennis ball, of mass 120 g, is dropped from a height of 5 m. Ignore air friction.
  - (a) What is the potential energy of the ball when it has fallen 3 m?
  - (b) What is the velocity of the ball when it hits the ground?
2. A bullet, mass 50 g, is shot vertically up in the air with a muzzle velocity of  $200 \text{ m} \cdot \text{s}^{-1}$ . Use the Principle of Conservation of Mechanical Energy to determine the height that the bullet will reach. Ignore air friction.
3. A skier, mass 50 kg, is at the top of a 6.4 m ski slope.
  - (a) Determine the maximum velocity that she can reach when she skies to the bottom of the slope.
  - (b) Do you think that she will reach this velocity? Why/Why not?



4. A pendulum bob of mass 1,5 kg, swings from a height A to the bottom of its arc at B. The velocity of the bob at B is  $4 \text{ m}\cdot\text{s}^{-1}$ . Calculate the height A from which the bob was released. Ignore the effects of air friction.
5. Prove that the velocity of an object, in free fall, in a closed system, is independent of its mass.

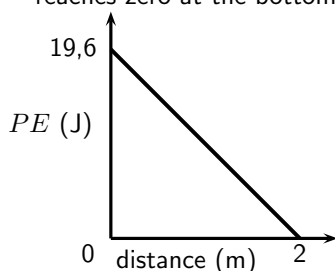
## 12.6 Energy graphs

Let us consider our example of the suitcase on the cupboard, once more.

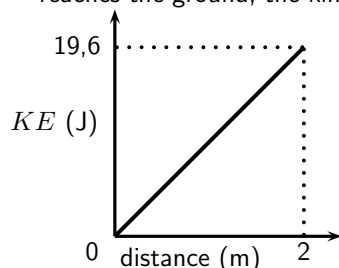


Let's look at each of these quantities and draw a graph for each. We will look at how each quantity changes as the suitcase falls from the top to the bottom of the cupboard.

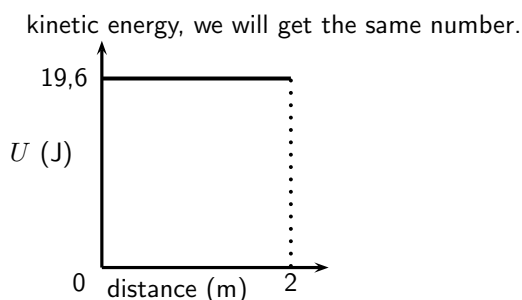
- **Potential energy:** The potential energy starts off at a maximum and decreases until it reaches zero at the bottom of the cupboard. It had fallen a distance of 2 metres.



- **Kinetic energy:** The kinetic energy is zero at the start of the fall. When the suitcase reaches the ground, the kinetic energy is a maximum. We also use distance on the  $x$ -axis.



- **Mechanical energy:** The mechanical energy is constant throughout the motion and is always a maximum. At any point in time, when we add the potential energy and the



## 12.7 Summary

- Mass is the amount of matter an object is made up of.
- Weight is the force with which the Earth attracts a body towards its centre.
- A body is in free fall if it is moving in the Earth's gravitational field and no other forces act on it.
- The equations of motion can be used for free fall problems. The acceleration ( $a$ ) is equal to the acceleration due to gravity ( $g$ ).
- The potential energy of an object is the energy the object has due to its position above a reference point.
- The kinetic energy of an object is the energy the object has due to its motion.
- Mechanical energy of an object is the sum of the potential energy and kinetic energy of the object.
- The unit for energy is the joule (J).
- The Law of Conservation of Energy states that energy cannot be created or destroyed, but can only be changed from one form into another.
- The Law of Conservation of Mechanical Energy states that the total mechanical energy of an isolated system remains constant.
- The table below summarises the most important equations:

Weight	$F_g = m \cdot g$
Equation of motion	$v_f = v_i + gt$
Equation of motion	$\Delta x = \frac{(v_i + v_f)}{2} t$
Equation of motion	$\Delta x = v_i t + \frac{1}{2} g t^2$
Equation of motion	$v_f^2 = v_i^2 + 2g\Delta x$
Potential Energy	$PE = mgh$
Kinetic Energy	$KE = \frac{1}{2} m v^2$
Mechanical Energy	$U = KE + PE$

## 12.8 End of Chapter Exercises: Gravity and Mechanical Energy

1. Give one word/term for the following descriptions.
  - (a) The force with which the Earth attracts a body.
  - (b) The unit for energy.
  - (c) The movement of a body in the Earth's gravitational field when no other forces act on it.
  - (d) The sum of the potential and kinetic energy of a body.

- (e) The amount of matter an object is made up of.
2. Consider the situation where an apple falls from a tree. Indicate whether the following statements regarding this situation are TRUE or FALSE. Write only 'true' or 'false'. If the statement is false, write down the correct statement.
- (a) The potential energy of the apple is a maximum when the apple lands on the ground.
  - (b) The kinetic energy remains constant throughout the motion.
  - (c) To calculate the potential energy of the apple we need the mass of the apple and the height of the tree.
  - (d) The mechanical energy is a maximum only at the beginning of the motion.
  - (e) The apple falls at an acceleration of  $9,8 \text{ m}\cdot\text{s}^{-2}$ .
3. [IEB 2005/11 HG] Consider a ball dropped from a height of 1 m on Earth and an identical ball dropped from 1 m on the Moon. Assume both balls fall freely. The acceleration due to gravity on the Moon is one sixth that on Earth. In what way do the following compare when the ball is dropped on Earth and on the Moon.

	Mass	Weight	Increase in kinetic energy
(a)	the same	the same	the same
(b)	the same	greater on Earth	greater on Earth
(c)	the same	greater on Earth	the same
(d)	greater on Earth	greater on Earth	greater on Earth

4. A man fires a rock out of a slingshot directly upward. The rock has an initial velocity of  $15 \text{ m}\cdot\text{s}^{-1}$ .
- (a) How long will it take for the rock to reach its highest point?
  - (b) What is the maximum height that the rock will reach?
  - (c) Draw graphs to show how the potential energy, kinetic energy and mechanical energy of the rock changes as it moves to its highest point.
5. A metal ball of mass 200 g is tied to a light string to make a pendulum. The ball is pulled to the side to a height (A), 10 cm above the lowest point of the swing (B). Air friction and the mass of the string can be ignored. The ball is let go to swing freely.
- (a) Calculate the potential energy of the ball at point A.
  - (b) Calculate the kinetic energy of the ball at point B.
  - (c) What is the maximum velocity that the ball will reach during its motion?
6. A truck of mass 1,2 tons is parked at the top of a hill, 150 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? Why/why not?
7. A stone is dropped from a window, 3 metres above the ground. The mass of the stone is 25 grams.
- (a) Use the Equations of Motion to calculate the velocity of the stone as it reaches the ground.
  - (b) Use the Principle of Conservation of Energy to prove that your answer in (a) is correct.



## Chapter 13

# Transverse Pulses - Grade 10

### 13.1 Introduction

This chapter forms the basis of the discussion into mechanical waves. Waves are all around us, even though most of us are not aware of it. The most common waves are waves in the sea, but waves can be created in any container of water, ranging from an ocean to a tea-cup. Waves do not only occur in water, they occur in any kind of medium. Earthquakes generate waves that travel through the rock of the Earth. When your friend speaks to you he produces *sound waves* that travel through the air to your ears. Light is made up of electromagnetic waves. A wave is simply moving energy.

### 13.2 What is a medium?

In this chapter, as well as in the following chapters, we will speak about waves moving in a medium. A medium is just the substance or material through which waves move. In other words the medium carries the wave from one place to another. The medium does not create the wave and the medium is not the wave. Therefore the medium does not travel with the wave as the wave propagates through it. Air is a medium for sound waves, water is a medium for water waves and rock is a medium for earthquakes (which are also a type of wave). Air, water and rock are therefore examples of media (media is the plural of medium).

**Definition: Medium**

A medium is the substance or material in which a wave will move.

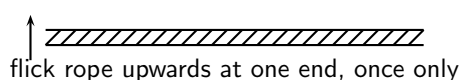
In each medium, the atoms that make up the medium are moved *temporarily* from their rest position. In order for a wave to travel, the different parts of the medium must be able to interact with each other.

### 13.3 What is a pulse?

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**Activity :: Investigation : Observation of Pulses**

Take a heavy rope. Have two people hold the rope stretched out horizontally. Flick the rope at one end only once.



What happens to the disturbance that you created in the rope? Does it stay at the place where it was created or does it move down the length of the rope?

---

In the activity, we created a *pulse*. A pulse is a *single* disturbance that moves through a medium. In a transverse pulse the displacement of the medium is perpendicular to the direction of motion of the pulse. Figure 13.1 shows an example of a transverse pulse. In the activity, the rope or spring was held horizontally and the pulse moved the rope up and down. This was an example of a transverse pulse.



**Definition: Pulse**

A pulse is a single disturbance that moves through a medium.

### 13.3.1 Pulse Length and Amplitude

The amplitude of a pulse is a measurement of how far the medium is displaced momentarily from a position of rest. The pulse length is a measurement of how long the pulse is. Both these quantities are shown in Figure 13.1.



**Definition: Amplitude**

The amplitude of a pulse is a measurement of how far the medium is displaced from rest.

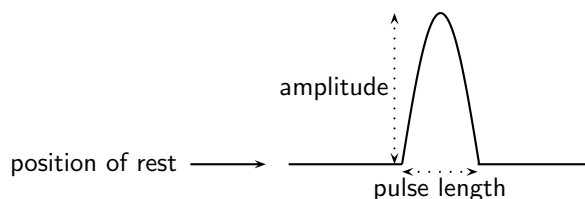
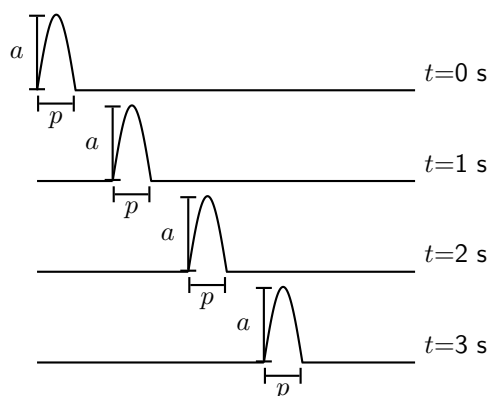


Figure 13.1: Example of a transverse pulse

**Activity :: Investigation : Pulse Length and Amplitude**

The graphs below show the positions of a pulse at different times.



Use your ruler to measure the lengths of  $a$  and  $p$ . Fill your answers in the table.

Time	$a$	$p$
$t = 0 \text{ s}$		
$t = 1 \text{ s}$		
$t = 2 \text{ s}$		
$t = 3 \text{ s}$		

What do you notice about the values of  $a$  and  $p$ ?

---

In the activity, we found that the values for how high the pulse ( $a$ ) is and how wide the pulse ( $p$ ) is the same at different times. *Pulse length* and *amplitude* are two important quantities of a pulse.

### 13.3.2 Pulse Speed



#### Definition: Pulse Speed

Pulse speed is the distance a pulse travels per unit time.

In Chapter 11 we saw that speed was defined as the distance travelled per unit time. We can use the same definition of speed to calculate how fast a pulse travels. If the pulse travels a distance  $d$  in a time  $t$ , then the pulse speed  $v$  is:

$$v = \frac{d}{t}$$



#### Worked Example 38: Pulse Speed

**Question:** A pulse covers a distance of 2 m in 4 s on a heavy rope. Calculate the pulse speed.

**Answer**

**Step 1 : Determine what is given and what is required**

We are given:

- the distance travelled by the pulse:  $d = 2 \text{ m}$
- the time taken to travel 2 m:  $t = 4 \text{ s}$

We are required to calculate the speed of the pulse.

**Step 2 : Determine how to approach the problem**

We can use:

$$v = \frac{d}{t}$$

to calculate the speed of the pulse.

**Step 3 : Calculate the pulse speed**

$$\begin{aligned} v &= \frac{d}{t} \\ &= \frac{2 \text{ m}}{4 \text{ s}} \\ &= 0,5 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

**Step 4 : Write the final answer**

The pulse speed is  $0,5 \text{ m} \cdot \text{s}^{-1}$ .

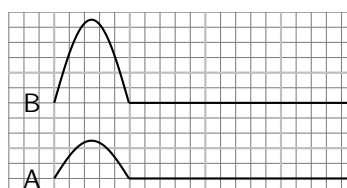


**Important:** The pulse speed depends on the properties of the medium and not on the amplitude or pulse length of the pulse.



### Exercise: Pulse Speed

1. A pulse covers a distance of 5 m in 15 seconds. Calculate the speed of the pulse.
2. A pulse has a speed of  $5 \text{ cm}\cdot\text{s}^{-1}$ . How far does it travel in 2,5 seconds?
3. A pulse has a speed of  $0,5 \text{ m}\cdot\text{s}^{-1}$ . How long does it take to cover a distance of 25 cm?
4. How long will it take a pulse moving at  $0,25 \text{ m}\cdot\text{s}^{-1}$  to travel a distance of 20 m?
5. The diagram shows two pulses in the same medium. Which has the higher speed? Explain your answer.



6. Ocean waves do not bring more water onto the shore until the beach is completely submerged. Explain why this is so.

## 13.4 Graphs of Position and Velocity

When a pulse moves through a medium, there are two different motions: the motion of the particles of the medium and the motion of the pulse. These two motions are at right angles to each other when the pulse is transverse. Each motion will be discussed.

Consider the situation shown in Figure 13.3. The dot represents one particle of the medium. We see that as the pulse moves to the right the particle only moves up and down.

### 13.4.1 Motion of a Particle of the Medium

First we consider the motion of a particle of the medium when a pulse moves through the medium. For the explanation we will zoom into the medium so that we are looking at the atoms of the medium. These atoms are connected to each other as shown in Figure 13.2.



Figure 13.2: Particles in a medium.

When a pulse moves through the medium, the particles in the medium **only** move up and down. We can see this in Figure 13.3 which shows the motion of a single particle as a pulse moves through the medium.



**Important:** A particle in the medium **only** moves up and down when a transverse pulse moves through the medium. The pulse moves from left to right (or right to left). The motion of the particle is perpendicular to the motion of a transverse pulse.



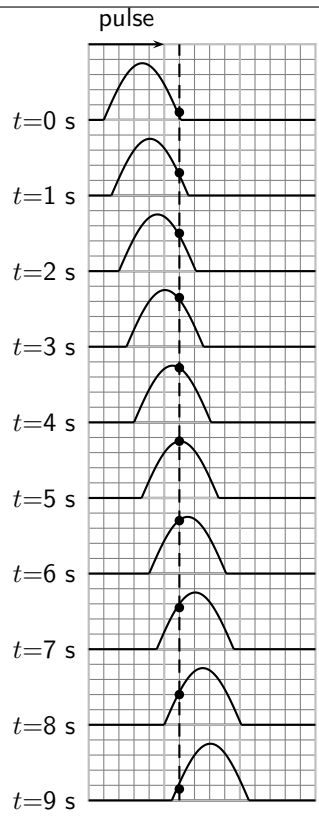


Figure 13.3: Positions of a pulse in a rope at different times. The pulse moves to the right as shown by the arrow. You can also see the motion of a point in the medium through which the pulse is travelling. Each block is 1 cm.

If you consider the motion of the particle as a function of time, you can draw a graph of position vs. time and velocity vs. time.

**Activity :: Investigation : Drawing a position-time graph**

1. Study Figure 13.3 and complete the following table:

time (s)	0	1	2	3	4	5	6	7	8	9
position (cm)										

2. Use your table to draw a graph of position vs. time for a particle in a medium.

The position vs. time graph for a particle in a medium when a pulse passes through the medium is shown in Figure 13.4

**Activity :: Investigation : Drawing a velocity-time graph**

1. Study Figure 13.4 and complete the following table:

time (s)	0	1	2	3	4	5	6	7	8	9
velocity (cm.s <sup>-1</sup> )										

2. Use your table to draw a graph of velocity vs time for a particle in a medium.

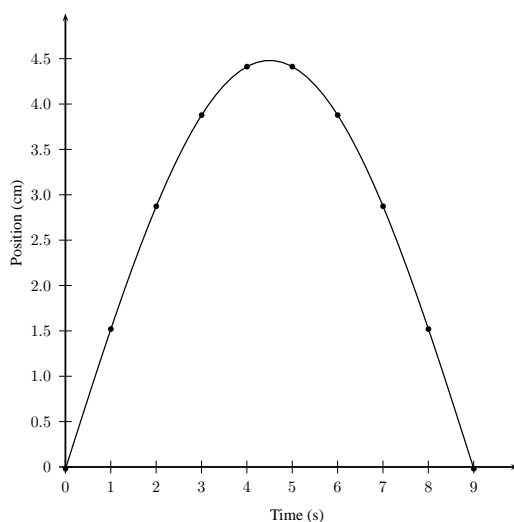


Figure 13.4: Position against Time graph of a particle in the medium through which a transverse pulse is travelling.

The velocity vs. time graph for a particle in a medium when a pulse passes through the medium is shown in Figure 13.5.

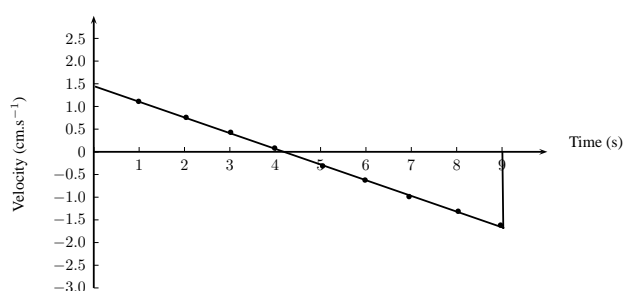


Figure 13.5: Velocity against Time graph of a particle in the medium through which a transverse pulse is travelling.

### 13.4.2 Motion of the Pulse

The motion of the pulse is much simpler than the motion of a particle in the medium.

**Important:** A point on a transverse pulse, eg. the peak, **only** moves in the direction of the motion of the pulse.

**Worked Example 39: Transverse pulse through a medium**  
**Question:**

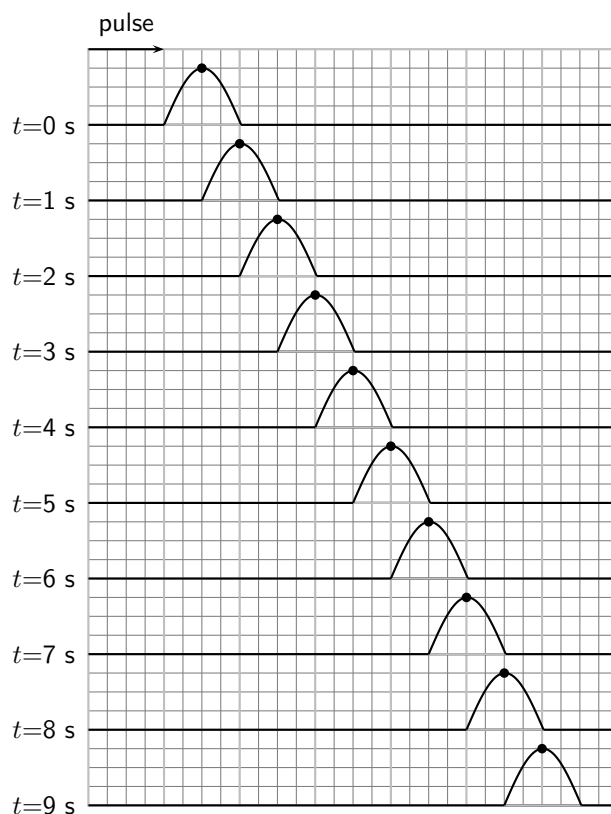


Figure 13.6: Position of the peak of a pulse at different times (since we know the shape of the pulse does not change we can look at only one point on the pulse to keep track of its position, the peak for example). The pulse moves to the right as shown by the arrow. Each square is 0,5 cm.

Given the series of snapshots of a transverse pulse moving through a medium, depicted in Figure 13.6, do the following:

- draw up a table of time, position and velocity,
- plot a position vs. time graph,
- plot a velocity vs. time graph.

#### Answer

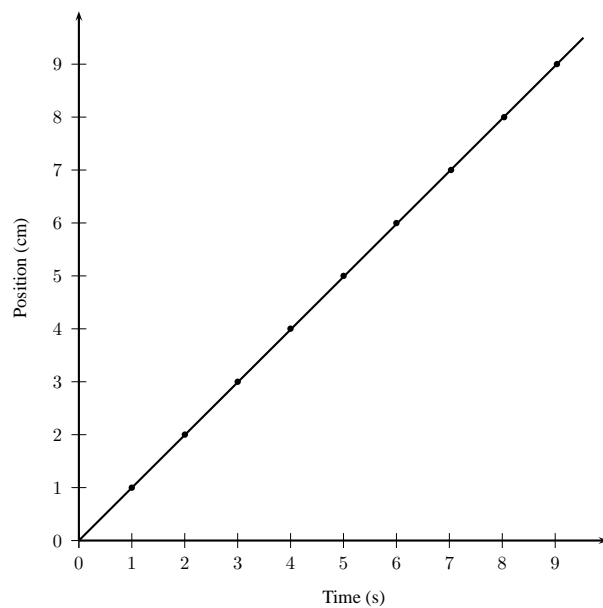
##### Step 1 : Interpreting the figure

Figure 13.6 shows the motion of a pulse through a medium and a dot to indicate the same position on the pulse. If we follow the dot, we can draw a graph of position vs time for a pulse. At  $t = 0$  s the dot is at 0cm. At  $t = 1$  s the dot is 1 cm away from its original position. At  $t = 2$  s the dot is 2 cm away from its original position, and so on.

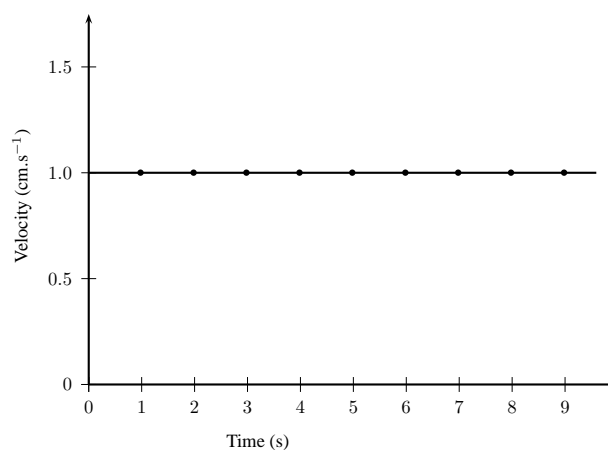
##### Step 2 : We can draw the following table:

time (s)	0	1	2	3	4	5	6	7	8	9
position (cm)	0	1	2	3	4	5	6	7	8	9
velocity ( $\text{cm.s}^{-1}$ )	1	1	1	1	1	1	1	1	1	1

##### Step 3 : A graph of position vs time is drawn as is shown in the figure.

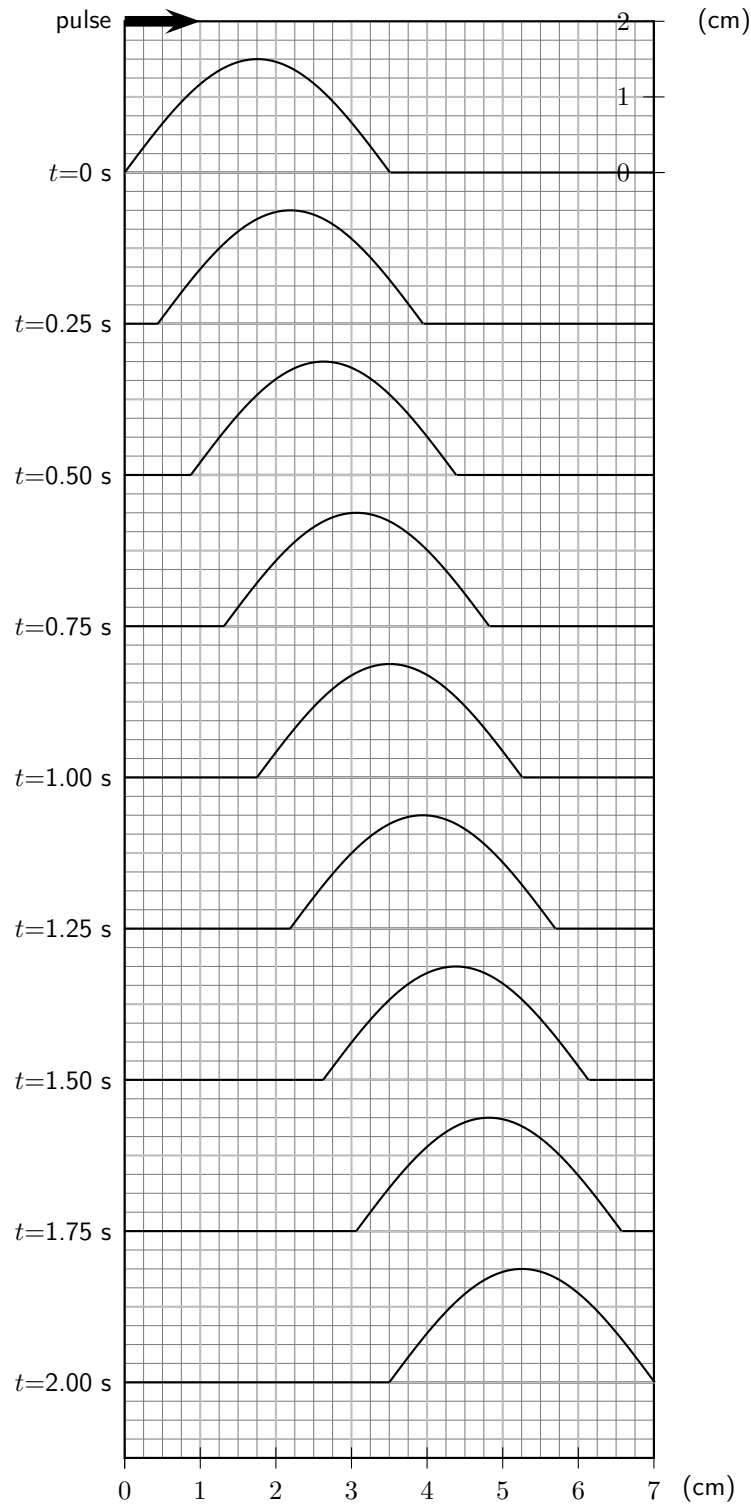


**Step 4 :** Similarly, a graph of velocity vs time is drawn and is shown in the figure below.



### Exercise: Travelling Pulse

1. A pulse is passed through a rope and the following pictures were obtained for each time interval:



(a) Complete the following table for a particle in the medium:

time (s)	0,00	0,25	0,50	0,75	1,00	1,25	1,50	1,75	2,00
position (mm)									
velocity (mm.s <sup>-1</sup> )									

- (b) Draw a position vs. time graph for the motion of the particle at 3 cm.  
(c) Draw a velocity vs. time graph for the motion of the particle at 3 cm.  
(d) Draw a position vs. time graph for the motion of the pulse through the rope.  
(e) Draw a velocity vs. time graph for the motion of the pulse through the rope.

## 13.5 Transmission and Reflection of a Pulse at a Boundary

What happens when a pulse travelling in one medium finds that medium is joined to another?

### Activity :: Investigation : Two ropes

Find two different ropes and tie both ropes together. Hold the joined ropes horizontally and create a pulse by flicking the rope up and down. What happens to the pulse when it encounters the join?

When a pulse is transmitted from one medium to another, like from a thin rope to a thicker one, the nature of the pulse will change where it meets the boundary of the two media (i.e. where the two ropes are joined). Part of the pulse will be reflected and part of it will be transmitted. Figure 13.7 shows the general case of a pulse meeting a boundary. The **incident pulse** is the one that arrives at the boundary. The **reflected pulse** is the one that moves back, away from the boundary. The **transmitted pulse** is the one that moves into the new medium, away from the boundary. The speed of the pulse depends on the mass of the rope; the pulse is faster in the thinner rope and slower in the thick rope. When the speed of the pulse increases, the pulse length will increase. If the speed decreases, the pulse length will decrease.

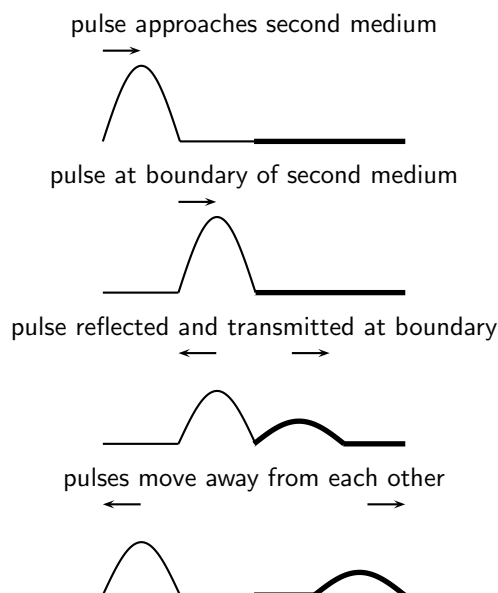


Figure 13.7: Reflection and transmission of a pulse at the boundary between two media.

Consider a pulse moving from a thin rope to a thick rope. As the pulse crosses the boundary, the speed of the pulse will decrease as it moves into the thicker rope. The pulse will move slower, so the pulse length will decrease. The pulse will be reflected and inverted in the thin rope. The reflected pulse will have the same length and speed but will have a smaller amplitude. This is illustrated in Figure 13.8.

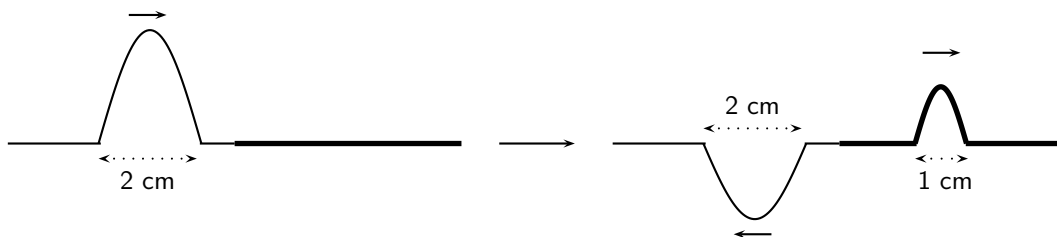


Figure 13.8: Reflection and transmission of a pulse at the boundary between two media.

When a pulse moves from a thick rope to a thin rope, the opposite will happen. As the pulse crosses the boundary, the speed of the pulse will increase as it moves into the thinner rope. The pulse in the thin rope will move faster, so the pulse length will increase. The pulse will be reflected but not inverted in the thick rope. The reflected pulse will have the same length and speed but will have a smaller amplitude. This is illustrated in Figure 13.9

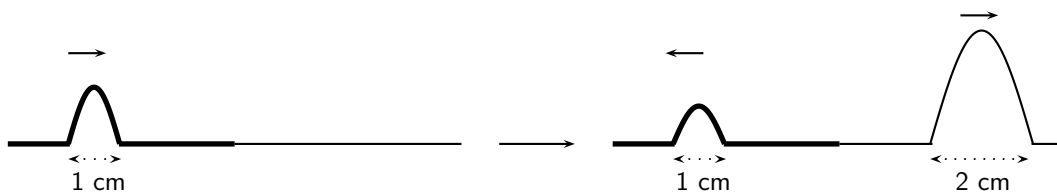


Figure 13.9: Reflection and transmission of a pulse at the boundary between two media.

?

### Exercise: Pulses at a Boundary I

- Fill in the blanks or select the correct answer: A pulse in a heavy rope is traveling towards the boundary with a thin piece of string.
  - The reflected pulse in the heavy rope **will/will not** be inverted because .....
  - The speed of the transmitted pulse will be **greater than/less than/the same as** the speed of the incident pulse.
  - The speed of the reflected pulse will be **greater than/less than/the same as** the speed of the incident pulse.
  - The pulse length of the transmitted pulse will be **greater than/less than/the same as** the pulse length of the incident pulse.
  - The frequency of the transmitted pulse will be **greater than/less than/the same as** the frequency of the incident pulse.
- A pulse in a light string is traveling towards the boundary with a heavy rope.
  - The reflected pulse in the light rope **will/will not** be inverted because .....
  - The speed of the transmitted pulse will be **greater than/less than/the same as** the speed of the incident pulse.
  - The speed of the reflected pulse will be **greater than/less than/the same as** the speed of the incident pulse.
  - The pulse length of the transmitted pulse will be **greater than/less than/the same as** the pulse length of the incident pulse.

## 13.6 Reflection of a Pulse from Fixed and Free Ends

Let us now consider what happens to a pulse when it reaches the end of a medium. The medium can be fixed, like a rope tied to a wall, or it can be free, like a rope tied loosely to a pole.

### 13.6.1 Reflection of a Pulse from a Fixed End

---

#### Activity :: Investigation : Reflection of a Pulse from a Fixed End

Tie a rope to a wall or some other object that cannot move. Create a pulse in the rope by flicking one end up and down. Observe what happens to the pulse when it reaches the wall.

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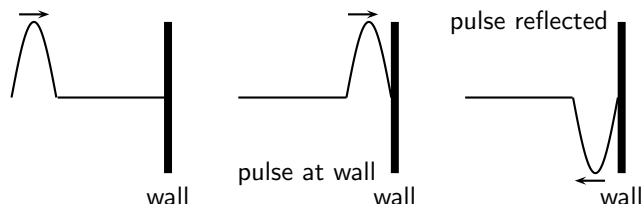


Figure 13.10: Reflection of a pulse from a fixed end.

When the end of the medium is fixed, for example a rope tied to a wall, a pulse reflects from the fixed end, but the pulse is inverted (i.e. it is upside-down). This is shown in Figure 13.10.

### 13.6.2 Reflection of a Pulse from a Free End

---

#### Activity :: Investigation : Reflection of a Pulse from a Free End

Tie a rope to a pole in such a way that the rope can move up and down the pole. Create a pulse in the rope by flicking one end up and down. Observe what happens to the pulse when it reaches the pole.

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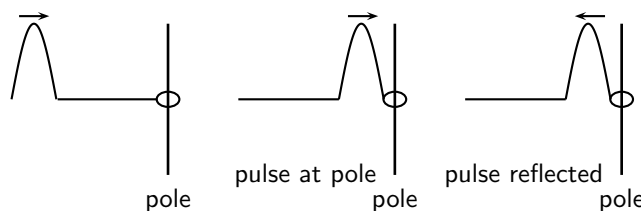


Figure 13.11: Reflection of a pulse from a free end.





**Important:** The fixed and free ends that were discussed in this section are examples of *boundary conditions*. You will see more of boundary conditions as you progress in the Physics syllabus.



### Exercise: Pulses at a Boundary II

1. A rope is tied to a tree and a single pulse is generated. What happens to the pulse as it reaches the tree? Draw a diagram to explain what happens.
2. A rope is tied to a ring that is loosely fitted around a pole. A single pulse is sent along the rope. What will happen to the pulse as it reaches the pole? Draw a diagram to explain your answer.

## 13.7 Superposition of Pulses

Two or more pulses can pass through the same medium at that same time. The resulting pulse is obtained by using the *principle of superposition*. The principle of superposition states that the effect of the pulses is the sum of their individual effects. After pulses pass through each other, each pulse continues along its original direction of travel, and their original amplitudes remain unchanged.

Constructive interference takes place when two pulses meet each other to create a larger pulse. The amplitude of the resulting pulse is the sum of the amplitudes of the two initial pulses. This is shown in Figure 13.12.



**Definition:** Constructive interference is when two pulses meet, resulting in a bigger pulse.

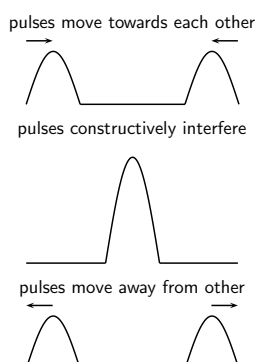


Figure 13.12: Superposition of two pulses: constructive interference.

Destructive interference takes place when two pulses meet and cancel each other. The amplitude of the resulting pulse is the sum of the amplitudes of the two initial pulses, but the one amplitude will be a negative number. This is shown in Figure 13.13. In general, amplitudes of individual pulses add together to give the amplitude of the resultant pulse.



**Definition:** Destructive interference is when two pulses meet, resulting in a smaller pulse.

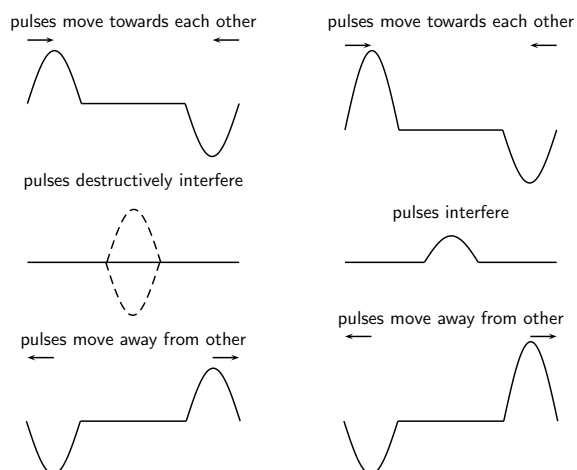
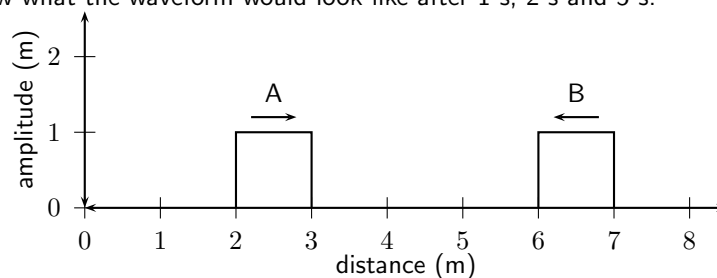


Figure 13.13: Superposition of two pulses. The left-hand series of images demonstrates destructive interference, since the pulses cancel each other. The right-hand series of images demonstrate a partial cancellation of two pulses, as their amplitudes are not the same in magnitude.



#### Worked Example 40: Superposition of Pulses

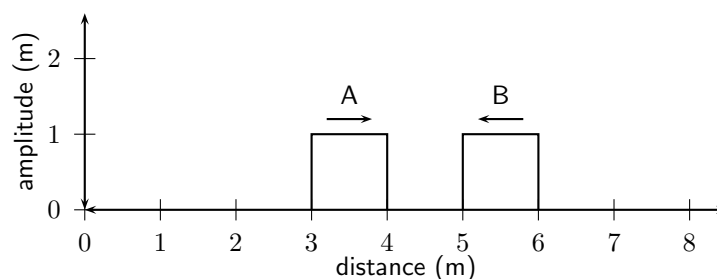
**Question:** The two pulses shown below approach each other at  $1 \text{ m} \cdot \text{s}^{-1}$ . Draw what the waveform would look like after 1 s, 2 s and 5 s.



#### Answer

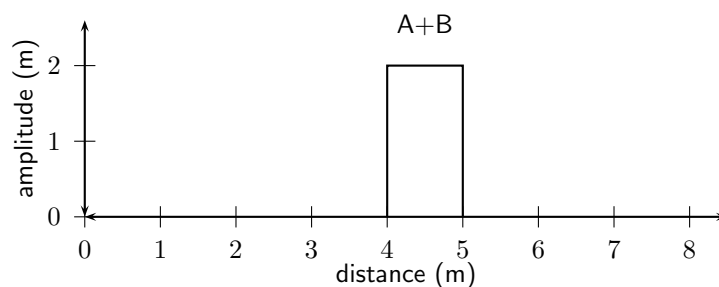
##### Step 1 : After 1 s

After 1 s, pulse A has moved 1 m to the right and pulse B has moved 1 m to the left.

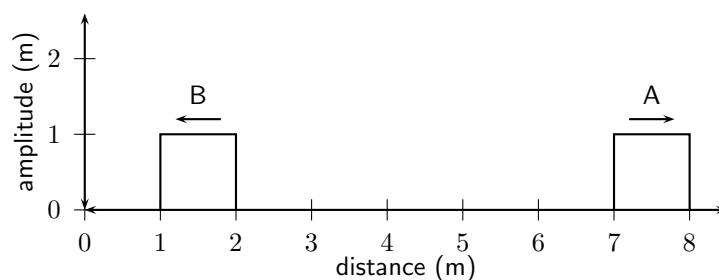


##### Step 2 : After 2 s

After 1 s more, pulse A has moved 1 m to the right and pulse B has moved 1 m to the left.

**Step 3 : After 5 s**

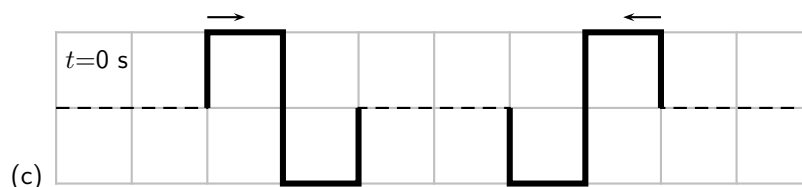
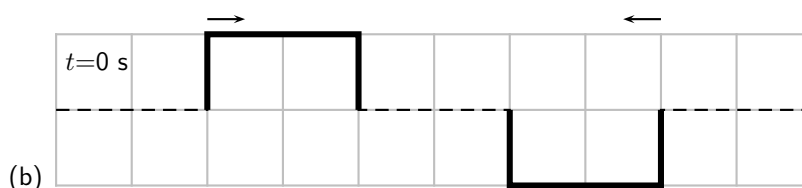
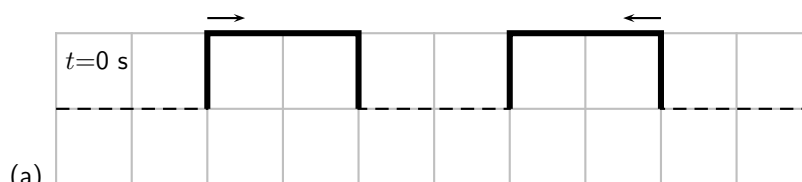
After 5 s more, pulse A has moved 5 m to the right and pulse B has moved 5 m to the left.

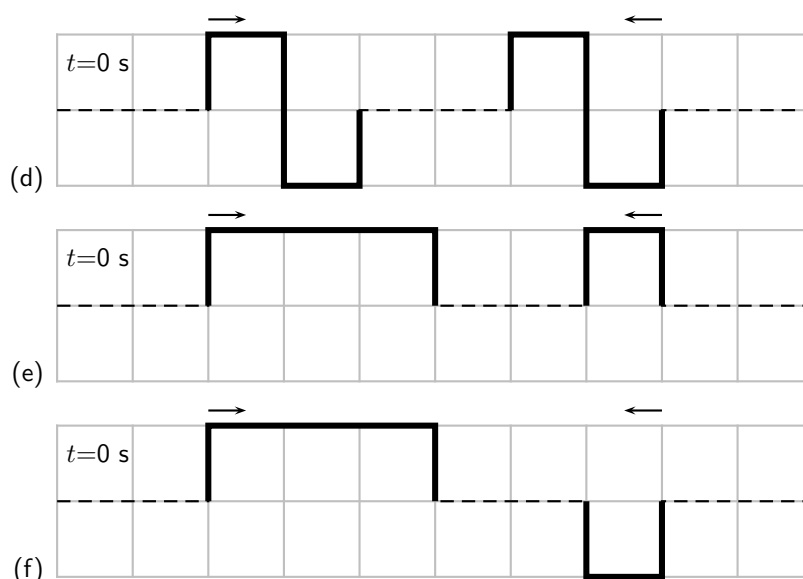


**Important:** The idea of superposition is one that occurs often in physics. You will see *much, much more* of superposition!

**Exercise: Superposition of Pulses**

- For each of the following pulses, draw the resulting wave forms after 1 s, 2 s, 3 s, 4 s and 5 s. Each pulse is travelling at  $1 \text{ m} \cdot \text{s}^{-1}$ . Each block represents 1 m. The pulses are shown as thick black lines and the undisplaced medium as dashed lines.

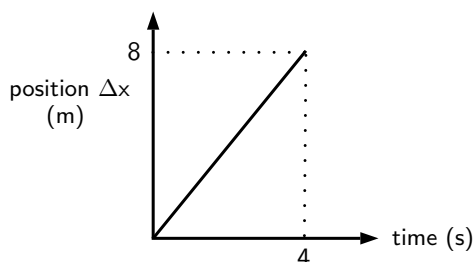




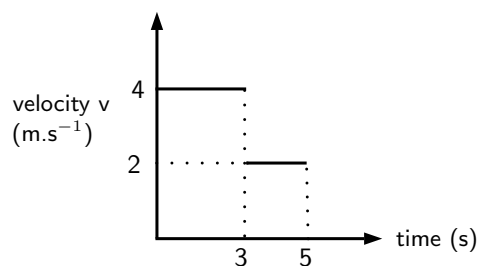
2. (a) What is superposition of waves?
- (b) What is constructive interference? Use the letter "c" to indicate where constructive interference took place in each of your answers for question 1. Only look at diagrams for  $t = 3$  s.
- (c) What is destructive interference? Use the letter "d" to indicate where destructive interference took place in each of your answers for question 1. Only look at diagrams for  $t = 2$  s.

## 13.8 Exercises - Transverse Pulses

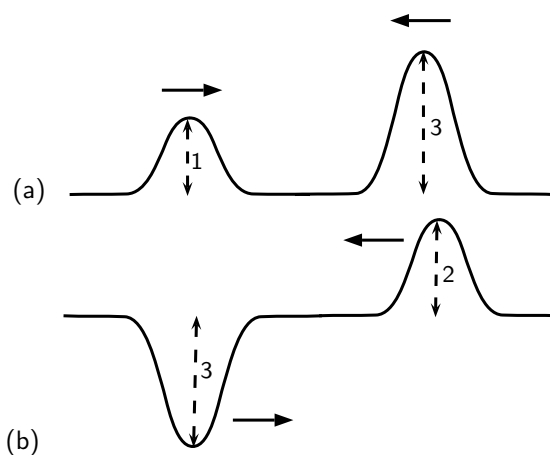
1. A heavy rope is flicked upwards, creating a single pulse in the rope. Make a drawing of the rope and indicate the following in your drawing:
  - (a) The direction of motion of the pulse
  - (b) Amplitude
  - (c) Pulse length
  - (d) Position of rest
2. A pulse has a speed of  $2,5\text{m}\cdot\text{s}^{-1}$ . How far will it have travelled in 6s?
3. A pulse covers a distance of 75cm in 2,5s. What is the speed of the pulse?
4. How long does it take a pulse to cover a distance of 200mm if its speed is  $4\text{m}\cdot\text{s}^{-1}$ ?
5. The following position-time graph for a pulse in a slinky spring is given. Draw an accurate sketch graph of the velocity of the pulse against time.



6. The following velocity-time graph for a particle in a medium is given. Draw an accurate sketch graph of the position of the particle vs. time.



7. Describe what happens to a pulse in a slinky spring when:
- the slinky spring is tied to a wall.
  - the slinky spring is loose, i.e. not tied to a wall.
- (Draw diagrams to explain your answers.)
8. The following diagrams each show two approaching pulses. Redraw the diagrams to show what type of interference takes place, and label the type of interference.



9. Two pulses, A and B, of identical shape and amplitude are simultaneously generated in two identical wires of equal mass and length. Wire A is, however, pulled tighter than wire B. Which pulse will arrive at the other end first, or will they both arrive at the same time?



## Chapter 14

# Transverse Waves - Grade 10

### 14.1 Introduction

Waves occur frequently in nature. The most obvious examples are waves in water, on a dam, in the ocean, or in a bucket. We are most interested in the properties that waves have. All waves have the same properties, so if we study waves in water, then we can transfer our knowledge to predict how other examples of waves will behave.

### 14.2 What is a transverse wave?

We have studied pulses in Chapter 13, and know that a pulse is a single disturbance that travels through a medium. A *wave* is a periodic, continuous disturbance that consists of a *train* of pulses.

**Definition: Wave**

A wave is a periodic, continuous disturbance that consists of a *train* of pulses.

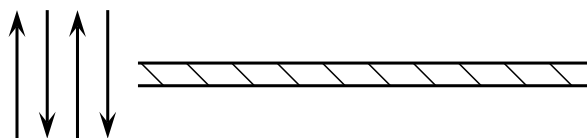
**Definition: Transverse wave**

A *transverse wave* is a wave where the movement of the particles of the medium is perpendicular to the direction of propagation of the wave.

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**Activity :: Investigation : Transverse Waves**

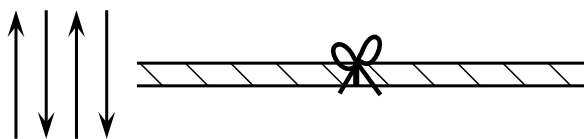
Take a rope or slinky spring. Have two people hold the rope or spring stretched out horizontally. Flick the one end of the rope up and down **continuously** to create a *train of pulses*.



Flick rope up and down

1. Describe what happens to the rope.
2. Draw a diagram of what the rope looks like while the pulses travel along it.

3. In which direction do the pulses travel?
4. Tie a ribbon to the middle of the rope. This indicates a particle in the rope.



Flick rope up and down

5. Flick the rope continuously. Watch the ribbon carefully as the pulses travel through the rope. What happens to the ribbon?
6. Draw a picture to show the motion of the ribbon. Draw the ribbon as a dot and use arrows to indicate how it moves.

---

In the Activity, you have created waves. The medium through which these waves propagated was the rope, which is obviously made up of a very large number of particles (atoms). From the activity, you would have noticed that the wave travelled from left to right, but the particles (the ribbon) moved only up and down.

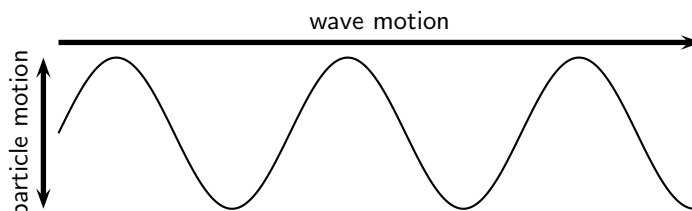


Figure 14.1: A transverse wave, showing the direction of motion of the wave perpendicular to the direction in which the particles move.

When the particles of a medium move at right angles to the direction of propagation of a wave, the wave is called *transverse*. For waves, there is no net displacement of the particles (they return to their equilibrium position), but there is a net displacement of the wave. There are thus two different motions: the motion of the particles of the medium and the motion of the wave.

### 14.2.1 Peaks and Troughs

Waves have moving *peaks* (or *crests*) and *troughs*. A peak is the highest point the medium rises to and a trough is the lowest point the medium sinks to.

Peaks and troughs on a transverse wave are shown in Figure 14.2.

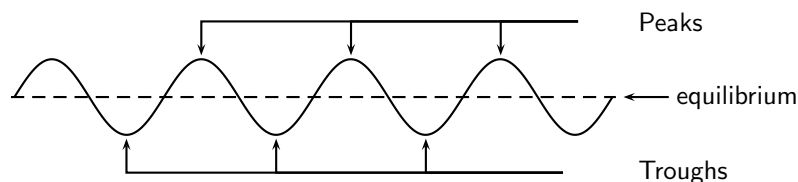


Figure 14.2: Peaks and troughs in a transverse wave.

#### Definition: Peaks and troughs

A *peak* is a point on the wave where the displacement of the medium is at a maximum. A point on the wave is a *trough* if the displacement of the medium at that point is at a minimum.





### 14.2.2 Amplitude and Wavelength

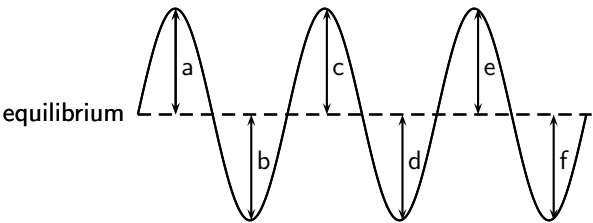
There are a few properties that we saw with pulses that also apply to waves. These are amplitude and wavelength (we called this pulse length).



**Definition: Amplitude**

The *amplitude* is the maximum displacement of a particle from its equilibrium position.

**Activity :: Investigation : Amplitude**

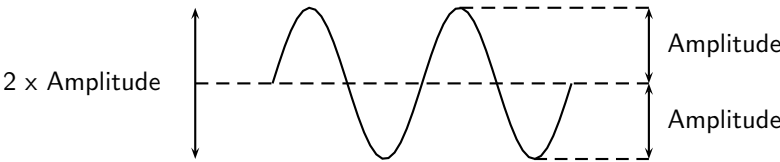


Fill in the table below by measuring the distance between the equilibrium and each peak and troughs in the wave above. Use your ruler to measure the distances.

Peak/Trough	Measurement (cm)
a	
b	
c	
d	
e	
f	

1. What can you say about your results?
2. Are the distances between the equilibrium position and each peak equal?
3. Are the distances between the equilibrium position and each trough equal?
4. Is the distance between the equilibrium position and peak equal to the distance between equilibrium and trough?

As we have seen in the activity on amplitude, the distance between the peak and the equilibrium position is equal to the distance between the trough and the equilibrium position. This distance is known as the *amplitude* of the wave, and is the characteristic height of wave, above or below the equilibrium position. Normally the symbol  $A$  is used to represent the amplitude of a wave. The SI unit of amplitude is the metre (m).

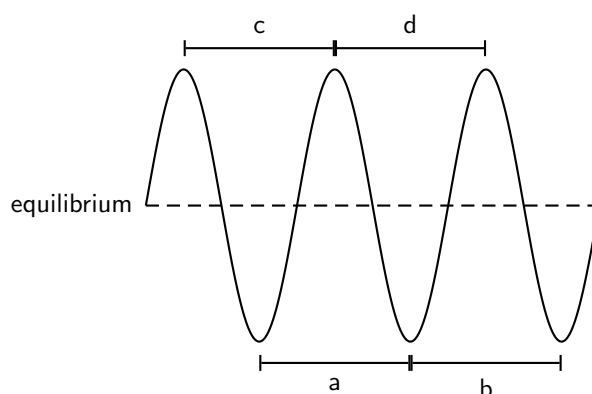


**Worked Example 41: Amplitude of Sea Waves**

**Question:** If the peak of a wave measures 2m above the still water mark in the harbour, what is the amplitude of the wave?

**Answer**

The definition of the amplitude is the height of a peak above the equilibrium position. The still water mark is the height of the water at equilibrium and the peak is 2 m above this, so the amplitude is 2m.

**Activity :: Investigation : Wavelength**

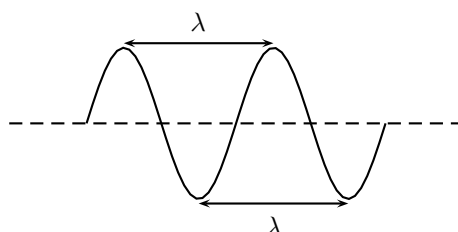
Fill in the table below by measuring the distance between peaks and troughs in the wave above.

	Distance(cm)
a	
b	
c	
d	

1. What can you say about your results?
2. Are the distances between peaks equal?
3. Are the distances between troughs equal?
4. Is the distance between peaks equal to the distance between troughs?

As we have seen in the activity on wavelength, the distance between two *adjacent* peaks is the same no matter which two adjacent peaks you choose. There is a fixed distance between the peaks. Similarly, we have seen that there is a fixed distance between the troughs, no matter which two troughs you look at. More importantly, the distance between two adjacent peaks is the same as the distance between two adjacent troughs. This distance is called the *wavelength* of the wave.

The symbol for the wavelength is  $\lambda$  (the Greek letter *lambda*) and wavelength is measured in metres (m).

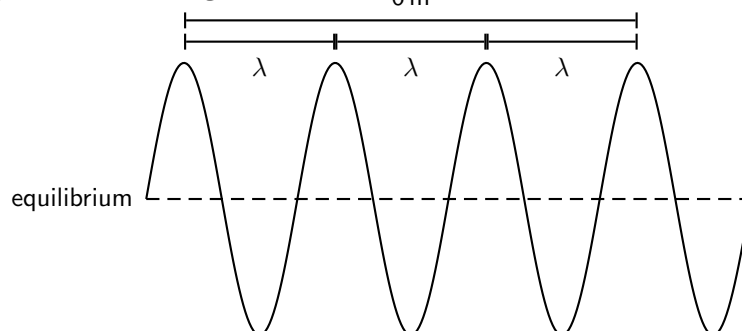


**Worked Example 42: Wavelength**

**Question:** The total distance between 4 consecutive peaks of a transverse wave is 6 m. What is the wavelength of the wave?

**Answer**

**Step 1 : Draw a rough sketch of the situation**

**Step 2 : Determine how to approach the problem**

From the sketch we see that 4 consecutive peaks is equivalent to 3 wavelengths.

**Step 3 : Solve the problem**

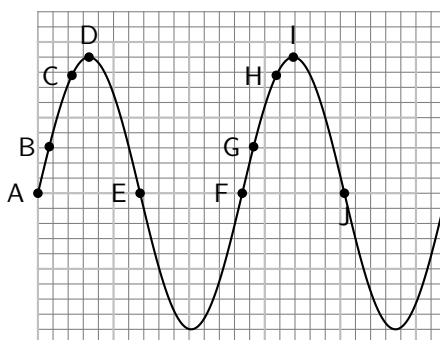
Therefore, the wavelength of the wave is:

$$\begin{aligned} 3\lambda &= 6 \text{ m} \\ \lambda &= \frac{6 \text{ m}}{3} \\ &= 2 \text{ m} \end{aligned}$$

### 14.2.3 Points in Phase

**Activity :: Investigation : Points in Phase**

Fill in the table by measuring the distance between the indicated points.



Points	Distance (cm)
A to F	
B to G	
C to H	
D to I	
E to J	

What do you find?

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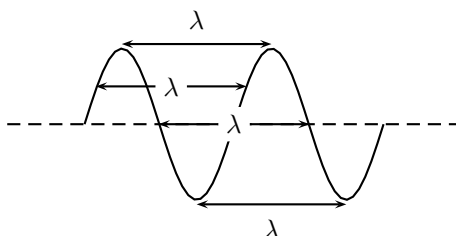
In the activity the distance between the indicated points was the same. These points are then said to be *in phase*. Two points in phase are separated by an integer (0,1,2,3,...) number of complete wave cycles. They do not have to be peaks or troughs, but they must be separated by a complete number of wavelengths.

We then have an alternate definition of the wavelength as the distance between any two adjacent points which are *in phase*.



**Definition: Wavelength of wave**

The wavelength of a wave is the distance between any two adjacent points that are in phase.



Points that are not in phase, those that are not separated by a complete number of wavelengths, are called *out of phase*. Examples of points like these would be *A* and *C*, or *D* and *E*, or *B* and *H* in the Activity.

### 14.2.4 Period and Frequency

Imagine you are sitting next to a pond and you watch the waves going past you. First one peak arrives, then a trough, and then another peak. Suppose you measure the time taken between one peak arriving and then the next. This time will be the same for any two successive peaks passing you. We call this time the *period*, and it is a characteristic of the wave.

The symbol  $T$  is used to represent the period. The period is measured in seconds (s).



**Definition: The period (T) is the time taken for two successive peaks (or troughs) to pass a fixed point.**

Imagine the pond again. Just as a peak passes you, you start your stopwatch and count each peak going past. After 1 second you stop the clock and stop counting. The number of peaks that you have counted in the 1 second is the *frequency* of the wave.



**Definition: The frequency is the number of successive peaks (or troughs) passing a given point in 1 second.**

The frequency and the period are related to each other. As the period is the time taken for 1 peak to pass, then the number of peaks passing the point in 1 second is  $\frac{1}{T}$ . But this is the frequency. So

$$f = \frac{1}{T}$$

or alternatively,

$$T = \frac{1}{f}$$

For example, if the time between two consecutive peaks passing a fixed point is  $\frac{1}{2}$  s, then the period of the wave is  $\frac{1}{2}$  s. Therefore, the frequency of the wave is:

$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{\frac{1}{2} \text{ s}} \\ &= 2 \text{ s}^{-1} \end{aligned}$$

The unit of frequency is the Hertz (Hz) or  $\text{s}^{-1}$ .



#### Worked Example 43: Period and Frequency

**Question:** What is the period of a wave of frequency 10 Hz?

**Answer**

**Step 1 : Determine what is given and what is required**

We are required to calculate the period of a 10 Hz wave.

**Step 2 : Determine how to approach the problem**

We know that:

$$T = \frac{1}{f}$$

**Step 3 : Solve the problem**

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{10 \text{ Hz}} \\ &= 0,1 \text{ s} \end{aligned}$$

**Step 4 : Write the answer**

The period of a 10 Hz wave is 0,1 s.

### 14.2.5 Speed of a Transverse Wave

In Chapter 11, we saw that speed was defined as

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}.$$

The distance between two successive peaks is 1 wavelength,  $\lambda$ . Thus in a time of 1 period, the wave will travel 1 wavelength in distance. Thus the speed of the wave,  $v$ , is:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{\lambda}{T}.$$

However,  $f = \frac{1}{T}$ . Therefore, we can also write:

$$\begin{aligned} v &= \frac{\lambda}{T} \\ &= \lambda \cdot \frac{1}{T} \\ &= \lambda \cdot f \end{aligned}$$

We call this equation the *wave equation*. To summarise, we have that  $v = \lambda \cdot f$  where

- $v$  = speed in  $\text{m} \cdot \text{s}^{-1}$

- $\lambda$  = wavelength in m
- $f$  = frequency in Hz


**Worked Example 44: Speed of a Transverse Wave 1**

**Question:** When a particular string is vibrated at a frequency of 10 Hz, a transverse wave of wavelength 0,25 m is produced. Determine the speed of the wave as it travels along the string.

**Answer**

**Step 1 : Determine what is given and what is required**

- frequency of wave:  $f = 10 \text{ Hz}$
- wavelength of wave:  $\lambda = 0,25 \text{ m}$

We are required to calculate the speed of the wave as it travels along the string. All quantities are in SI units.

**Step 2 : Determine how to approach the problem**

We know that the speed of a wave is:

$$v = f \cdot \lambda$$

and we are given all the necessary quantities.

**Step 3 : Substituting in the values**

$$\begin{aligned} v &= f \cdot \lambda \\ &= (10 \text{ Hz})(0,25 \text{ m}) \\ &= 2,5 \text{ m} \cdot \text{s}^{-1} \end{aligned}$$

**Step 4 : Write the final answer**

The wave travels at  $2,5 \text{ m} \cdot \text{s}^{-1}$  along the string.


**Worked Example 45: Speed of a Transverse Wave 2**

**Question:** 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 cm. If the cork is 2 m from the edge of the pool, how long does it take a ripple passing the cork to reach the edge?

**Answer**

**Step 1 : Determine what is given and what is required**

We are given:

- frequency of wave:  $f = 1 \text{ Hz}$
- wavelength of wave:  $\lambda = 20 \text{ cm}$
- distance of cork from edge of pool:  $d = 2 \text{ m}$

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.

**Step 2 : Determine how to approach the problem**

The time taken for the ripple to reach the edge of the pool is obtained from:

$$t = \frac{d}{v} \quad \left( \text{from } v = \frac{d}{t} \right)$$

We know that

$$v = f \cdot \lambda$$

Therefore,

$$t = \frac{d}{f \cdot \lambda}$$

**Step 3 : Convert wavelength to SI units**

$$20 \text{ cm} = 0,2 \text{ m}$$

**Step 4 : Solve the problem**

$$\begin{aligned} t &= \frac{d}{f \cdot \lambda} \\ &= \frac{2 \text{ m}}{(1 \text{ Hz})(0,2 \text{ m})} \\ &= 10 \text{ s} \end{aligned}$$

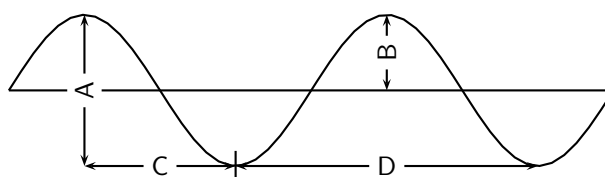
**Step 5 : Write the final answer**

A ripple passing the leaf will take 10 s to reach the edge of the pool.

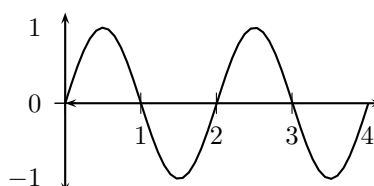
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### Exercise: Waves

- When the particles of a medium move perpendicular to the direction of the wave motion, the wave is called a ..... wave.
- A transverse wave is moving downwards. In what direction do the particles in the medium move?
- Consider the diagram below and answer the questions that follow:



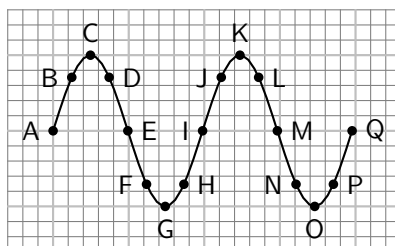
- the wavelength of the wave is shown by letter .....
  - the amplitude of the wave is shown by letter .....
- Draw 2 wavelengths of the following transverse waves on the same graph paper. Label all important values.
    - Wave 1: Amplitude = 1 cm, wavelength = 3 cm
    - Wave 2: Peak to trough distance (vertical) = 3 cm, peak to peak distance (horizontal) = 5 cm
  - You are given the transverse wave below.



Draw the following:

- A wave with twice the amplitude of the given wave.

- (b) A wave with half the amplitude of the given wave.
  - (c) A wave travelling at the same speed with twice the frequency of the given wave.
  - (d) A wave travelling at the same speed with half the frequency of the given wave.
  - (e) A wave with twice the wavelength of the given wave.
  - (f) A wave with half the wavelength of the given wave.
  - (g) A wave travelling at the same speed with twice the period of the given wave.
  - (h) A wave travelling at the same speed with half the period of the given wave.
6. A transverse wave travelling at the same speed with an amplitude of 5 cm has a frequency of 15 Hz. The horizontal distance from a crest to the nearest trough is measured to be 2,5 cm. Find the
    - (a) period of the wave.
    - (b) speed of the wave.
  7. A fly flaps its wings back and forth 200 times each second. Calculate the period of a wing flap.
  8. As the period of a wave increases, the frequency **increases/decreases/does not change**.
  9. Calculate the frequency of rotation of the second hand on a clock.
  10. Microwave ovens produce radiation with a frequency of 2 450 MHz (1 MHz =  $10^6$  Hz) and a wavelength of 0,122 m. What is the wave speed of the radiation?
  11. 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.
12. Tom is fishing from a pier and notices that four wave crests pass by in 8 s and 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.

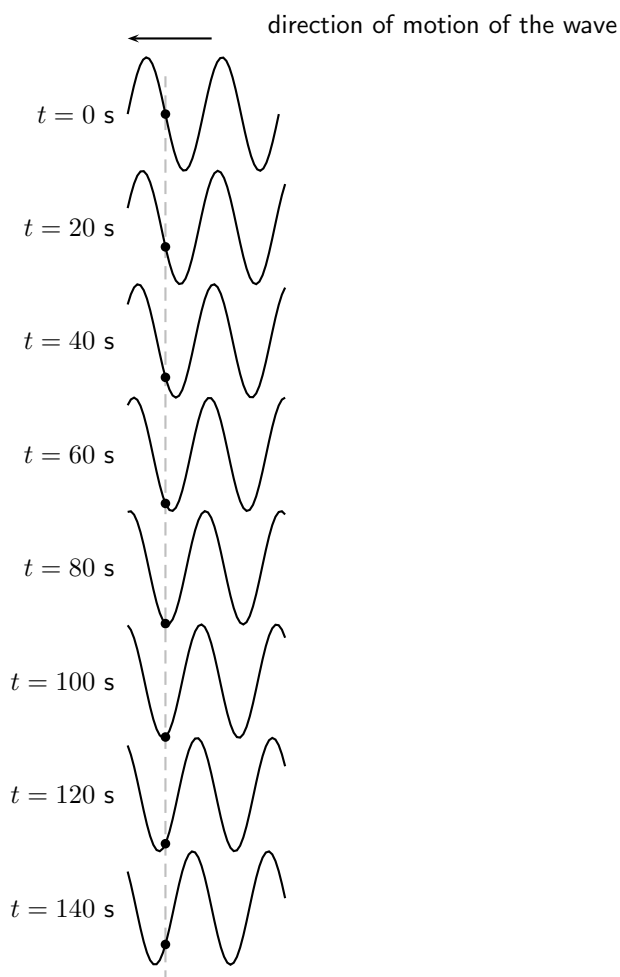
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## 14.3 Graphs of Particle Motion

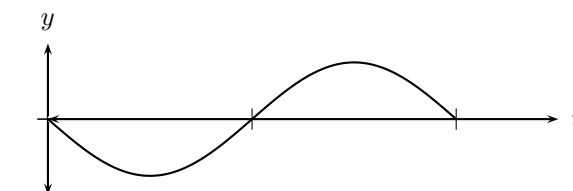
In Chapter 13, we saw that when a pulse moves through a medium, there are two different motions: the motion of the particles of the medium and the motion of the pulse. These two motions are at right angles to each other when the pulse is transverse. Since a transverse wave is a series of transverse pulses, the particle in the medium and the wave move in exactly the same way as for the pulse.

When a transverse wave moves horizontally through the medium, the particles in the medium **only** move up and down. We can see this in the figure below, which shows the motion of a single particle as a transverse wave moves through the medium.



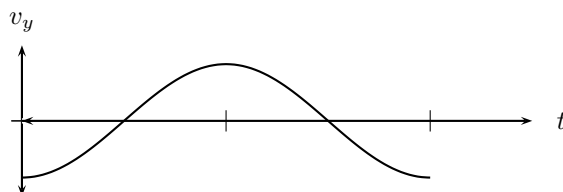
**Important:** A particle in the medium **only** moves up and down when a transverse wave moves horizontally through the medium.

As in Chapter 11, we can draw a graph of the particles' position as a function of time. For the wave shown in the above figure, we can draw the graph shown below.



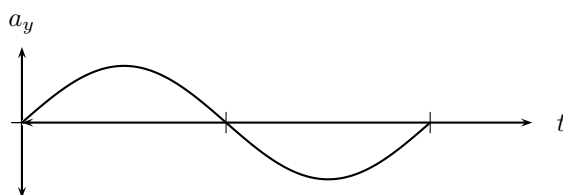
Graph of particle position as a function of time.

The graph of the particle's velocity as a function of time is obtained by taking the gradient of the position vs. time graph. The graph of velocity vs. time for the position vs. time graph above, is shown in the graph below.



Graph of particle velocity as a function of time.

The graph of the particle's acceleration as a function of time is obtained by taking the gradient of the velocity vs. time graph. The graph of acceleration vs. time for the position vs. time graph shown above, is shown below.



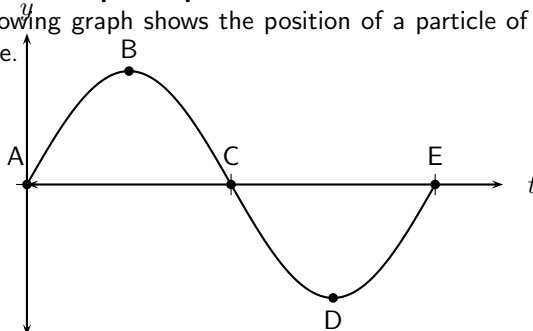
Graph of particle acceleration as a function of time.

As for motion in one dimension, these graphs can be used to describe the motion of the particle in the medium. This is illustrated in the worked examples below.



#### Worked Example 46: Graphs of particle motion 1

**Question:** The following graph shows the position of a particle of a wave as a function of time.



1. Draw the corresponding velocity vs. time graph for the particle.
2. Draw the corresponding acceleration vs. time graph for the particle.

#### Answer

##### Step 1 : Determine what is given and what is required.

The  $y$  vs.  $t$  graph is given.

The  $v_y$  vs.  $t$  and  $a_y$  vs.  $t$  graphs are required.

##### Step 2 : Draw the velocity vs. time graph

To find the velocity of the particle we need to find the gradient of the  $y$  vs.  $t$  graph at each time.

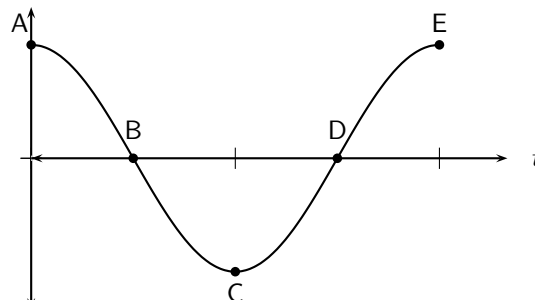
At point A the gradient is a maximum and positive.

At point B the gradient is zero.

At point C the gradient is a maximum, but negative.

At point D the gradient is zero.

At point E the gradient is a maximum and positive again.



### Step 3 : Draw the acceleration vs. time graph

To find the acceleration of the particle we need to find the gradient of the  $v_y$  vs.  $t$  graph at each time.

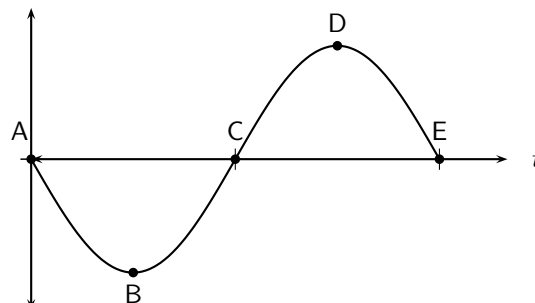
At point A the gradient is zero.

At point B the gradient is negative and a maximum.

At point C the gradient is zero.

At point D the gradient is positive and a maximum.

At point E the gradient is zero.



### Extension: Mathematical Description of Waves

If you look carefully at the pictures of waves you will notice that they look very much like *sine* or *cosine* functions. This is correct. Waves can be described by trigonometric functions that are functions of time or of position. Depending on which case we are dealing with the function will be a function of  $t$  or  $x$ . For example, a function of position would be:

$$y(x) = A \sin \left( 360^\circ \frac{x}{\lambda} + \phi \right)$$

where  $A$  is the amplitude,  $\lambda$  the wavelength and  $\phi$  is a *phase shift*. The phase shift accounts for the fact that the wave at  $x = 0$  does not start at the equilibrium position. A function of time would be:

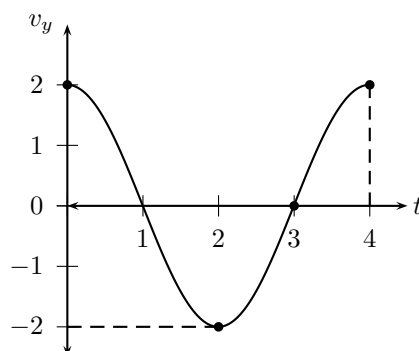
$$y(t) = A \sin \left( 360^\circ \frac{t}{T} + \phi \right)$$

where  $T$  is the period of the wave. Descriptions of the wave incorporate the amplitude, wavelength, frequency or period and a phase shift.



### Exercise: Graphs of Particle Motion

1. The following velocity vs. time graph for a particle in a wave is given.



- (a) Draw the corresponding position vs. time graph for the particle.  
 (b) Draw the corresponding acceleration vs. time graph for the particle.

---

## 14.4 Standing Waves and Boundary Conditions

### 14.4.1 Reflection of a Transverse Wave from a Fixed End

We have seen that when a pulse meets a fixed endpoint, the pulse is reflected, but it is inverted. Since a transverse wave is a series of pulses, a transverse wave meeting a fixed endpoint is also reflected and the reflected wave is inverted. That means that the peaks and troughs are swapped around.

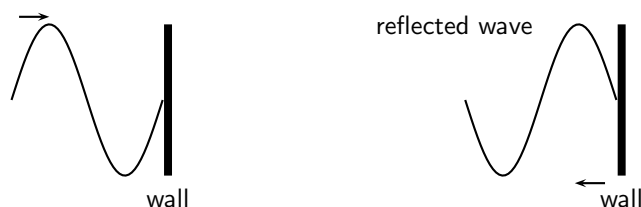


Figure 14.3: Reflection of a transverse wave from a fixed end.

### 14.4.2 Reflection of a Transverse Wave from a Free End

If transverse waves are reflected from an end, which is free to move, the waves sent down the string are reflected but do not suffer a phase shift as shown in Figure 14.4.

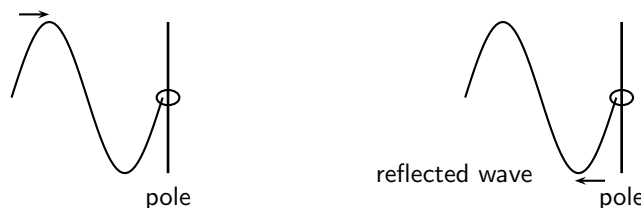


Figure 14.4: Reflection of a transverse wave from a free end.

### 14.4.3 Standing Waves

What happens when a reflected transverse wave meets an incident transverse wave? When two waves move in opposite directions, through each other, interference takes place. If the two waves have the same frequency and wavelength then *standing waves* are generated.

Standing waves are so-called because they appear to be standing still.

---

#### Activity :: Investigation : Creating Standing Waves

Tie a rope to a fixed object such that the tied end does not move. Continuously move the free end up and down to generate firstly transverse waves and later standing waves.

---

We can now look closely how standing waves are formed. Figure 14.5 shows a reflected wave meeting an incident wave.

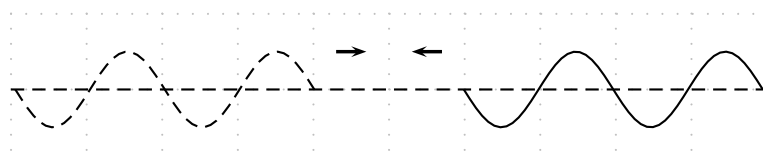


Figure 14.5: A reflected wave (solid line) approaches the incident wave (dashed line).

When they touch, both waves have an amplitude of zero:

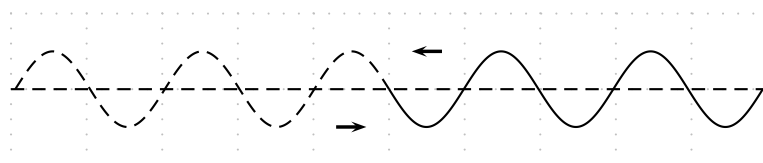


Figure 14.6: A reflected wave (solid line) meets the incident wave (dashed line).

If we wait for a short time the ends of the two waves move past each other and the waves overlap. To find the resultant wave, we add the two together.

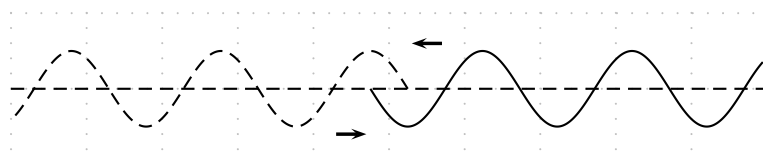
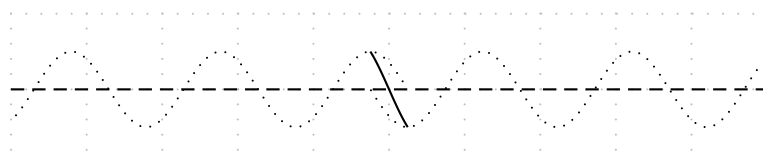
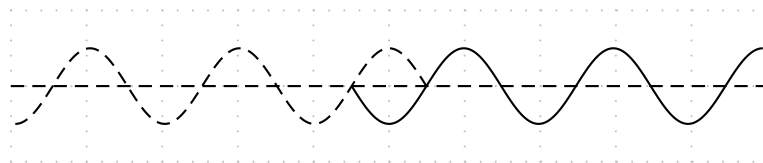


Figure 14.7: A reflected wave (solid line) overlaps slightly with the incident wave (dashed line).

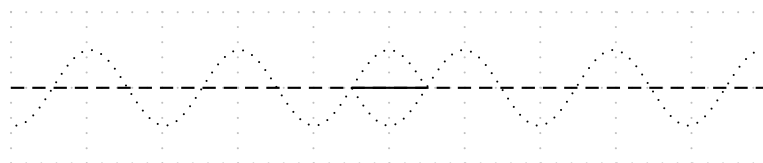
In this picture, we show the two waves as dotted lines and the sum of the two in the overlap region is shown as a solid line:



The important thing to note in this case is that there are some points where the two waves always destructively interfere to zero. If we let the two waves move a little further we get the picture below:

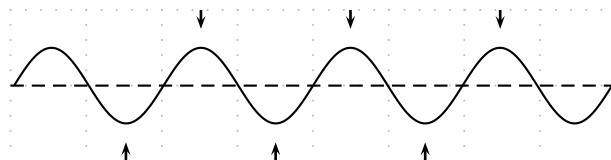


Again we have to add the two waves together in the overlap region to see what the sum of the waves looks like.

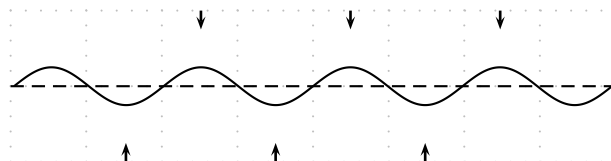


In this case the two waves have moved half a cycle past each other but because they are completely out of phase they cancel out completely.

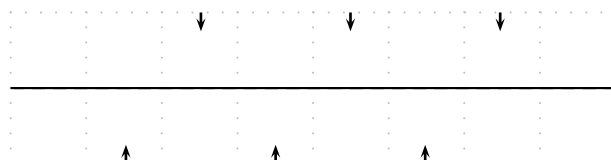
When the waves have moved past each other so that they are overlapping for a large region the situation looks like a wave oscillating in place. The following sequence of diagrams show what the resulting wave will look like. To make it clearer, the arrows at the top of the picture show peaks where maximum positive constructive interference is taking place. The arrows at the bottom of the picture show places where maximum negative interference is taking place.



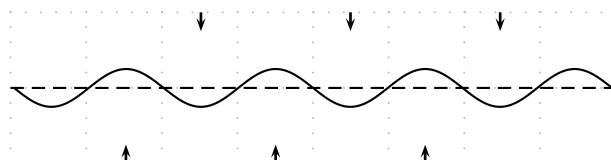
As time goes by the peaks become smaller and the troughs become shallower but they do not move.



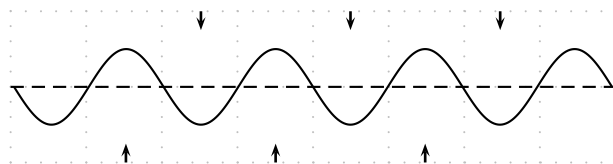
For an instant the entire region will look completely flat.



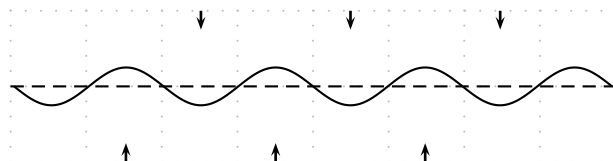
The various points continue their motion in the same manner.



Eventually the picture looks like the complete reflection through the  $x$ -axis of what we started with:



Then all the points begin to move back. Each point on the line is oscillating up and down with a different amplitude.



If we look at the overall result, we get a standing wave.

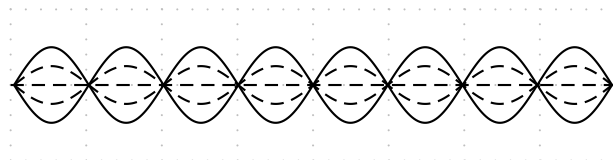
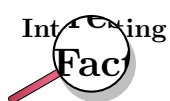


Figure 14.8: A standing wave

If we superimpose the two cases where the peaks were at a maximum and the case where the same waves were at a minimum we can see the lines that the points oscillate between. We call this the *envelope* of the standing wave as it contains all the oscillations of the individual points. To make the concept of the envelope clearer let us draw arrows describing the motion of points along the line.



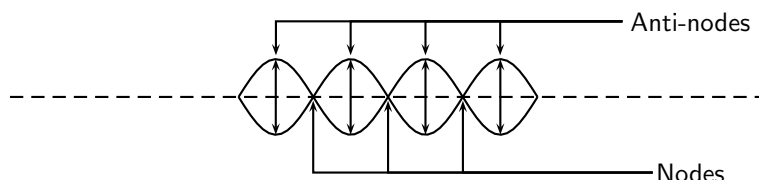
Every point in the medium containing a standing wave oscillates up and down and the amplitude of the oscillations depends on the location of the point. It is convenient to draw the envelope for the oscillations to describe the motion. We cannot draw the up and down arrows for every single point!



Standing waves can be a problem in for example indoor concerts where the dimensions of the concert venue coincide with particular wavelengths. Standing waves can appear as ‘feedback’, which would occur if the standing wave was picked up by the microphones on stage and amplified.

### 14.4.4 Nodes and Anti-nodes

A node is a point on a wave where no displacement takes place at any time. In a standing wave, a node is a place where two waves cancel out completely as the two waves destructively interfere in the same place. A fixed end of a rope is a node. An anti-node is a point on a wave where maximum displacement takes place. In a standing wave, an anti-node is a place where the two waves constructively interfere. Anti-nodes occur midway between nodes. A free end of a rope is an anti-node.



#### Definition: Node

A node is a point on a standing wave where no displacement takes place at any time. A fixed end of a rope is a node.

#### Definition: Anti-Node

An anti-node is a point on standing a wave where maximum displacement takes place. A free end of a rope is an anti-node.

**Important:** The distance between two anti-nodes is only  $\frac{1}{2}\lambda$  because it is the distance from a peak to a trough in one of the waves forming the standing wave. It is the same as the distance between two adjacent nodes. This will be important when we work out the allowed wavelengths in tubes later. We can take this further because half-way between any two anti-nodes is a node. Then the distance from the node to the anti-node is half the distance between two anti-nodes. This is half of half a wavelength which is one quarter of a wavelength,  $\frac{1}{4}\lambda$ .

### 14.4.5 Wavelengths of Standing Waves with Fixed and Free Ends

There are many applications which make use of the properties of waves and the use of fixed and free ends. Most musical instruments rely on the basic picture that we have presented to create specific sounds, either through standing pressure waves or standing vibratory waves in strings.

The key is to understand that a standing wave must be created in the medium that is oscillating. There are restrictions as to what wavelengths can form standing waves in a medium.

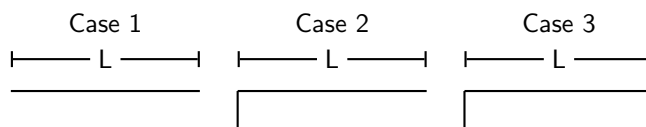
For example, if we consider a rope that can move in a pipe such that it can have

- both ends free to move (Case 1)
- one end free and one end fixed (Case 2)
- both ends fixed (Case 3).

Each of these cases is slightly different because the free or fixed end determines whether a node or anti-node will form when a standing wave is created in the rope. These are the main restrictions when we determine the wavelengths of potential standing waves. These restrictions are known as *boundary conditions* and **must** be met.



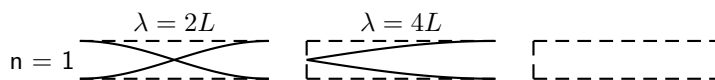
In the diagram below you can see the three different cases. It is possible to create standing waves with different frequencies and wavelengths as long as the end criteria are met.



The longer the wavelength the less the number of anti-nodes in the standing waves. We cannot have a standing wave with no anti-nodes because then there would be no oscillations. We use  $n$  to number the anti-nodes. If all of the tubes have a length  $L$  and we know the end constraints we can find the wavelength,  $\lambda$ , for a specific number of anti-nodes.

### One Node

Let's work out the longest wavelength we can have in each tube, i.e. the case for  $n = 1$ .



**Case 1:** In the first tube, both ends must be anti-nodes, so we must place one node in the middle of the tube. We know the distance from one anti-node to another is  $\frac{1}{2}\lambda$  and we also know this distance is  $L$ . So we can equate the two and solve for the wavelength:

$$\begin{aligned}\frac{1}{2}\lambda &= L \\ \lambda &= 2L\end{aligned}$$

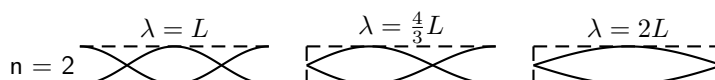
**Case 2:** In the second tube, one end must be a node and the other must be an anti-node. Since we are looking at the case with one node, we are forced to have it at the end. We know the distance from one node to another is  $\frac{1}{2}\lambda$  but we only have half this distance contained in the tube. So :

$$\begin{aligned}\frac{1}{2}\left(\frac{1}{2}\lambda\right) &= L \\ \lambda &= 4L\end{aligned}$$

**Case 3:** Here both ends are closed and so we must have two nodes so it is impossible to construct a case with only one node.

### Two Nodes

Next we determine which wavelengths could be formed if we had two nodes. Remember that we are dividing the tube up into smaller and smaller segments by having more nodes so we expect the wavelengths to get shorter.



**Case 1:** Both ends are open and so they must be anti-nodes. We can have two nodes inside the tube only if we have one anti-node contained inside the tube and one on each end. This means we have 3 anti-nodes in the tube. The distance between any two anti-nodes is half a wavelength. This means there is half wavelength between the left side and the middle and another half wavelength between the middle and the right side so there must be one wavelength inside the tube. The safest thing to do is work out how many half wavelengths there are and equate this to the length of the tube  $L$  and then solve for  $\lambda$ .

$$2\left(\frac{1}{2}\lambda\right) = L$$

$$\lambda = L$$

**Case 2:** We want to have two nodes inside the tube. The left end must be a node and the right end must be an anti-node. We can have one node inside the tube as drawn above. Again we can count the number of distances between adjacent nodes or anti-nodes. If we start from the left end we have one half wavelength between the end and the node inside the tube. The distance from the node inside the tube to the right end which is an anti-node is half of the distance to another node. So it is half of half a wavelength. Together these add up to the length of the tube:

$$\frac{1}{2}\lambda + \frac{1}{2}\left(\frac{1}{2}\lambda\right) = L$$

$$\frac{2}{4}\lambda + \frac{1}{4}\lambda = L$$

$$\frac{3}{4}\lambda = L$$

$$\lambda = \frac{4}{3}L$$

**Case 3:** In this case both ends have to be nodes. This means that the length of the tube is one half wavelength: So we can equate the two and solve for the wavelength:

$$\frac{1}{2}\lambda = L$$

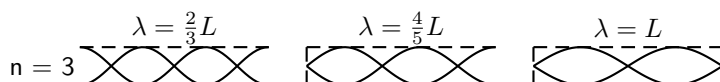
$$\lambda = 2L$$



**Important:** If you ever calculate a longer wavelength for more nodes you have made a mistake. Remember to check if your answers make sense!

### Three Nodes

To see the complete pattern for all cases we need to check what the next step for case 3 is when we have an additional node. Below is the diagram for the case where  $n = 3$ .



**Case 1:** Both ends are open and so they must be anti-nodes. We can have three nodes inside the tube only if we have two anti-nodes contained inside the tube and one on each end. This means we have 4 anti-nodes in the tube. The distance between any two anti-nodes is half a wavelength. This means there is half wavelength between every adjacent pair of anti-nodes. We count how many gaps there are between adjacent anti-nodes to determine how many half wavelengths there are and equate this to the length of the tube  $L$  and then solve for  $\lambda$ .

$$3\left(\frac{1}{2}\lambda\right) = L$$

$$\lambda = \frac{2}{3}L$$

**Case 2:** We want to have three nodes inside the tube. The left end must be a node and the right end must be an anti-node, so there will be two nodes between the ends of the tube. Again

we can count the number of distances between adjacent nodes or anti-nodes, together these add up to the length of the tube. Remember that the distance between the node and an adjacent anti-node is only half the distance between adjacent nodes. So starting from the left end we count 3 nodes, so 2 half wavelength intervals and then only a node to anti-node distance:

$$\begin{aligned} 2\left(\frac{1}{2}\lambda\right) + \frac{1}{2}\left(\frac{1}{2}\lambda\right) &= L \\ \lambda + \frac{1}{4}\lambda &= L \\ \frac{5}{4}\lambda &= L \\ \lambda &= \frac{4}{5}L \end{aligned}$$

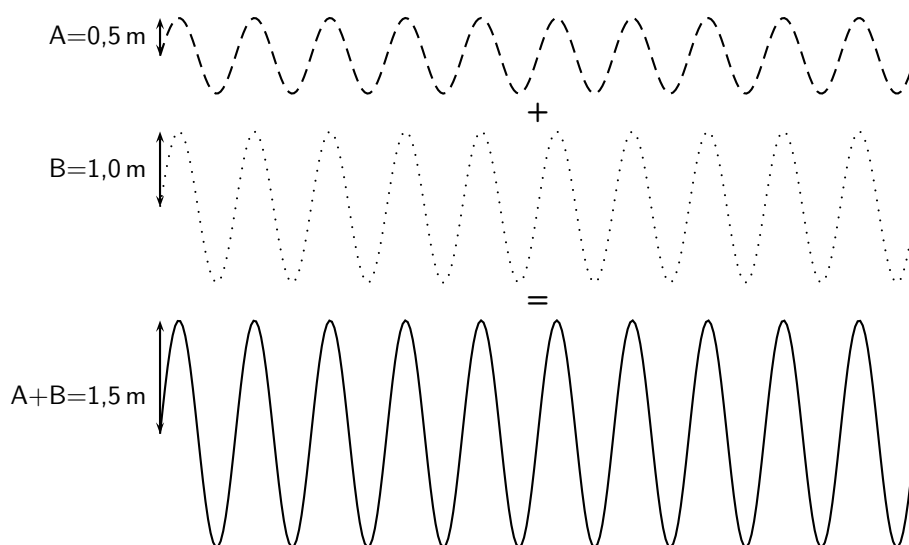
**Case 3:** In this case both ends have to be nodes. With one node in between there are two sets of adjacent nodes. This means that the length of the tube consists of two half wavelength sections:

$$\begin{aligned} 2\left(\frac{1}{2}\lambda\right) &= L \\ \lambda &= L \end{aligned}$$

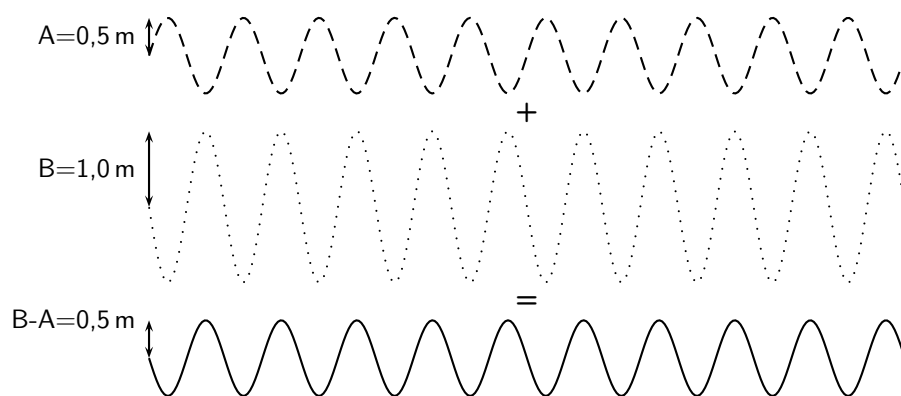
### 14.4.6 Superposition and Interference

If two waves meet interesting things can happen. Waves are basically collective motion of particles. So when two waves meet they both try to impose their collective motion on the particles. This can have quite different results.

If two identical (same wavelength, amplitude and frequency) waves are both trying to form a peak then they are able to achieve the sum of their efforts. The resulting motion will be a peak which has a height which is the sum of the heights of the two waves. If two waves are both trying to form a trough in the same place then a deeper trough is formed, the depth of which is the sum of the depths of the two waves. Now in this case, the two waves have been trying to do the same thing, and so add together constructively. This is called *constructive interference*.

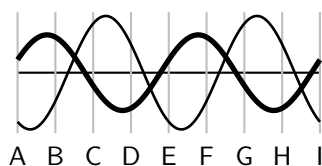


If one wave is trying to form a peak and the other is trying to form a trough, then they are competing to do different things. In this case, they can cancel out. The amplitude of the resulting wave will depend on the amplitudes of the two waves that are interfering. If the depth of the trough is the same as the height of the peak nothing will happen. If the height of the peak is bigger than the depth of the trough, a smaller peak will appear. And if the trough is deeper then a less deep trough will appear. This is *destructive interference*.



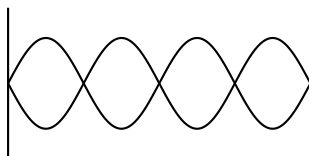
### Exercise: Superposition and Interference

- For each labelled point, indicate whether constructive or destructive interference takes place at that point.

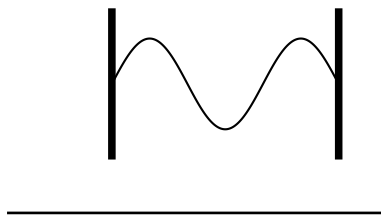


Position	Constructive/Destructive
A	
B	
C	
D	
E	
F	
G	
H	
I	

- A ride at the local amusement park is called "Standing on Standing Waves". Which position (a node or an antinode) on the ride would give the greatest thrill?
- How many nodes and how many anti-nodes appear in the standing wave below?



- For a standing wave on a string, you are given three statements:  
 A you can have any  $\lambda$  and any  $f$  as long as the relationship,  $v = \lambda \cdot f$  is satisfied.  
 B only certain wavelengths and frequencies are allowed  
 C the wave velocity is only dependent on the medium  
 Which of the statements are true:  
 (a) A and C only  
 (b) B and C only  
 (c) A, B, and C  
 (d) none of the above
- Consider the diagram below of a standing wave on a string 9 m long that is tied at both ends. The wave velocity in the string is  $16 \text{ m} \cdot \text{s}^{-1}$ . What is the wavelength?

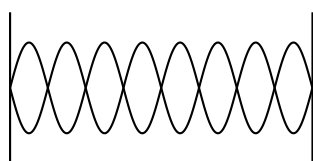


## 14.5 Summary

1. A wave is formed when a continuous number of pulses are transmitted through a medium.
2. A peak is the highest point a particle in the medium rises to.
3. A trough is the lowest point a particle in the medium sinks to.
4. In a transverse wave, the particles move perpendicular to the motion of the wave.
5. The amplitude is the maximum distance from equilibrium position to a peak (or trough), or the maximum displacement of a particle in a wave from its position of rest.
6. The wavelength ( $\lambda$ ) is the distance between any two adjacent points on a wave that are in phase. It is measured in metres.
7. The period ( $T$ ) of a wave is the time it takes a wavelength to pass a fixed point. It is measured in seconds (s).
8. The frequency ( $f$ ) of a wave is how many waves pass a point in a second. It is measured in hertz (Hz) or  $\text{s}^{-1}$ .
9. Frequency:  $f = \frac{1}{T}$
10. Period:  $T = \frac{1}{f}$
11. Speed:  $v = f\lambda$  or  $v = \frac{\lambda}{T}$ .
12. When a wave is reflected from a fixed end, the resulting wave will move back through the medium, but will be inverted. When a wave is reflected from a free end, the waves are reflected, but not inverted.

## 14.6 Exercises

1. A standing wave is formed when:
  - (a) a wave refracts due to changes in the properties of the medium
  - (b) a wave reflects off a canyon wall and is heard shortly after it is formed
  - (c) a wave refracts and reflects due to changes in the medium
  - (d) two identical waves moving different directions along the same medium interfere
2. How many nodes and anti-nodes are shown in the diagram?



3. Draw a transverse wave that is reflected from a fixed end.
4. Draw a transverse wave that is reflected from a free end.

5. A wave travels along a string at a speed of  $1,5 \text{ m}\cdot\text{s}^{-1}$ . If the frequency of the source of the wave is  $7,5 \text{ Hz}$ , calculate:
- (a) the wavelength of the wave
  - (b) the period of the wave

## Chapter 15

# Geometrical Optics - Grade 10

### 15.1 Introduction

You are indoors on a sunny day. A beam of sunlight through a window lights up a section of the floor. How would you draw this sunbeam? You might draw a series of parallel lines showing the path of the sunlight from the window to the floor. This is not exactly accurate – no matter how hard you look, you will not find unique lines of light in the sunbeam! However, this is a good way to draw light. It is also a good way to model light geometrically, as we will see in this chapter.

These narrow, imaginary lines of light are called **light rays**. Since light is an electromagnetic wave, you could think of a light ray as the path of a point on the crest of a wave. Or, you could think of a light ray as the path taken by a minuscule particle that carries light. We will always draw them the same way: as straight lines between objects, images, and optical devices.

We can use light rays to model mirrors, lenses, telescopes, microscopes, and prisms. The study of how light interacts with materials is **optics**. When dealing with light rays, we are usually interested in the shape of a material and the angles at which light rays hit it. From these angles, we can work out, for example, the distance between an object and its reflection. We therefore refer to this kind of optics as **geometrical optics**.

### 15.2 Light Rays

In physics we use the idea of a *light ray* to indicate the direction that light travels. Light rays are lines with arrows and are used to show the path that light travels. In Figure 15.1, the light rays from the object enters the eye and the eye sees the object.

The most important thing to remember is that we can only see an object when light from the object enters our eyes. The object must be a source of light (for example a light bulb) or else it must reflect light from a source (for example the moon), and the reflected light enters our eyes.



**Important:** We cannot see an object unless light from that object enters our eyes.



**Definition: Light ray**

Light rays are straight lines with arrows to show the path of light.



**Important:** Light rays are not an exact description of a general source of light. They are merely used to show the path that light travels.

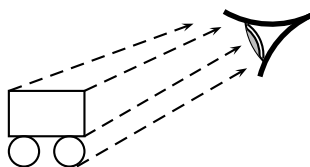


Figure 15.1: We can only see an object when light from that object enters our eyes. We draw light as lines with arrows to show the direction the light travels. When the light travels from the object to the eye, the eye can see the object. Light rays entering the eye from the cart are shown as dashed lines. The second wheel of the cart will be invisible as no straight, unobstructed lines exist between it and the eye.

### Activity :: Investigation : Light travels in straight lines

#### Apparatus:

You will need a candle, matches and three sheets of paper.

#### Method:

1. Make a small hole in the middle of each of the three sheets of paper.
2. Light the candle.
3. Look at the burning candle through the hole in the first sheet of paper.
4. Place the second sheet of paper between you and the candle so that you can still see the candle through the holes.
5. Now do the same with the third sheet so that you can still see the candle. The sheets of paper must not touch each other.

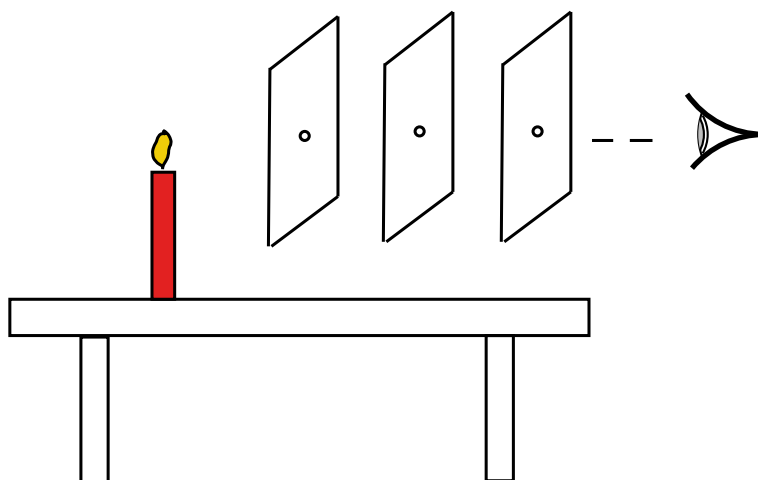


Figure 15.2: Light travels in straight lines

6. What do you notice about the holes in the paper?

#### Conclusions:

In the investigation you will notice that the holes in the paper need to be in a straight line. This shows that light travels in a straight line. We cannot see around corners. This also proves that light does not bend around a corner, but travels straight.

### Activity :: Investigation : Light travels in straight lines



On a sunny day, stand outside and look at something in the distance, for example a tree, a flower or a car. From what we have learnt, we can see the tree, flower or car because light from the object is entering our eye. Now take a sheet of paper and hold it about 20 cm in front of your face. Can you still see the tree, flower or car? Why not?

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Figure 15.3 shows that a sheet of paper in front of your eye prevents light rays from reaching your eye.

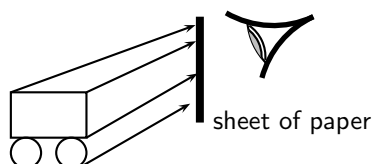
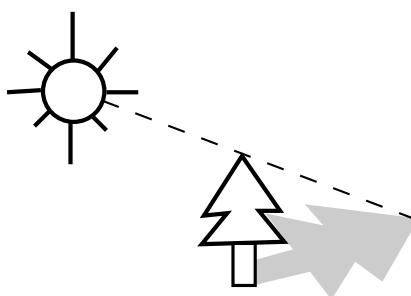


Figure 15.3: The sheet of paper prevents the light rays from reaching the eye, and the eye cannot see the object.

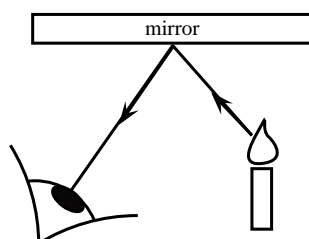
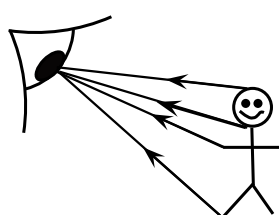
### 15.2.1 Shadows

Objects cast shadows when light shines on them. This is more evidence that light travels in straight lines. The picture below shows how shadows are formed.



### 15.2.2 Ray Diagrams

A ray diagram is a drawing that shows the path of light rays. Light rays are drawn using straight lines and arrow heads. The figure below shows some examples of ray diagrams.





### Exercise: Light Rays

1. Are light rays real? Explain.
2. Give evidence to support the statement: "Light travels in straight lines". Draw a ray diagram to prove this.
3. You are looking at a burning candle. Draw the path of light that enables you to see that candle.

## 15.3 Reflection

When you smile into a mirror, you see your own face smiling back at you. This is caused by the reflection of light rays on the mirror. Reflection occurs when a light ray bounces off a surface.

### 15.3.1 Terminology

In Chapters 13 and 14 we saw that when a pulse or wave strikes a surface it is *reflected*. This means that waves bounce off things. Sound waves bounce off walls, light waves bounce off mirrors, radar waves bounce off aeroplanes and it can explain how bats can fly at night and avoid things as thin as telephone wires. The phenomenon of reflection is a very important and useful one.

We will use the following terminology. The incoming light ray is called the **incident ray**. The light ray moving away from the surface is the **reflected ray**. The most important characteristic of these rays is their angles in relation to the reflecting surface. 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**,  $\theta_i$  is measured between the incident ray and the surface normal. The **angle of reflection**,  $\theta_r$  is measured between the reflected ray and the surface normal. This is shown in Figure 15.4.

When a ray of light is reflected, the reflected ray lies in the same plane as the incident ray and the normal. This plane is called the **plane of incidence** and is shown in Figure 15.5.

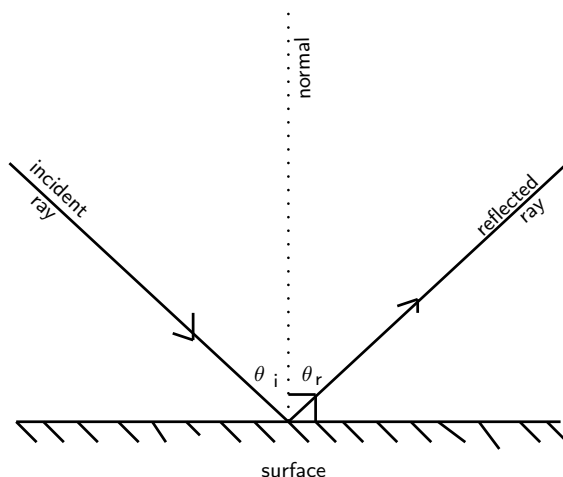


Figure 15.4: The angles of incidence and reflection are measured with respect to the surface normal.

### 15.3.2 Law of Reflection

The **Law of Reflection** states that the angles of incidence and reflection are always equal and that the reflected ray always lies in the plane of incidence.

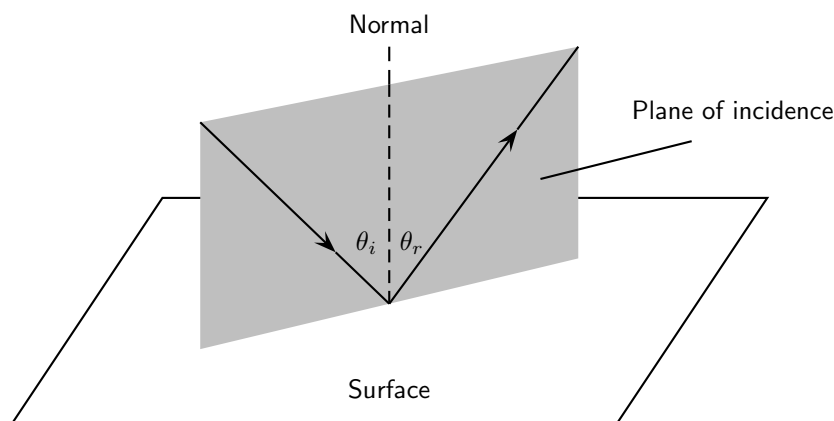


Figure 15.5: The plane of incidence is the plane including the incident ray, reflected ray, and the surface normal.



**Definition: Law of Reflection**

The Law of Reflection states that the angle of incidence is equal to the angle of reflection.

$$\theta_i = \theta_r$$

The simplest example of the law of incidence is if the angle of incidence is  $0^\circ$ . In this case, the angle of reflection is also  $0^\circ$ . You see this when you look straight into a mirror.

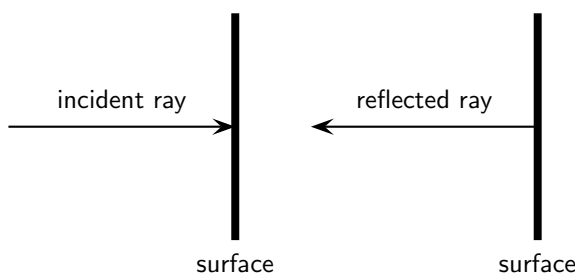


Figure 15.6: When a wave strikes a surface at right angles to the surface, then the wave is reflected directly back.

If the angle of incidence is not  $0^\circ$ , then the angle of reflection is also not  $0^\circ$ . For example, if a light strikes a surface at  $60^\circ$  to the surface normal, then the angle that the reflected ray makes with the surface normal is also  $60^\circ$  as shown in Figure 15.7.



**Worked Example 47: Law of Reflection**

**Question:** An incident ray strikes a smooth reflective surface at an angle of  $33^\circ$  to the surface normal. Calculate the angle of reflection.

**Answer**

**Step 1 : Determine what is given and what is required**

We are given the angle between the incident ray and the surface normal. This is the angle of incidence.

We are required to calculate the angle of reflection.

**Step 2 : Determine how to approach the problem**

We can use the Law of Reflection, which states that the angle of incidence is equal to the angle of reflection.

**Step 3 : Calculate the angle of reflection**

We are given the angle of incidence to be  $33^\circ$ . Therefore, the angle of reflection is also  $33^\circ$ .

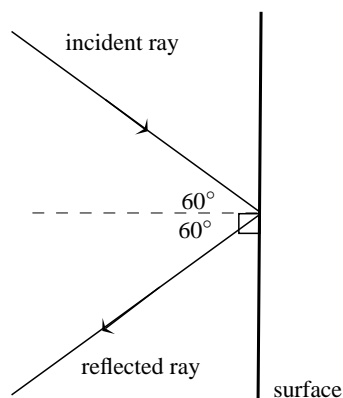


Figure 15.7: Ray diagram showing angle of incidence and angle of reflection. The Law of Reflection states that when a light ray reflects off a surface, the angle of reflection  $\theta_r$  is the same as the angle of incidence  $\theta_i$ .

### 15.3.3 Types of Reflection

The Law of Reflection holds for every light ray. Does this mean that when parallel rays approach a surface, the reflected rays will also be parallel? This depends on the texture of the reflecting surface.

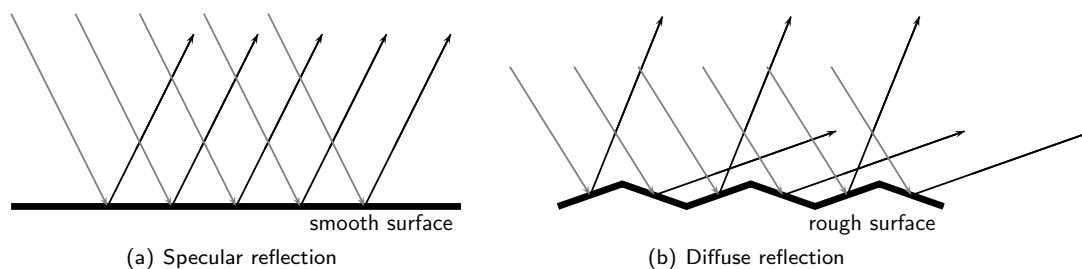


Figure 15.8: Specular and diffuse reflection.

#### Specular Reflection

Figure 15.8(a) shows a surface that is flat and even. Parallel incident light rays hit the smooth surface and parallel reflected light rays leave the surface. This type of reflection is called **specular reflection**. Specular reflection occurs when rays are reflected from a smooth, shiny surface. The normal to the surface is the same at every point on the surface. Parallel incident rays become parallel reflected rays. When you look in a mirror, the image you see is formed by specular reflection.

#### Diffuse Reflection

Figure 15.8(b) shows a surface with bumps and curves. When multiple rays hit this uneven surface, **diffuse reflection** occurs. The incident rays are parallel but the reflected rays are not. Each point on the surface has a different normal. This means the angle of incidence is different at each point. Then according to the Law of Reflection, each angle of reflection is different. Diffuse reflection occurs when light rays are reflected from bumpy surfaces. You can still see a reflection as long as the surface is not too bumpy. Diffuse reflection enables us to see all objects that are not sources of light.

**Activity :: Experiment : Specular and Diffuse Reflection**

A bouncing ball can be used to demonstrate the basic difference between specular and diffuse reflection.

**Aim:**

To demonstrate and compare specular and diffuse reflection.

**Apparatus:**

You will need:

1. a small ball (a tennis ball or a table tennis ball is perfect)
2. a smooth surface, like the floor inside the classroom
3. a very rough surface, like a rocky piece of ground

**Method:**

1. Bounce the ball on the smooth floor and observe what happens.
2. Bounce the ball on the rough ground floor and observe what happens.
3. What do you observe?
4. What is the difference between the two surfaces?

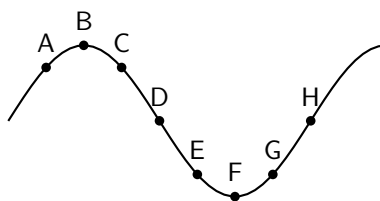
**Conclusions:**

You should have seen that the ball bounces (is reflected off the floor) in a predictable manner off the smooth floor, but bounces unpredictably on the rough ground.

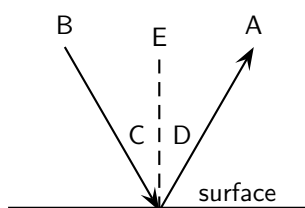
The ball can be seen to be a ray of light and the floor or ground is the reflecting surface. For specular reflection (smooth surface), the ball bounces predictably. For diffuse reflection (rough surface), the ball bounces unpredictably.

**Exercise: Reflection**

1. The diagram shows a curved surface. Draw normals to the surface at the marked points.

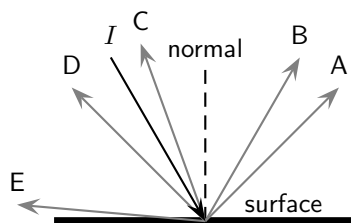


2. Which of the points, A–H, in the diagram, correspond to the following:
  - (a) normal
  - (b) angle of incidence
  - (c) angle of reflection
  - (d) incident ray
  - (e) reflected ray



3. State the Law of Reflection. Draw a diagram, label the appropriate angles and write a mathematical expression for the Law of Reflection.

4. Draw a ray diagram to show the relationship between the angle of incidence and the angle of reflection.
5. The diagram shows an incident ray  $I$ . Which of the other 5 rays (A, B, C, D, E) best represents the reflected ray of  $I$ ?



6. A ray of light strikes a surface at  $15^\circ$  to the surface normal. 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.
7. A ray of light leaves a surface at  $45^\circ$  to the surface normal. 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.
8. A ray of light strikes a surface at  $25^\circ$  to the surface. 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.
9. A ray of light leaves a surface at  $65^\circ$  to the surface. 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.
10. Explain the difference between specular and diffuse reflection.
11. We see an object when the light that is reflected by the object enters our eyes. Do you think the reflection by most objects is specular reflection or diffuse reflection? Explain.
12. A beam of light (for example from a torch) is generally not visible at night, as it travels through air. Try this for yourself. However, if you shine the torch through dust, the beam is visible. Explain why this happens.
13. If a torch beam is shone across a classroom, only students in the direct line of the beam would be able to see that the torch is shining. However, if the beam strikes a wall, the entire class will be able to see the spot made by the beam on the wall. Explain why this happens.
14. A scientist looking into a flat mirror hung perpendicular to the floor cannot see her feet but she can see the hem of her lab coat. Draw a ray diagram to help explain the answers to the following questions:
  - (a) Will she be able to see her feet if she backs away from the mirror?
  - (b) What if she moves towards the mirror?

## 15.4 Refraction

In the previous sections we studied light reflecting off various surfaces. What happens when light passes *through* a medium? The speed of light, like that of all waves, is dependent on the medium in which it is travelling. When light moves from one medium into another (for example, from air to glass), the speed of light changes. The effect is that the light ray passing into a new medium is **refracted**, or bent. Refraction is therefore the bending of light as it moves from one optical medium to another.

**Definition: Refraction**

Refraction is the bending of light that occurs because light travels at different speeds in different materials.

When light travels from one medium to another, it will be bent away from its original path. When it travels from an optically dense medium like water or glass to a less dense medium like air, it will be refracted away from the normal (Figure 15.9). Whereas, if it travels from a less dense medium to a denser one, it will be refracted towards the normal (Figure 15.10).

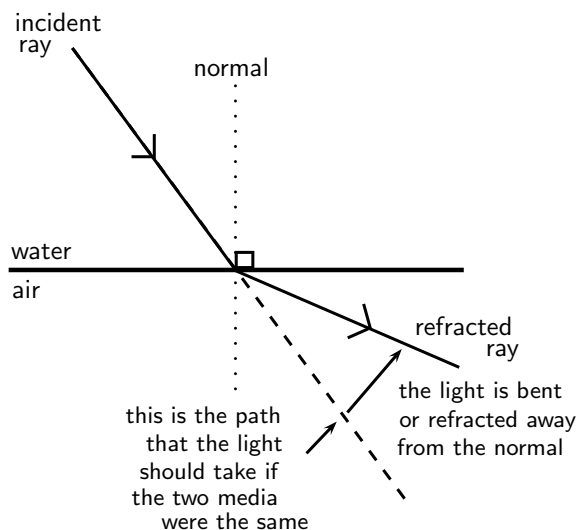


Figure 15.9: Light is moving from an optically dense medium to an optically less dense medium. Light is refracted away from the normal.

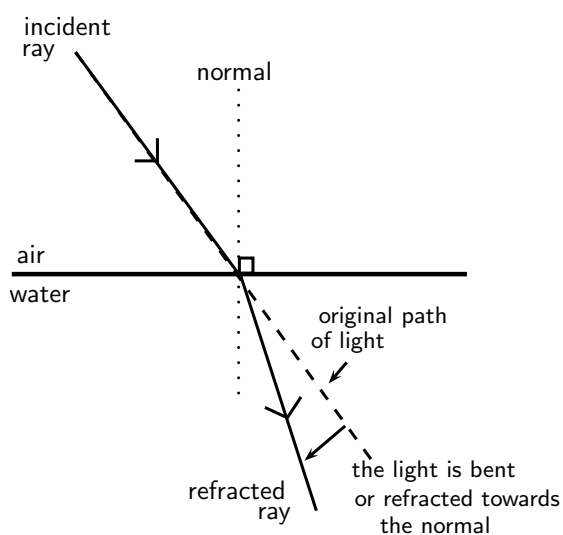


Figure 15.10: Light is moving from an optically less dense medium to an optically denser medium. Light is refracted towards the normal.

Just as we defined an angle of reflection in the previous section, we can similarly define an angle of refraction as the angle between the surface normal and the refracted ray. This is shown in Figure 15.11.

### 15.4.1 Refractive Index

Which is easier to travel through, air or water? People usually travel faster through air. So does light! The speed of light and therefore the degree of bending of the light depends on the

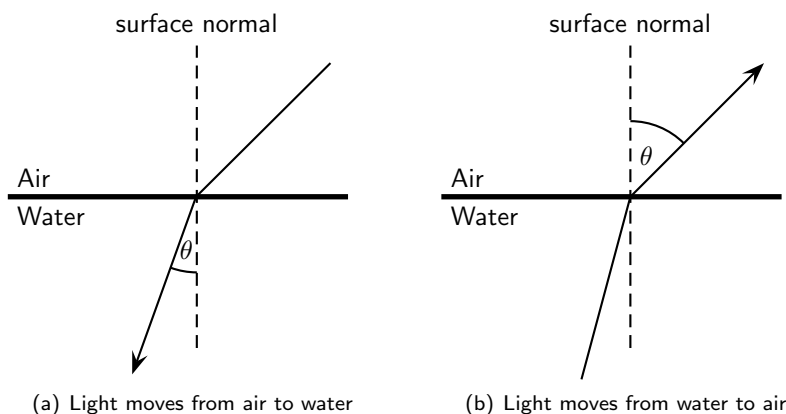


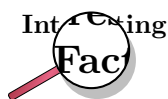
Figure 15.11: Light moving from one medium to another bends towards or away from the surface normal. The angle of refraction  $\theta$  is shown.

*refractive index* of 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.



**Definition: Refractive Index**

The refractive index of a material is the ratio of the speed of light in a vacuum to its speed in the medium.



The symbol  $c$  is used to represent the speed of light in a vacuum.

$$c = 299\,792\,485 \text{ m} \cdot \text{s}^{-1}$$

For purposes of calculation, we use  $3 \times 10^8 \text{ m} \cdot \text{s}^{-1}$ . A vacuum is a region with no matter in it, not even air. However, the speed of light in air is very close to that in a vacuum.



**Definition: Refractive Index**

The refractive index (symbol  $n$ ) of a material 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.

$$n = \frac{c}{v}$$

where

- $n$  = refractive index (no unit)
- $c$  = speed of light in a vacuum ( $3,00 \times 10^8 \text{ m} \cdot \text{s}^{-1}$ )
- $v$  = speed of light in a given medium ( $\text{m} \cdot \text{s}^{-1}$ )



*Extension: Refractive Index and Speed of Light*

Using

$$n = \frac{c}{v}$$

we can also examine how the speed of light changes in different media, because the speed of light in a vacuum ( $c$ ) is constant.

If the refractive index  $n$  increases, the speed of light in the material  $v$  must decrease. Light therefore travels slowly through materials of high  $n$ .



Table 15.1 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.

Medium	Refractive Index
Vacuum	1
Helium	1,000036
Air*	1,0002926
Carbon dioxide	1,00045
Water: Ice	1,31
Water: Liquid (20°C)	1,333
Acetone	1,36
Ethyl Alcohol (Ethanol)	1,36
Sugar solution (30%)	1,38
Fused quartz	1,46
Glycerine	1,4729
Sugar solution (80%)	1,49
Rock salt	1,516
Crown Glass	1,52
Sodium chloride	1,54
Polystyrene	1,55 to 1,59
Bromine	1,661
Sapphire	1,77
Glass (typical)	1,5 to 1,9
Cubic zirconia	2,15 to 2,18
Diamond	2,419
Silicon	4,01

Table 15.1: Refractive indices of some materials.  $n_{\text{air}}$  is calculated at STP.

### 15.4.2 Snell's Law

Now that we know that the degree of bending, or the angle of refraction, is dependent on the refractive index of a medium, how do we calculate the angle of refraction?

The angles of incidence and refraction when light travels from one medium to another can be calculated using Snell's Law.



#### Definition: Snell's Law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where

$n_1$  = Refractive index of material 1

$n_2$  = Refractive index of material 2

$\theta_1$  = Angle of incidence

$\theta_2$  = Angle of refraction

Remember that angles of incidence and refraction are measured from the normal, which is an imaginary line perpendicular to the surface.

Suppose we have two media with refractive indices  $n_1$  and  $n_2$ . A light ray is incident on the surface between these materials with an **angle of incidence**  $\theta_1$ . The refracted ray that passes through the second medium will have an **angle of refraction**  $\theta_2$ .

**Worked Example 48: Using Snell's Law**

**Question:** A light ray with an angle of incidence of  $35^\circ$  passes from water to air. Find the angle of refraction using Snell's Law and Table 15.1. Discuss the meaning of your answer.

**Answer****Step 1 : Determine the refractive indices of water and air**

From Table 15.1, the refractive index is 1,333 for water and about 1 for air. We know the angle of incidence, so we are ready to use Snell's Law.

**Step 2 : Substitute values**

According to Snell's Law:

$$\begin{aligned} n_1 \sin \theta_1 &= n_2 \sin \theta_2 \\ 1,33 \sin 35^\circ &= 1 \sin \theta_2 \\ \sin \theta_2 &= 0,763 \\ \theta_2 &= 49,7^\circ \text{ or } 130,3^\circ \end{aligned}$$

Since  $130,3^\circ$  is larger than  $90^\circ$ , the solution is:

$$\theta_2 = 49,7^\circ$$

**Step 3 : Discuss the answer**

The light ray passes from a medium of high refractive index to one of low refractive index. Therefore, the light ray is bent away from the normal.

**Worked Example 49: Using Snell's Law**

**Question:** A light ray passes from water to diamond with an angle of incidence of  $75^\circ$ . Calculate the angle of refraction. Discuss the meaning of your answer.

**Answer****Step 1 : Determine the refractive indices of water and air**

From Table 15.1, the refractive index is 1,333 for water and 2,42 for diamond. We know the angle of incidence, so we are ready to use Snell's Law.

**Step 2 : Substitute values and solve**

According to Snell's Law:

$$\begin{aligned} n_1 \sin \theta_1 &= n_2 \sin \theta_2 \\ 1,33 \sin 75^\circ &= 2,42 \sin \theta_2 \\ \sin \theta_2 &= 0,531 \\ \theta_2 &= 32,1^\circ. \end{aligned}$$

**Step 3 : Discuss the answer**

The light ray passes from a medium of low refractive index to one of high refractive index. Therefore, the light ray is bent towards the normal.

If

$$n_2 > n_1$$

then from Snell's Law,

$$\sin \theta_1 > \sin \theta_2.$$

For angles smaller than  $90^\circ$ ,  $\sin \theta$  increases as  $\theta$  increases. Therefore,

$$\theta_1 > \theta_2.$$

This means that the angle of incidence is greater than the angle of refraction and the light ray is bent toward the normal.

Similarly, if

$$n_2 < n_1$$

then from Snell's Law,

$$\sin \theta_1 < \sin \theta_2.$$

For angles smaller than  $90^\circ$ ,  $\sin \theta$  increases as  $\theta$  increases. Therefore,

$$\theta_1 < \theta_2.$$

This means that the angle of incidence is less than the angle of refraction and the light ray is away toward the normal.

Both these situations can be seen in Figure 15.12.

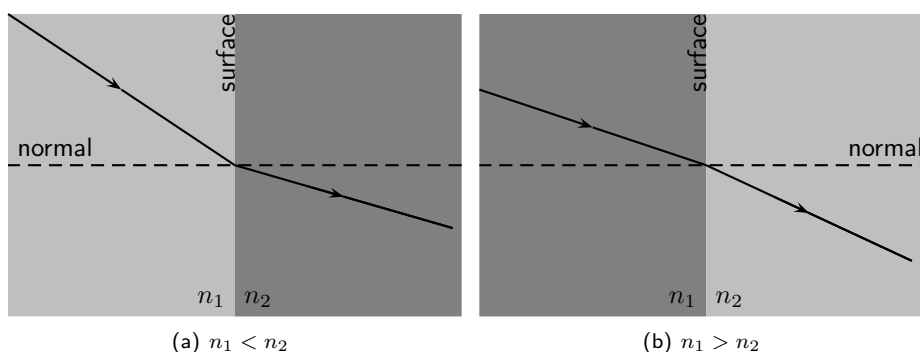


Figure 15.12: Refraction of two light rays. (a) A ray travels from a medium of low refractive index to one of high refractive index. The ray is bent towards the normal. (b) A ray travels from a medium with a high refractive index to one with a low refractive index. The ray is bent away from the normal.

What happens to a ray that lies along the normal line? In this case, the angle of incidence is  $0^\circ$  and

$$\begin{aligned} \sin \theta_2 &= \frac{n_1}{n_2} \sin \theta_1 \\ &= 0 \\ \therefore \theta_2 &= 0. \end{aligned}$$

This shows that if the light ray is incident at  $0^\circ$ , then the angle of refraction is also  $0^\circ$ . The ray passes through the surface unchanged, i.e. no refraction occurs.

### Activity :: Investigation : Snell's Law 1

The angles of incidence and refraction were measured in five unknown media and recorded in the table below. Use your knowledge about Snell's Law to identify each of the unknown media A - E. Use Table 15.1 to help you.

Medium 1	$n_1$	$\theta_1$	$\theta_2$	$n_2$	Unknown Medium
Air	1,000036	38	11,6	?	A
Air	1,000036	65	38,4	?	B
Vacuum	1	44	0,419	?	C
Air	1,000036	15	29,3	?	D
Vacuum	1	20	36,9	?	E

### Activity :: Investigation : Snell's Law 2

Zingi and Tumi performed an investigation to identify an unknown liquid. They shone a beam of light into the unknown liquid, varying the angle of incidence and recording the angle of refraction. Their results are recorded in the following table:

Angle of Incidence	Angle of Refraction
0,0°	0,00°
5,0°	3,76°
10,0°	7,50°
15,0°	11,2°
20,0°	14,9°
25,0°	18,5°
30,0°	22,1°
35,0°	25,5°
40,0°	28,9°
45,0°	32,1°
50,0°	35,2°
55,0°	38,0°
60,0°	40,6°
65,0°	43,0°
70,0°	?
75,0°	?
80,0°	?
85,0°	?

1. Write down an aim for the investigation.
2. Make a list of all the apparatus they used.
3. Identify the unknown liquid.
4. Predict what the angle of refraction will be for 70°, 75°, 80° and 85°.

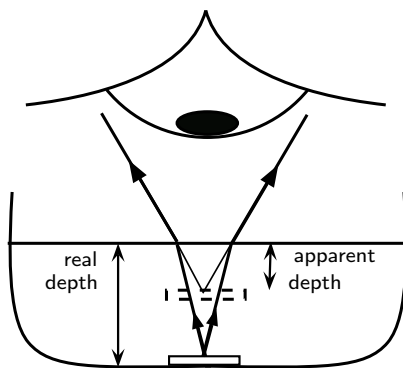
### 15.4.3 Apparent Depth

Imagine a coin on the bottom of a shallow pool of water. If you reach for the coin, you will miss it because the light rays from the coin are refracted at the water's surface.

Consider a light ray that travels from an underwater object to your eye. The ray is refracted at the water surface and then reaches your eye. Your eye does not know Snell's Law; it assumes light rays travel in straight lines. Your eye therefore sees the image of the coin at a shallower location. This shallower location is known as the *apparent depth*.

The refractive index of a medium can also be expressed as

$$n = \frac{\text{real depth}}{\text{apparent depth}}.$$

**Worked Example 50: Apparent Depth 1**

**Question:** A coin is placed at the bottom of a 40 cm deep pond. The refractive index for water is 1,33. How deep does the coin appear to be?

**Answer**

**Step 1 : Identify what is given and what is asked**

$n = 1,33$

real depth = 40 cm

apparent depth = ?

**Step 2 : Substitute values and find answer**

$$n = \frac{\text{real depth}}{\text{apparent depth}}$$

$$1,33 = \frac{40}{x}$$

$$x = \frac{40}{1,33} = 30,08 \text{ cm}$$

The coin appears to be 30,08 cm deep.

**Worked Example 51: Apparent Depth 2**

**Question:** A R1 coin appears to be 7 cm deep in a colourless liquid known to be listed in Table 15.1. The depth of the liquid is 10,43 cm.

1. Determine the refractive index of the liquid.
2. Identify the liquid.

**Answer**

**Step 1 : Identify what is given and what is asked**

real depth = 7 cm

apparent depth = 10,43 cm

$n = ?$

Identify the liquid.

**Step 2 : Calculate refractive index**

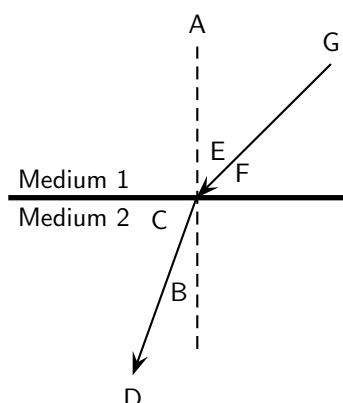
$$\begin{aligned}
 n &= \frac{\text{real depth}}{\text{apparent depth}} \\
 &= \frac{10,43}{7} \\
 &= 1,49
 \end{aligned}$$

**Step 3 : Identify the liquid**

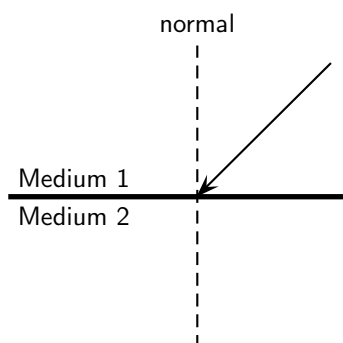
Use Table 15.1. The liquid is an 80% sugar solution.

**Exercise: Refraction**

1. Explain refraction in terms of a change of wave speed in different media.
2. In the diagram, label the following:
  - (a) angle of incidence
  - (b) angle of refraction
  - (c) incident ray
  - (d) refracted ray
  - (e) normal



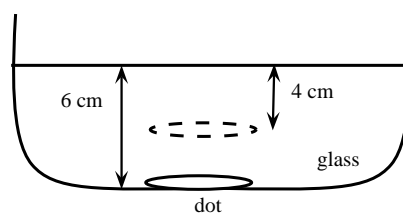
3. What is *the angle of refraction*?
4. Describe what is meant by *the refractive index of a medium*.
5. State Snell's Law.
6. In the diagram, a ray of light strikes the interface between two media.



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.
7. Light travels from a region of glass into a region of glycerine, making an angle of incidence of  $40^\circ$ .
    - (a) Describe the path of the light as it moves into the glycerine.
    - (b) Calculate the angle of refraction.
  8. A ray of light travels from silicon to water. If the ray of light in the water makes an angle of  $69^\circ$  to the surface normal, what is the angle of incidence in the silicon?
  9. Light travels from a medium with  $n = 1,25$  into a medium of  $n = 1,34$ , at an angle of  $27^\circ$  from the interface normal.
    - (a) What happens to the speed of the light? Does it increase, decrease, or remain the same?
    - (b) What happens to the wavelength of the light? Does it increase, decrease, or remain the same?
    - (c) Does the light bend towards the normal, away from the normal, or not at all?
  10. Light travels from a medium with  $n = 1,63$  into a medium of  $n = 1,42$ .
    - (a) What happens to the speed of the light? Does it increase, decrease, or remain the same?
    - (b) What happens to the wavelength of the light? Does it increase, decrease, or remain the same?
    - (c) Does the light bend towards the normal, away from the normal, or not at all?
  11. Light is incident on a glass prism. The prism is surrounded by air. The angle of incidence is  $23^\circ$ . Calculate the angle of reflection and the angle of refraction.
  12. Light is refracted at the interface between air and an unknown medium. If the angle of incidence is  $53^\circ$  and the angle of refraction is  $37^\circ$ , calculate the refractive index of the unknown, second medium.
  13. A coin is placed in a bowl of acetone ( $n = 1,36$ ). The coin appears to be 10 cm deep. What is the depth of the acetone?
  14. A dot is drawn on a piece of paper and a glass prism placed on the dot according to the diagram.



- (a) Use the information supplied to determine the refractive index of glass.
  - (b) Draw a ray diagram to explain how the image of the dot is above where the dot really is.
15. Light is refracted at the interface between a medium of refractive index 1,5 and a second medium of refractive index 2,1. If the angle of incidence is  $45^\circ$ , calculate the angle of refraction.
16. A ray of light strikes the interface between air and diamond. If the incident ray makes an angle of  $30^\circ$  with the interface, calculate the angle made by the refracted ray with the interface.
17. **Challenge Question:** What values of  $n$  are physically impossible to achieve? Explain your answer. The values provide the limits of possible refractive indices.
18. **Challenge Question:** You have been given a glass beaker full of an unknown liquid. How would you identify what the liquid is? You have the following pieces of equipment available for the experiment: a laser, a protractor, a ruler, a pencil, and a reference guide containing optical properties of various liquids.

## 15.5 Mirrors

A mirror is a highly reflective surface. The most common mirrors are flat and are known as **plane mirrors**. Household mirrors are plane mirrors. They are made of a flat piece of glass with a thin layer of silver nitrate or aluminium on the back. However, other mirrors are curved and are either **convex mirrors** or are **concave mirrors**. The reflecting properties of all three types of mirrors will be discussed in this section.

### 15.5.1 Image Formation



#### Definition: Image

An image is a representation of an object formed by a mirror or lens. Light from the image is seen.

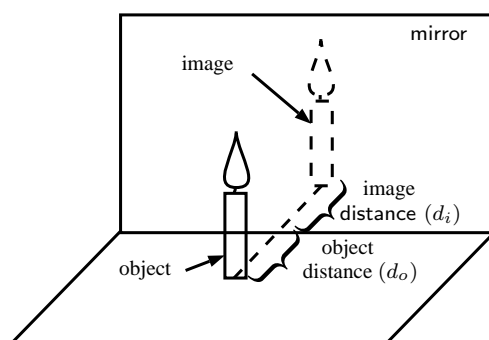


Figure 15.13: An object formed in a mirror is real and upright.

If you place a candle in front of a mirror, you now see two candles. The actual, physical candle is called the **object** and the picture you see in the mirror is called the **image**. The **object** is the source of the incident rays. The **image** is the picture that is formed by the reflected rays.

The object could be an actual source that emits light, such as a light bulb or a candle. More commonly, the object reflects light from another source. When you look at your face in the mirror, your face does not emit light. Instead, light from a light bulb or from the sun reflects off your face and then hits the mirror. However, in working with light rays, it is easiest to pretend the light is coming from the object.

An image formed by reflection may be real or virtual. A **real** image occurs when light rays actually intersect at the image. A real image is inverted, or upside down. A **virtual** image occurs when light rays do not actually meet at the image. Instead, you "see" the image because your eye projects light rays backward. You are fooled into seeing an image! A virtual image is erect, or right side up (upright).

You can tell the two types apart by putting a screen at the location of the image. A real image can be formed on the screen because the light rays actually meet there. A virtual image cannot be seen on a screen, since it is not really there.

To describe objects and images, we need to know their locations and their sizes. The distance from the mirror to the object is the **object distance**,  $d_o$ .

The distance from the mirror to the image is the **image distance**,  $d_i$ .

### 15.5.2 Plane Mirrors



1. Stand one step away from a large mirror
2. What do you observe in the mirror? This is called your image.
3. What size is your image? Bigger, smaller or the same size as you?
4. How far is your image from you? How far is your image from the mirror?
5. Is your image upright or upside down?
6. Take one step backwards. What does your image do? How far are you away from your image?
7. If it were a real object, which foot would the image of you right show fit?

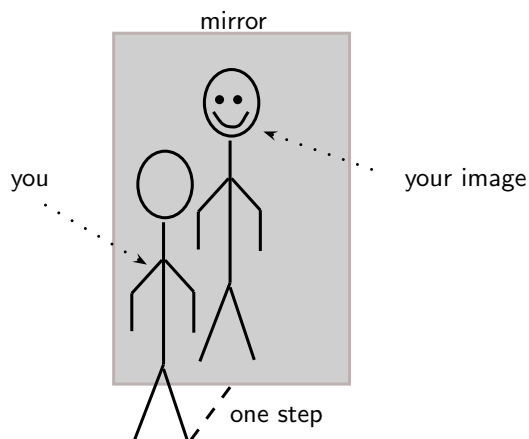


Figure 15.14: An image in a mirror is virtual, upright, the same size and inverted front to back.

---

When you look into a mirror, you see an *image* of yourself.

The image created in the mirror has the following properties:

1. The image is *virtual*.
2. The image is the same distance behind the mirror as the object is in front of the mirror.
3. The image is inverted front to back.
4. The image is the same size as the object.
5. The image is upright.

Virtual images are images formed in places where light does not really reach. Light does not really pass through the mirror to create the image; it only appears to an observer as though the light were coming from behind the mirror. Whenever a mirror creates an image which is virtual, the image will always be located behind the mirror where light does not really pass.



**Definition: Virtual Image**

A virtual image is upright, on the opposite side of the mirror as the object, and light does not actually reach it.

### 15.5.3 Ray Diagrams

We draw *ray diagrams* to predict the image that is formed by a plane mirror. A ray diagram is a geometrical picture that is used for analyzing the images formed by mirrors and lenses. We draw a few characteristic rays from the object to the mirror. We then follow ray-tracing rules to find the path of the rays and locate the image.

**Important:** A mirror obeys the Law of Reflection.

The ray diagram for the image formed by a plane mirror is the simplest possible ray diagram. Figure 15.15 shows an object placed in front of a plane mirror. It is convenient to have a central line that runs perpendicular to the mirror. This imaginary line is called the **principal axis**.

**Important: Ray diagrams**

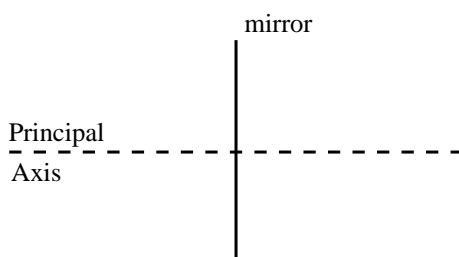
The following should be remembered when drawing ray diagrams:

1. Objects are represented by arrows. The length of the arrow represents the height of the object.
2. If the arrow points upwards, then the object is described as upright or erect. If the arrow points downwards then the object is described as inverted.
3. If the object is real, then the arrow is drawn with a solid line. If the object is virtual, then the arrow is drawn with a dashed line.

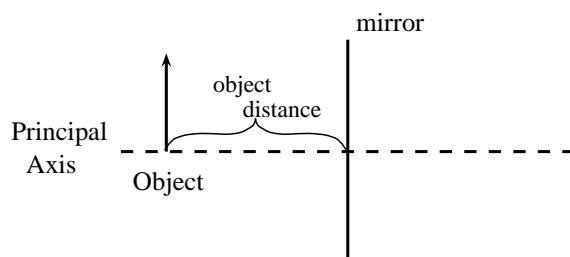
#### Method: Ray Diagrams for Plane Mirrors

Ray diagrams are used to find the position and size and whether the image is real or virtual.

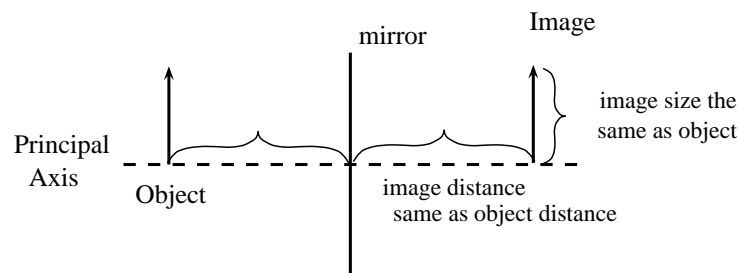
1. Draw the plane mirror as a straight line on a principal axis.



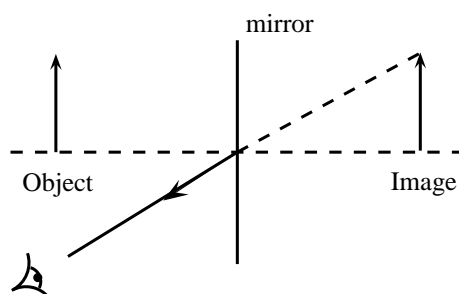
2. Draw the object as an arrow in front of the mirror.



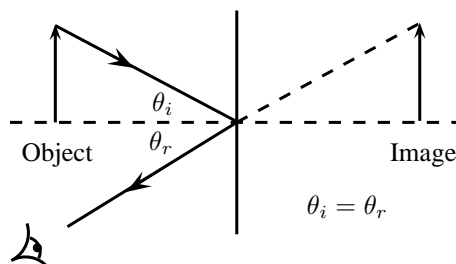
3. Draw the image of the object, by using the principle that the image is placed at the same distance behind the mirror that the object is in front of the mirror. The image size is also the same as the object size.



4. Place a dot at the point the eye is located.
5. Pick one point on the image and draw the reflected ray that travels to the eye as it sees this point. Remember to add an arrowhead.



6. Draw the incident ray for light traveling from the corresponding point on the object to the mirror, such that the law of reflection is obeyed.



7. Continue for other extreme points on the object (i.e. the tip and base of the arrow).

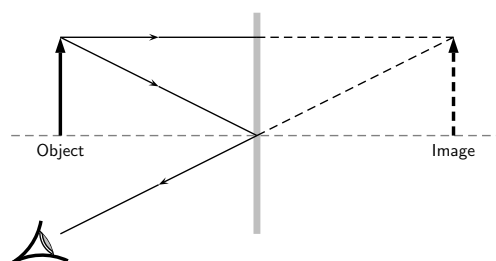


Figure 15.15: Ray diagram to predict the image formed by a plane mirror.

Suppose a light ray leaves the top of the object traveling parallel to the principal axis. The ray will hit the mirror at an angle of incidence of 0 degrees. We say that the ray hits the mirror *normally*. According to the law of reflection, the ray will be reflected at 0 degrees. The ray then bounces back in the same direction. We also project the ray back behind the mirror because this is what your eye does.

Another light ray leaves the top of the object and hits the mirror at its centre. This ray will be reflected at the same angle as its angle of incidence, as shown. If we project the ray backward behind the mirror, it will eventually cross the projection of the first ray we drew. We have found the location of the image! It is a virtual image since it appears in an area that light cannot

actually reach (behind the mirror). You can see from the diagram that the image is erect and is the same size as the object. This is exactly as we expected.

We use a dashed line to indicate that the image is virtual.

### 15.5.4 Spherical Mirrors

The second class of mirrors that we will look at are spherical mirrors. These mirrors are called spherical mirrors because if you take a sphere and cut it as shown in Figure 15.16 and then polish the inside of one and the outside of the other, you will get a *concave mirror* and *convex mirror* as shown. These two mirrors will be studied in detail.

The centre of curvature is the point at the centre of the sphere and describes how big the sphere is.

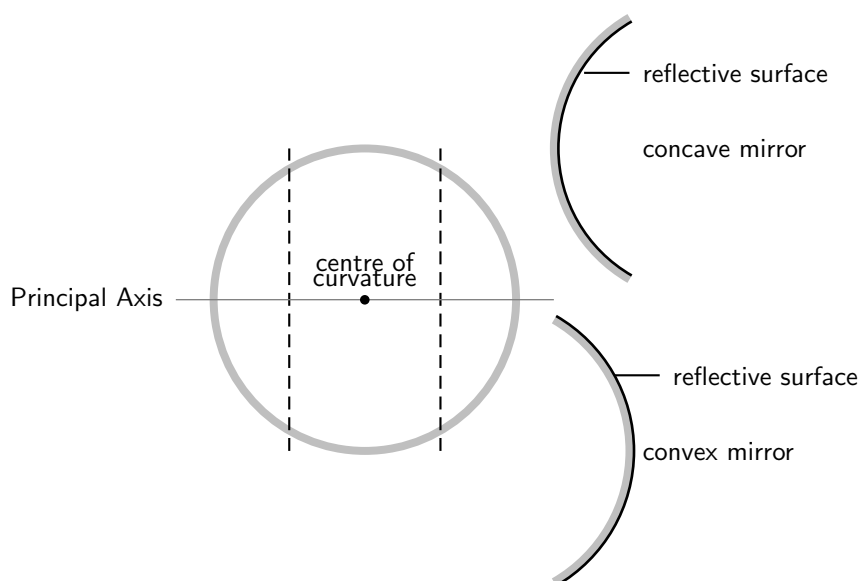


Figure 15.16: When a sphere is cut and then polished to a reflective surface on the inside a concave mirror is obtained. When the outside is polished to a reflective surface, a convex mirror is obtained.

### 15.5.5 Concave Mirrors

The first type of curved mirror we will study are concave mirrors. Concave mirrors have the shape shown in Figure 15.17. As with a plane mirror, the principal axis is a line that is perpendicular to the centre of the mirror.

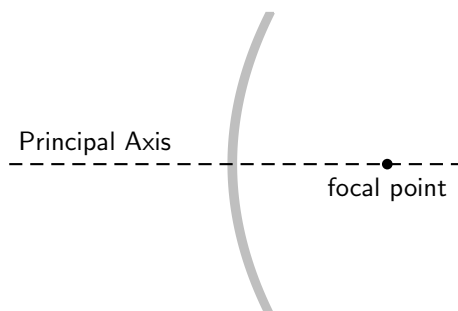


Figure 15.17: Concave mirror with principal axis.

If you think of light reflecting off a concave mirror, you will immediately see that things will look very different compared to a plane mirror. The easiest way to understand what will happen is

to draw a ray diagram and work out where the images will form. Once we have done that it is easy to see what properties the image has.

First we need to define a very important characteristic of the mirror. We have seen that the centre of curvature is the centre of the sphere from which the mirror is cut. We then define that a distance that is half-way between the centre of curvature and the mirror on the principal axis. This point is known as the *focal point* and the distance from the focal point to the mirror is known as the *focal length* (symbol  $f$ ). Since the focal point is the midpoint of the line segment joining the vertex and the center of curvature, the focal length would be one-half the radius of curvature. This fact can come in very handy, remember if you know one then you know the other!



**Definition: Focal Point**

The focal point of a mirror is the midpoint of a line segment joining the vertex and the centre of curvature. It is the position at which all parallel rays are focussed.

Why are we making such a big deal about this point we call the focal point? It has an important property we will use often. A ray parallel to the principal axis hitting the mirror will always be reflected through the focal point. The focal point is the position at which all parallel rays are *focussed*.

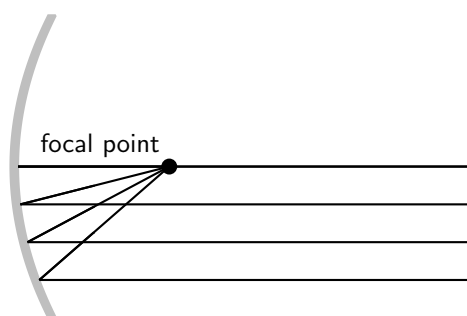


Figure 15.18: All light rays pass through the focal point.

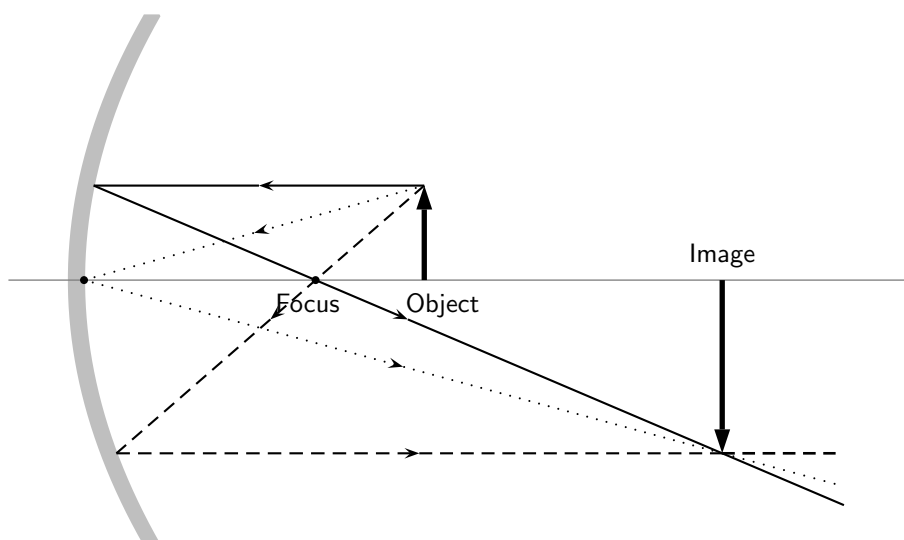


Figure 15.19: A concave mirror with three rays drawn to locate the image. Each incident ray is reflected according to the Law of Reflection. The intersection of the reflected rays gives the location of the image. Here the image is real and inverted.

From Figure 15.19, we see that the image created by a concave mirror is real and inverted, as compared to the virtual and erect image created by a plane mirror.



**Definition: Real Image**

A real image can be cast on a screen; it is inverted, and on the same side of the mirror as the object.



*Extension: Convergence*

A concave mirror is also known as a converging mirror. Light rays appear to converge to the focal point of a concave mirror.

### 15.5.6 Convex Mirrors

The second type of curved mirror we will study are convex mirrors. Convex mirrors have the shape shown in Figure 15.20. As with a plane mirror, the principal axis is a line that is perpendicular to the centre of the mirror.

We have defined the focal point as that point that is half-way along the principal axis between the centre of curvature and the mirror. Now for a convex mirror, this point is *behind* the mirror. A convex mirror has a *negative* focal length because the focal point is behind the mirror.

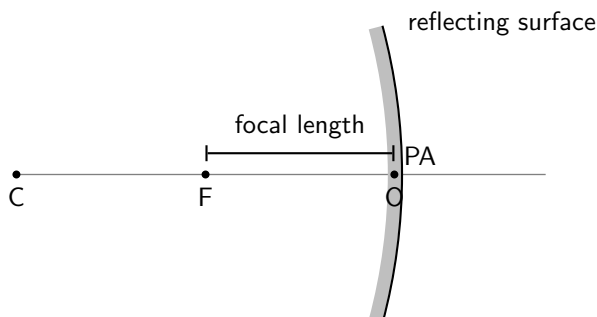


Figure 15.20: Convex mirror with principle axis, focal point (F) and centre of curvature (C). The centre of the mirror is the optical centre (O).

To determine what the image from a convex mirror looks like and where the image is located, we need to remember that a mirror obeys the laws of reflection and that light appears to come from the image. The image created by a convex mirror is shown in Figure 15.21.

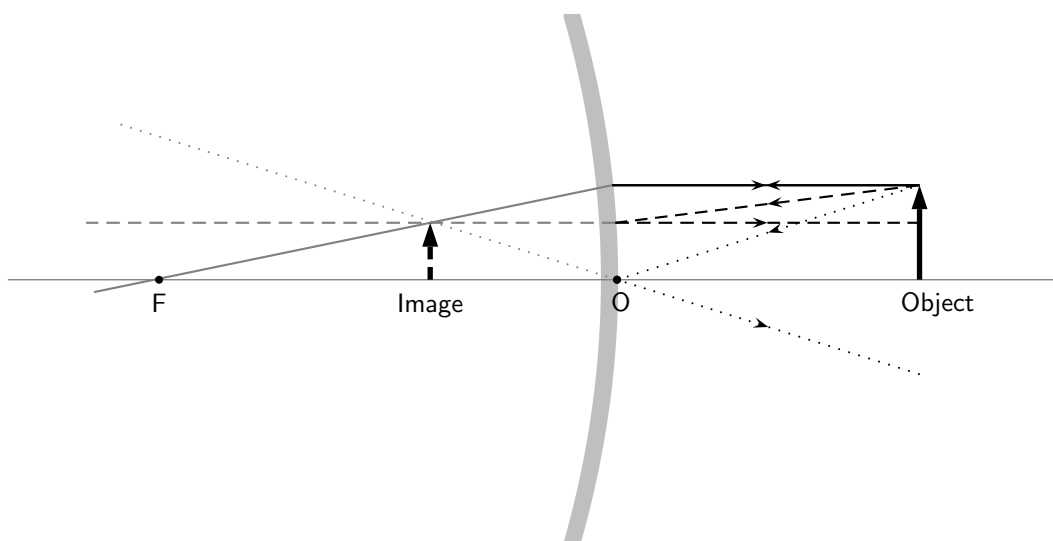


Figure 15.21: A convex mirror with three rays drawn to locate the image. Each incident ray is reflected according to the Law of Reflection. The reflected rays diverge. If the reflected rays are extended behind the mirror, then their intersection gives the location of the image behind the mirror. For a convex mirror, the image is virtual and upright.

From Figure 15.21, we see that the image created by a convex mirror is virtual and upright, as compared to the real and inverted image created by a concave mirror.



*Extension: Divergence*

A convex mirror is also known as a diverging mirror. Light rays appear to diverge from the focal point of a convex mirror.

### 15.5.7 Summary of Properties of Mirrors

The properties of mirrors are summarised in Table 15.2.

Table 15.2: Summary of properties of concave and convex mirrors.

Plane	Concave	Convex
–	converging	diverging
virtual image	real image	virtual image
upright	inverted	upright
image behind mirror	image in front of mirror	image behind mirror

### 15.5.8 Magnification

In Figures 15.19 and 15.21, the height of the object and image arrows were different. In any optical system where images are formed from objects, the ratio of the image height,  $h_i$ , to the object height,  $h_o$  is known as the magnification,  $m$ .

$$m = \frac{h_i}{h_o}$$

This is true for the mirror examples we showed above and will also be true for lenses, which will be introduced in the next sections. For a plane mirror, the height of the image is the same as the

height of the object, so the magnification is simply  $m = \frac{h_i}{h_o} = 1$ . If the magnification is greater than 1, the image is larger than the object and is said to be *magnified*. If the magnification is less than 1, the image is smaller than the object so the image is said to be *diminished*.



### Worked Example 52: Magnification

**Question:** A concave mirror forms an image that is 4,8 cm high. The height of the object is 1,6 cm. Calculate the magnification of the mirror.

**Answer**

**Step 1 : Identify what is given and what is asked.**

Image height  $h_i = 4,8$  cm

Object height  $h_o = 1,6$  cm

Magnification  $m = ?$

**Step 2 : Substitute the values and calculate m.**

$$\begin{aligned} m &= \frac{h_i}{h_o} \\ &= \frac{4,8}{1,6} \\ &= 3 \end{aligned}$$

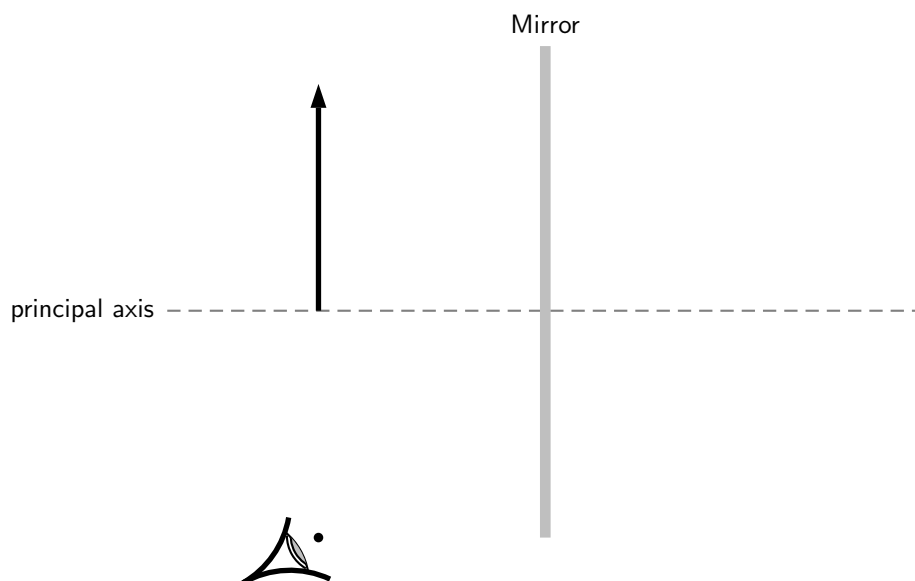
The magnification is 3 times.



### Exercise: Mirrors

1. List 5 properties of a virtual image created by reflection from a plane mirror.
2. What angle does the principal axis make with a plane mirror?
3. Is the principal axis a normal to the surface of the plane mirror?
4. Do the reflected rays that contribute to forming the image from a plane mirror obey the law of reflection?
5. If a candle is placed 50 cm in front of a plane mirror, how far behind the plane mirror will the image be? Draw a ray diagram to show how the image is formed.
6. If a stool 0,5 m high is placed 2 m in front of a plane mirror, how far behind the plane mirror will the image be and how high will the image be?
7. If Susan stands 3 m in front of a plane mirror, how far from Susan will her image be located?
8. Explain why ambulances have the word 'ambulance' reversed on the front bonnet of the car?
9. Complete the diagram by filling in the missing lines to locate the image.





10. An object 2 cm high is placed 4 cm in front of a plane mirror. Draw a ray diagram, showing the object, the mirror and the position of the image.
11. The image of an object is located 5 cm behind a plane mirror. Draw a ray diagram, showing the image, the mirror and the position of the object.
12. How high must a mirror be so that you can see your whole body in it? Does it make a difference if you change the distance you stand in front of the mirror? Explain.
13. If 1-year old Tommy crawls towards a mirror at a rate of  $0,3 \text{ m}\cdot\text{s}^{-1}$ , at what speed will Tommy and his image approach each other?
14. Use a diagram to explain how light converges to the focal point of a concave mirror.
15. Use a diagram to explain how light diverges away from the focal point of a convex mirror.
16. An object 1 cm high is placed 4 cm from a concave mirror. If the focal length of the mirror is 2 cm, find the position and size of the image by means of a ray diagram. Is the image real or virtual?
17. An object 2 cm high is placed 4 cm from a convex mirror. If the focal length of the mirror is 4 cm, find the position and size of the image by means of a ray diagram. Is the image real or virtual?
18. Calculate the magnification for each of the mirrors in the previous two questions.

## 15.6 Total Internal Reflection and Fibre Optics

### 15.6.1 Total Internal Reflection

#### Activity :: Investigation : Total Internal Reflection

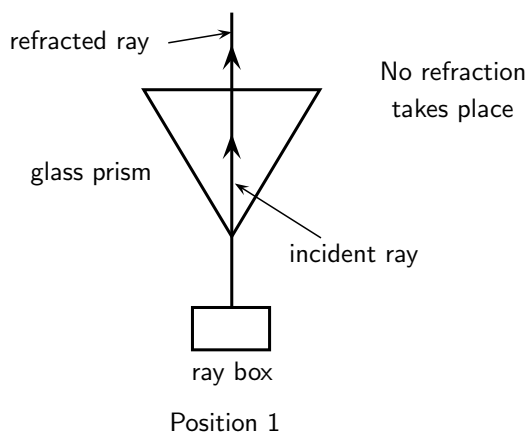
Work in groups of four. Each group will need a raybox (or torch) with slit, triangular glass prism and protractor. If you do not have a raybox, use a torch and stick two pieces of tape over the lens so that only a thin beam of light is visible.

#### Aim:

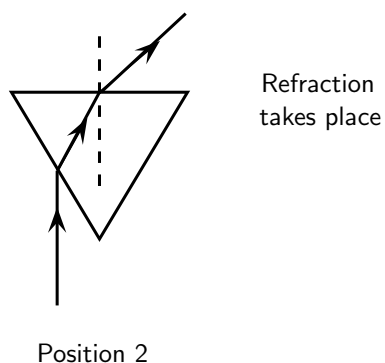
To investigate total internal reflection.

#### Method:

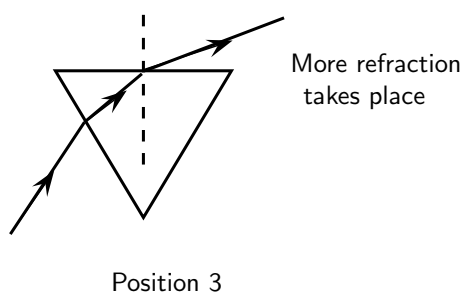
1. Place the raybox next to the glass block so that the light shines right through without any refraction. See "Position 1" in diagram.



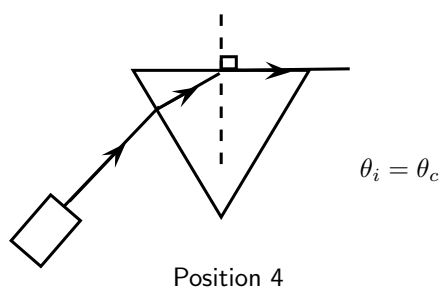
2. Move the raybox such that the light is refracted by the glass. See "Position 2".



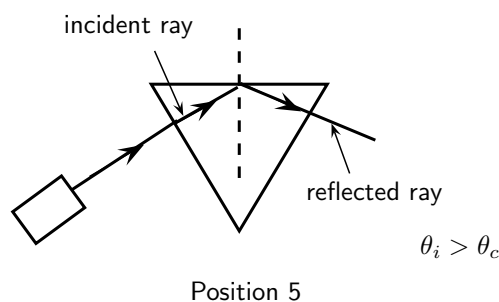
3. Move the raybox further and observe what happens.



4. Move the raybox until the refracted ray seems to disappear. See "Position 4". The angle of the incident light is called the critical angle.



5. Move the raybox further and observe what happens. See "Position 5". The light shines back into the glass block. This is called total internal reflection.



When we increase the angle of incidence, we reach a point where the angle of refraction is  $90^\circ$  and the refracted ray runs along the surface of the medium. This angle of incidence is called the critical angle.



**Definition: Critical Angle**

The critical angle is the angle of incidence where the angle of refraction is  $90^\circ$ . The light must shine from a dense to a less dense medium.

If the angle of incidence is bigger than this critical angle, the refracted ray will not emerge from the medium, but will be reflected back into the medium. This is called total internal reflection.

Total internal reflection takes place when

- light shines from an optically denser medium to an optically less dense medium.
- the angle of incidence is greater than the critical angle.



**Definition: Total Internal Reflection**

Total internal reflection takes place when light is reflected back into the medium because the angle of incidence is greater than the critical angle.

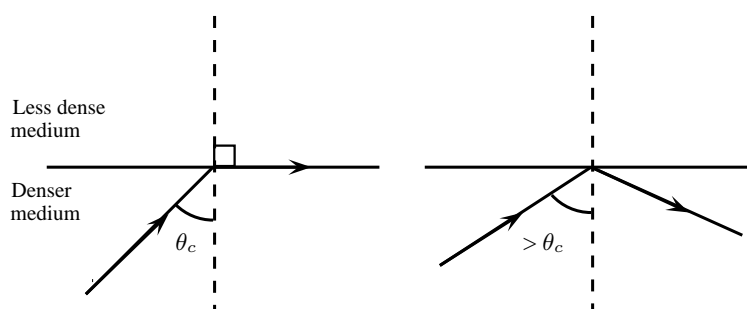


Figure 15.22: Diagrams to show the critical angle and total internal reflection.

Each medium has its own unique critical angle. For example, the critical angle for glass is  $42^\circ$ , and that of water is  $48,8^\circ$ . We can calculate the critical angle for any medium.

### Calculating the Critical Angle

Now we shall learn how to derive the value of the critical angle for two given media. The process is fairly simple and involves just the use of Snell's Law that we have already studied. To recap, 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,  $\theta_1$  is the angle of incidence and  $\theta_2$  is the angle of refraction. For total internal reflection we know that the angle of incidence is the critical angle. So,

$$\theta_1 = \theta_c.$$

However, we also know that the angle of refraction at the critical angle is  $90^\circ$ . 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  $\theta_c$  gives:

$$\begin{aligned} n_1 \sin \theta_c &= n_2 \sin 90^\circ \\ \sin \theta_c &= \frac{n_2}{n_1} (1) \\ \therefore \theta_c &= \sin^{-1} \left( \frac{n_2}{n_1} \right) \end{aligned}$$



**Important:** Take care that for total internal reflection the incident ray is always in the denser medium.



#### Worked Example 53: Critical Angle 1

**Question:** Given that the refractive indices of air and water are 1 and 1,33, respectively, find the critical angle.

**Answer**

##### Step 1 : Determine how to approach the problem

We know that the critical angle is given by:

$$\theta_c = \sin^{-1} \left( \frac{n_2}{n_1} \right)$$

##### Step 2 : Solve the problem

$$\begin{aligned} \theta_c &= \sin^{-1} \left( \frac{n_2}{n_1} \right) \\ &= \sin^{-1} \left( \frac{1}{1,33} \right) \\ &= 48,8^\circ \end{aligned}$$

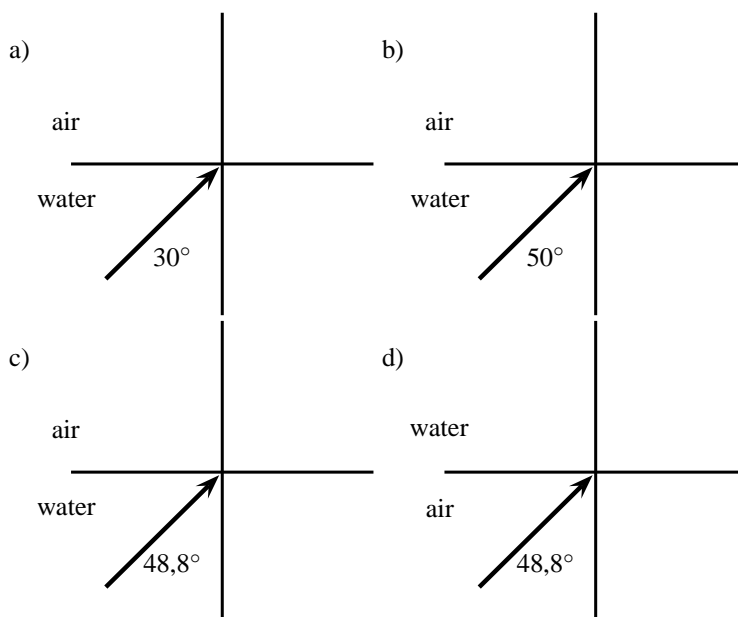
##### Step 3 : Write the final answer

The critical angle for light travelling from water to air is  $48,8^\circ$ .



#### Worked Example 54: Critical Angle 2

**Question:** Complete the following ray diagrams to show the path of light in each situation.

**Answer****Step 1 : Identify what is given and what is asked**

The critical angle for water is  $48,8^\circ$ .

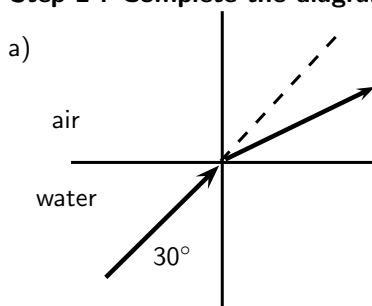
We are asked to complete the diagrams.

For incident angles smaller than  $48,8^\circ$  refraction will occur.

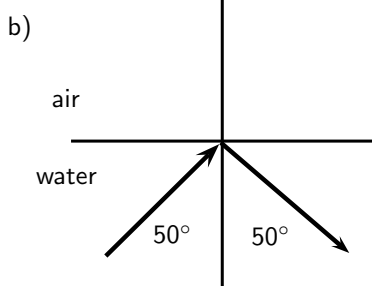
For incident angles greater than  $48,8^\circ$  total internal reflection will occur.

For incident angles equal to  $48,8^\circ$  refraction will occur at  $90^\circ$ .

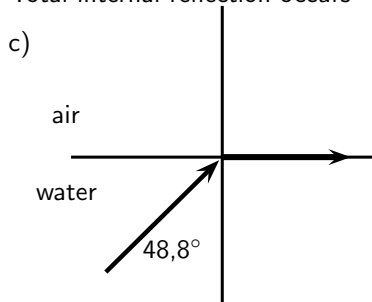
The light must travel from a high optical density to a lower one.

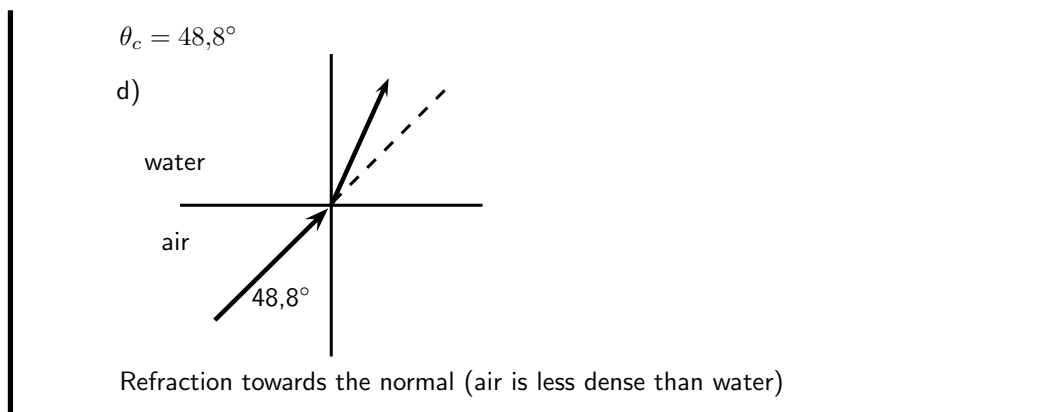
**Step 2 : Complete the diagrams**

Refraction occurs (ray is bent away from the normal)



Total internal reflection occurs





### 15.6.2 Fibre Optics

Total internal reflection is a powerful tool since it can be used to confine light. One of the most common applications of total internal reflection is in *fibre optics*. An optical fibre is a thin, transparent fibre, usually made of glass or plastic, for transmitting light. Optical fibres are usually thinner than a human hair! The construction of a single optical fibre is shown in Figure 15.23.

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  $125\ \mu\text{m}$  ( $125 \times 10^{-6}\text{ m}$ ) and that of the core is just about  $50\ \mu\text{m}$  ( $50 \times 10^{-6}\text{ m}$ ). The mode of operation of the optical fibres, as mentioned above, depends on the phenomenon of total internal reflection. The difference in refractive index of the cladding and the core allows total internal reflection 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.

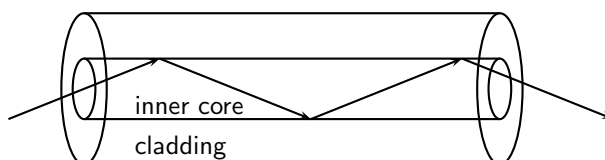


Figure 15.23: Structure of a single optical fibre.

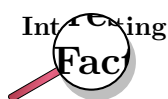
#### Fibre Optics in Telecommunications

Optical fibres are most common in telecommunications, because information can be transported over long distances, with minimal loss of data. The minimised loss of data gives optical fibres an advantage over conventional cables.

Data is transmitted from one end of the fibre to another in the form of laser pulses. A single strand is capable of handling over 3000 simultaneous transmissions which is a huge improvement over the conventional co-axial cables. Multiple signal transmission is achieved by sending individual light pulses at slightly different angles. For example if one of the pulses makes a  $72,23^\circ$  angle of incidence then a separate pulse can be sent at an angle of  $72,26^\circ$ ! The transmitted data is received almost instantaneously at the other end of the cable since the information coded onto the laser travels at the speed of light! During transmission over long distances *repeater stations* are used to amplify the signal which has weakened somewhat by the time it reaches the station. The amplified signals are then relayed towards their destination and may encounter several other repeater stations on the way.

#### Fibre Optics in Medicine

Optic fibres are used in medicine in *endoscopes*.



Endoscopy means *to look inside* and refers to looking inside the human body for diagnosing medical conditions.

The main part of an endoscope is the optical fibre. Light is shone down the optical fibre and a medical doctor can use the endoscope to look inside a patient. Endoscopes are used to examine the inside of a patient's stomach, by inserting the endoscope down the patient's throat.

Endoscopes allow minimally invasive surgery. This means that a person can be diagnosed and treated through a small incision. This has advantages over open surgery because endoscopy is quicker and cheaper and the patient recovers more quickly. The alternative is open surgery which is expensive, requires more time and is more traumatic for the patient.



### Exercise: Total Internal Reflection and Fibre Optics

1. Describe total internal reflection, 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. Will light travelling from diamond to silicon ever undergo total internal reflection?
4. Will light travelling from sapphire to diamond undergo total internal reflection?
5. What is the critical angle for light traveling from air to acetone?
6. Light traveling from diamond to water strikes the interface with an angle of incidence of  $86^\circ$ . Calculate the critical angle to determine whether the light be totally internally reflected and so be trapped within the water.
7. Which of the following interfaces will have the largest critical angle?
  - (a) a glass to water interface
  - (b) a diamond to water interface
  - (c) a diamond to glass interface
8. If the fibre optic strand is made from glass, determine the critical angle of the light ray so that the ray stays within the fibre optic strand.
9. A glass slab is inserted in a tank of water. If the refractive index of water is 1,33 and that of glass is 1,5, find the critical angle.
10. A diamond ring is placed in a container full of glycerin. If the critical angle is found to be  $37,4^\circ$  and the refractive index of glycerin is given to be 1,47, find the refractive index of diamond.
11. An optical fibre is made up of a core of refractive index 1,9, while the refractive index of the cladding is 1,5. Calculate the maximum angle which a light pulse can make with the wall of the core. NOTE: The question does not ask for the angle of incidence but for the angle made by the ray with the wall of the core, which will be equal to  $90^\circ$  - angle of incidence.

## 15.7 Summary

1. We can see objects when light from the objects enters our eyes.
2. Light rays are thin imaginary lines of light and are indicated in drawings by means of arrows.
3. Light travels in straight lines. Light can therefore not travel around corners. Shadows are formed because light shines in straight lines.
4. Light rays reflect off surfaces. The incident ray shines in on the surface and the reflected ray is the one that bounces off the surface. The surface normal is the perpendicular line to the surface where the light strikes the surface.
5. The angle of incidence is the angle between the incident ray and the surface, and the angle of reflection is the angle between the reflected ray and the surface.
6. The Law of Reflection states the angle of incidence is equal to the angle of reflection and that the reflected ray lies in the plane of incidence.
7. Specular reflection takes place when parallel rays fall on a surface and they leave the object as parallel rays. Diffuse reflection takes place when parallel rays are reflected in different directions.
8. Refraction is the bending of light when it travels from one medium to another. Light travels at different speeds in different media.
9. The refractive index of a medium is a measure of how easily light travels through the medium. It is a ratio of the speed of light in a vacuum to the speed of light in the medium.  

$$n = \frac{c}{v}$$
10. Snell's Law gives the relationship between the refractive indices, angles of incidence and reflection of two media.  

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$
11. Light travelling from one medium to another of lighter optical density will be refracted towards the normal.  
 Light travelling from one medium to another of lower optical density will be refracted away from the normal.
12. Objects in a medium (e.g. under water) appear closer to the surface than they really are. This is due to the refraction of light, and the refractive index of the medium.  

$$n = \frac{\text{real depth}}{\text{apparent depth}}$$
13. Mirrors are highly reflective surfaces. Flat mirrors are called plane mirrors. Curved mirrors can be convex or concave. The properties of the images formed by mirrors are summarised in Table 3.2.
14. A real image can be cast on a screen, is inverted and in front of the mirror.  
 A virtual image cannot be cast on a screen, is upright and behind the mirror.
15. The magnification of a mirror is how many times the image is bigger or smaller than the object.  

$$m = \frac{\text{image height } (h_i)}{\text{object height } (h_o)}$$
16. The critical angle of a medium is the angle of incidence when the angle of refraction is  $90^\circ$  and the refracted ray runs along the interface between the two media.
17. Total internal reflection takes place when light travels from one medium to another of lower optical density. If the angle of incidence is greater than the critical angle for the medium, the light will be reflected back into the medium. No refraction takes place.
18. Total internal reflection is used in optical fibres in telecommunication and in medicine in endoscopes. Optical fibres transmit information much more quickly and accurately than traditional methods.

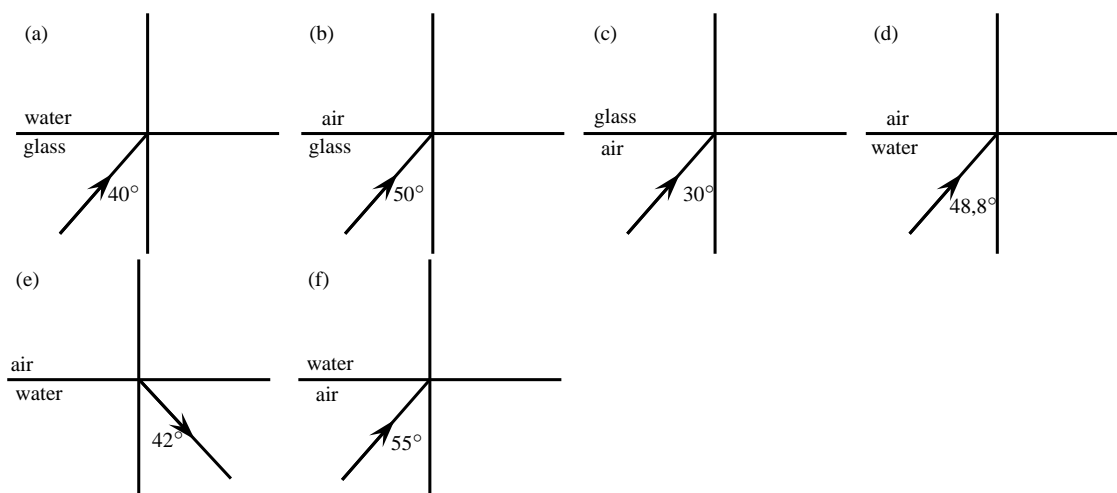


## 15.8 Exercises

- Give one word for each of the following descriptions:
  - The image that is formed by a plane mirror.
  - The perpendicular line that is drawn at right angles to a reflecting surface at the point of incidence.
  - The bending of light as it travels from one medium to another.
  - The ray of light that falls in on an object.
  - A type of mirror that focuses all rays behind the mirror.
- State whether the following statements are TRUE or FALSE. If they are false, rewrite the statement correcting it.
  - The refractive index of a medium is an indication of how fast light will travel through the medium.
  - Total internal refraction takes place when the incident angle is larger than the critical angle.
  - The magnification of an object can be calculated if the speed of light in a vacuum and the speed of light in the medium is known.
  - The speed of light in a vacuum is about  $3 \times 10^8 \text{ m.s}^{-1}$ .
  - Specular reflection takes place when light is reflected off a rough surface.
- Choose words from Column B to match the concept/description in Column A. All the appropriate words should be identified. Words can be used more than once.

Column A	Column B
(a) Real image	Upright
(b) Virtual image	Can be cast on a screen
(c) Concave mirror	In front
(d) Convex mirror	Behind
(e) Plane mirror	Inverted
	Light travels to it
	Upside down
	Light does not reach it
	Erect
	Same size

- Complete the following ray diagrams to show the path of light.



- A ray of light strikes a surface at  $35^\circ$  to the surface normal. 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.
- Light travels from glass ( $n = 1,5$ ) to acetone ( $n = 1,36$ ). The angle of incidence is  $25^\circ$ .

- 6.1 Describe the path of light as it moves into the acetone.
- 6.2 Calculate the angle of refraction.
- 6.3 What happens to the speed of the light as it moves from the glass to the acetone?
- 6.4 What happens to the wavelength of the light as it moves into the acetone?
- 6.5 What is the name of the phenomenon that occurs at the interface between the two media?
7. A stone lies at the bottom of a swimming pool. The water is 120 cm deep. The refractive index of water is 1,33. How deep does the stone appear to be?
8. Light strikes the interface between air and an unknown medium with an incident angle of  $32^\circ$ . The angle of refraction is measured to be  $48^\circ$ . Calculate the refractive index of the medium and identify the medium.
9. Explain what total internal reflection is and how it is used in medicine and telecommunications. Why is this technology much better to use?
10. A candle 10 cm high is placed 25 cm in front of a plane mirror. Draw a ray diagram to show how the image is formed. Include all labels and write down the properties of the image.
11. A virtual image, 4 cm high, is formed 3 cm from a plane mirror. Draw a labelled ray diagram to show the position and height of the object. What is the magnification?
12. An object, 3 cm high, is placed 4 cm from a concave mirror of focal length 2 cm. Draw a labelled ray diagram to find the position, height and properties of the image.
13. An object, 2 cm high, is placed 3 cm from a convex mirror. The magnification is 0,5. Calculate the focal length of the mirror.

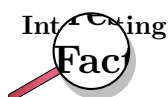
## Chapter 16

# Magnetism - Grade 10

### 16.1 Introduction

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. A second object can feel a magnetic force from the first object because it feels the magnetic field of the first object.

Humans have known about magnetism for many thousands of years. For example, *lodestone* is a magnetised form of the iron oxide mineral *magnetite*. It has the property of attracting iron objects. It is referred to in old European and Asian historical records; from around 800 BCE in Europe and around 2 600 BCE in Asia.

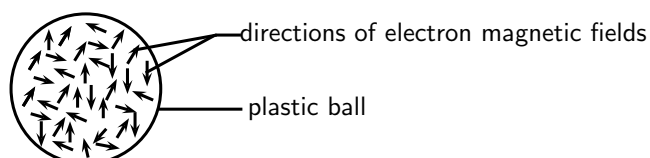


The root of the English word *magnet* is from the Greek word *magnes*, probably from Magnesia in Asia Minor, once an important source of lodestone.

### 16.2 Magnetic fields

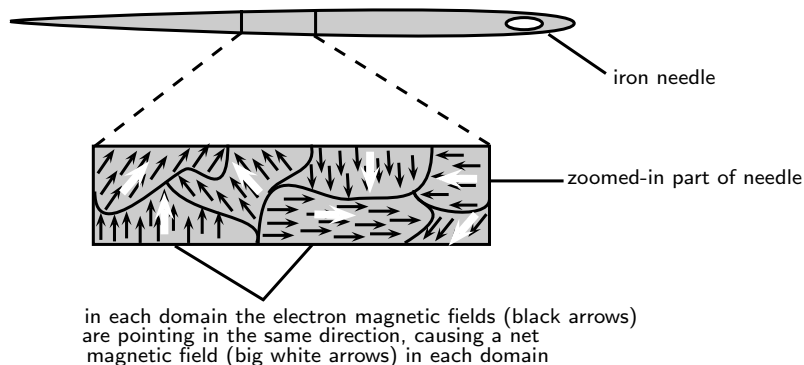
A magnetic field is a region in space where a magnet or object made of magnetic material will experience a non-contact force.

Electrons inside any object have magnetic fields associated with them. In most materials these fields point in all 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.

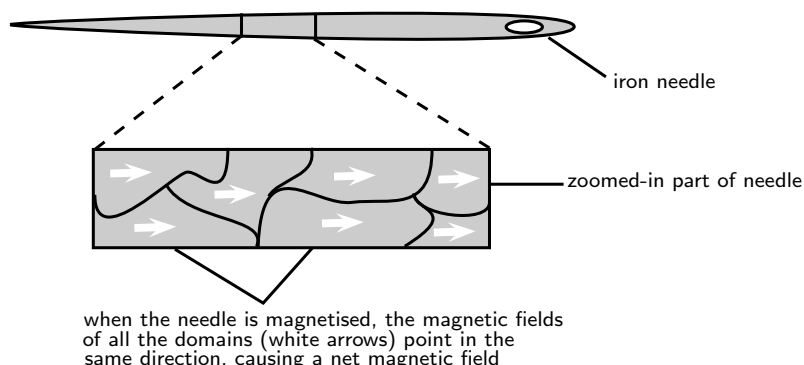


The electron magnetic fields point in all directions and so there is no net (total) magnetic field for the whole ball

In some materials (e.g. iron), called **ferromagnetic** materials, 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. The picture shows a piece of an iron needle zoomed in to show the domains with the electric fields lined up inside them.



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. It is *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 the picture below, the needle has been magnetised because the magnetic fields in all the domains are pointing in the same direction.



### Activity :: Investigation : Ferromagnetic materials and magnetisation

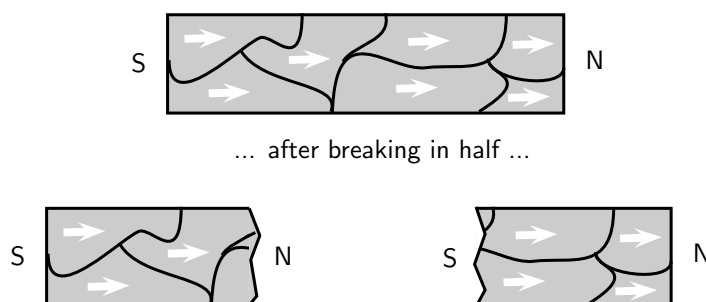
1. Find 2 paper clips. Put the paper clips close together and observe what happens.
  - 1.1 What happens to the paper clips?
  - 1.2 Are the paper clips magnetic?
2. Now take a permanent bar magnet and rub it once along 1 of the paper clips. Remove the magnet and put the paper clip which was touched by the magnet close to the other paper clip and observe what happens.
  - 2.1 Does the untouched paper clip feel a force on it? If so, is the force attractive or repulsive?
3. Rub the same paper clip a few more times with the bar magnet, in the same direction as before. Put the paper clip close to the other one and observe what happens.

- 3.1 Is there any difference to what happened in step 2?
  - 3.2 If there is a difference, what is the reason for it?
  - 3.3 Is the paper clip which was rubbed repeatedly by the magnet now magnetised?
  - 3.4 What is the difference between the two paper clips at the level of their atoms and electrons?
  4. Now, find a *metal* knitting needle, or a plastic ruler, or other plastic object. Rub the bar magnet along the knitting needle a few times in the same direction. Now put the knitting needle close to the paper clips and observe what happens.
    - 4.1 Does the knitting needle attract the paper clips?
    - 4.2 What does this tell you about the material of the knitting needle? Is it ferromagnetic?
  5. Repeat this experiment with objects made from other materials.
    - 5.1 Which materials appear to be ferromagnetic and which are not? Put your answers in a table.
- 

## 16.3 Permanent magnets

### 16.3.1 The poles of permanent magnets

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 south magnetic pole on its own.



Magnetic fields are *different* from gravitational and electric fields. 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).

### 16.3.2 Magnetic attraction and repulsion

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 a N pole and a S pole will be drawn towards each other.



#### Definition: Attraction and Repulsion

Like poles of magnets *repel* each other whilst *unlike* poles *attract* each other.

**Worked Example 55: Attraction and Repulsion**

**Question:** Do you think the following magnets will repel or be attracted to each other?

**Answer****Step 1 : Determine what is required**

We are required to determine whether the two magnets will repel each other or be attracted to each other.

**Step 2 : Determine what is given**

We are given two magnets with the N pole of one approaching the N pole of the other.

**Step 3 : Determine the conclusion**

Since both poles are the same, the magnets will repel each other.

**Worked Example 56: Attraction and repulsion**

**Question:** Do you think the following magnets will repel or be attracted to each other?

**Answer****Step 1 : Determine what is required**

We are required to determine whether the two magnets will repel each other or be attracted to each other.

**Step 2 : Determine what is given**

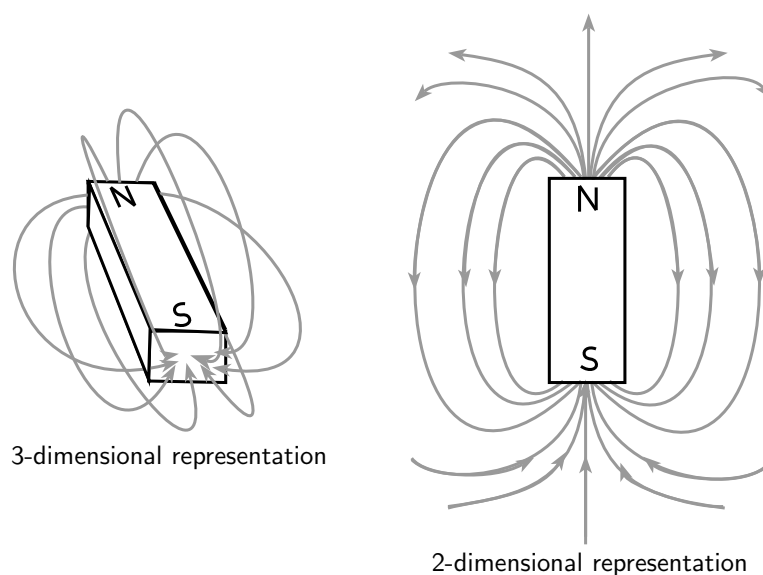
We are given two magnets with the N pole of one approaching the S pole of the other.

**Step 3 : Determine the conclusion**

Since both poles are the different, the magnets will be attracted to each other.

### 16.3.3 Representing magnetic fields

Magnetic fields can be *represented* using **magnetic field lines** starting at the North pole and ending at the South pole. Although the magnetic field of a permanent magnet is everywhere surrounding the magnet (in all three dimensions), we draw only some of the field lines to represent the field (usually only a two-dimensional cross-section is shown in drawings).



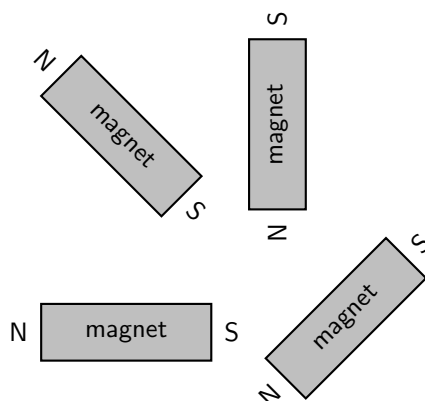
In areas where the magnetic field is strong, the field lines are closer together. Where the field is weaker, the field lines are drawn further apart. The number of field lines drawn crossing a given two-dimensional surface is referred to as the **magnetic flux**. The magnetic flux is used as a measure of the strength of the magnetic field over that surface.

### Important:

1. Field lines *never* cross.
2. Arrows drawn on the field lines indicate the direction of the field.
3. A magnetic field points from the north to the south pole of a magnet.

### Activity :: Investigation : Field around a Bar Magnet

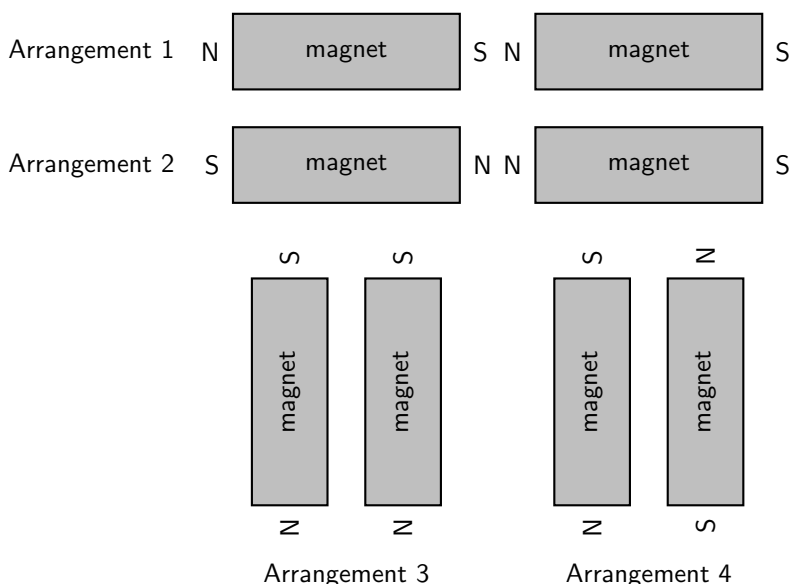
Take a bar magnet and place it on a flat surface. Place a sheet of white paper over the bar magnet and sprinkle some iron filings onto the paper. Give the paper a shake to evenly distribute the iron filings. In your workbook, draw the bar magnet and the pattern formed by the iron filings. Draw the pattern formed when you rotate the bar magnet to a different angle as shown below.



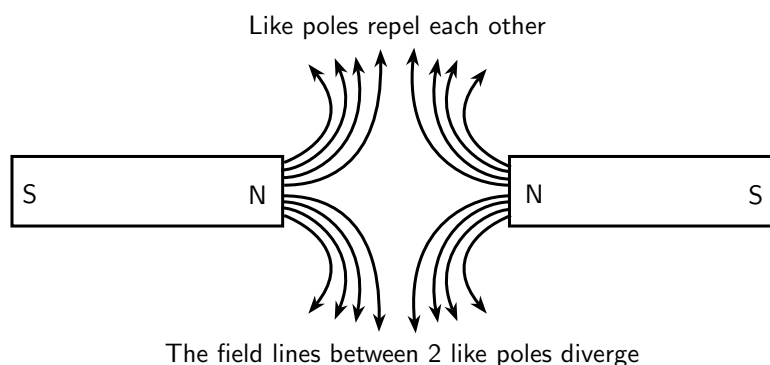
As the activity shows, one can map the magnetic field of a magnet by placing it underneath a piece of paper and sprinkling iron filings on top. The iron filings line themselves up parallel to the magnetic field.

### Activity :: Investigation : Field around a Pair of Bar Magnets

Take two bar magnets and place them a short distance apart such that they are repelling each other. Place a sheet of white paper over the bar magnets and sprinkle some iron filings onto the paper. Give the paper a shake to evenly distribute the iron filings. In your workbook, draw both the bar magnets and the pattern formed by the iron filings. Repeat the procedure for two bar magnets attracting each other and draw what the pattern looks like for this situation. Make a note of the shape of the lines formed by the iron filings, as well as their size and their direction for both arrangements of the bar magnet. What does the pattern look like when you place both bar magnets side by side?

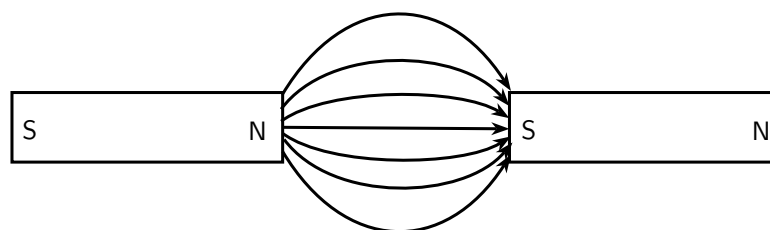


As already said, opposite poles of a magnet attract each other and bringing them together causes their magnetic field lines to *converge* (come together). Like poles of a magnet repel each other and bringing them together causes their magnetic field lines to *diverge* (bend out from each other).





Unlike poles attract each other



The magnetic field lines between 2 unlike poles converge



#### Extension: Ferromagnetism and Retentivity

**Ferromagnetism** is a phenomenon shown by materials like iron, nickel or cobalt. These materials can form permanent magnets. They always magnetise so as to be attracted to a magnet, no matter which magnetic pole is brought toward the unmagnetised iron/nickel/cobalt.

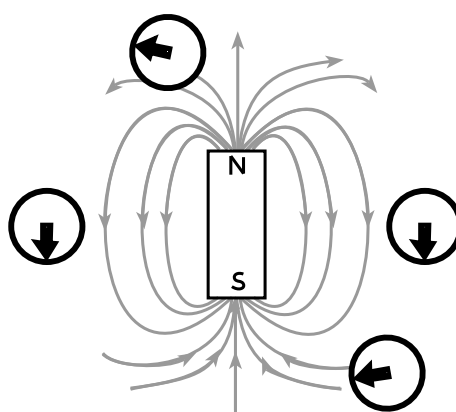
The ability of a ferromagnetic material to retain its magnetisation *after* an external field is removed is called its **retentivity**.

**Paramagnetic** materials are materials like aluminium or platinum, which become magnetised in an external magnetic field in a similar way to ferromagnetic materials. However, they lose their magnetism when the external magnetic field is removed.

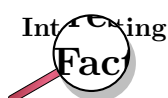
**Diamagnetism** is shown by materials like copper or bismuth, which become magnetised in a magnetic field with a polarity *opposite* to the external magnetic field. Unlike iron, they are slightly repelled by a magnet.

## 16.4 The compass and the earth's magnetic field

A **compass** is an instrument which 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. Therefore, when in the presence of a magnetic field, the needle is able to line up in the same direction as the field.

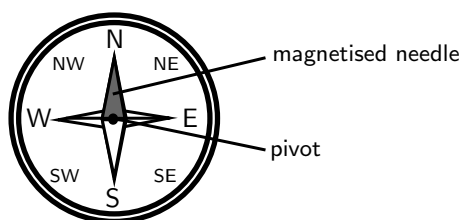


The direction of the compass arrow is the same as the direction of the magnetic field



Lodestone, a magnetised form of iron-oxide, was found to orientate itself in a north-south direction if left free to rotate by suspension on a string or on a float in water. Lodestone was therefore used as an early navigational compass.

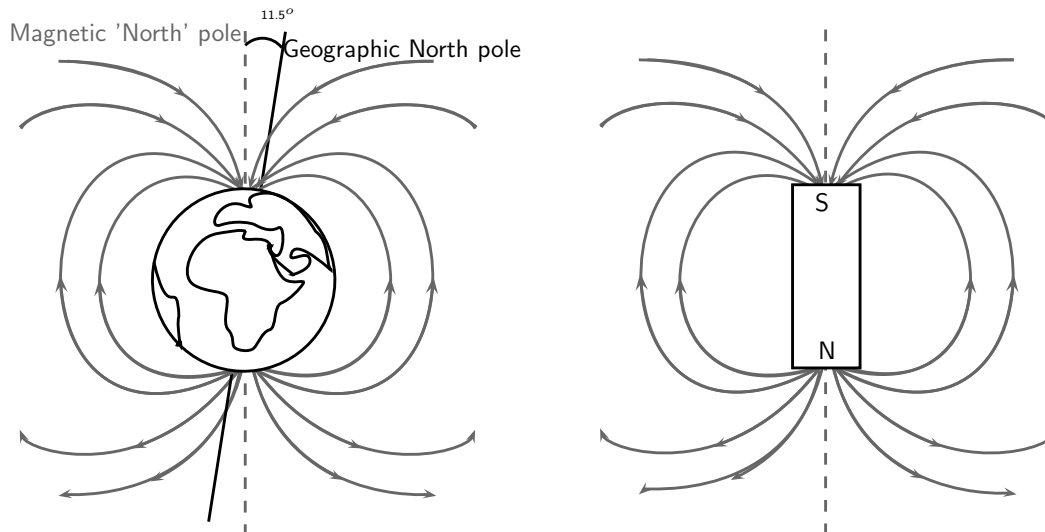
Compasses are mainly used in navigation to find direction on the earth. This works because the earth itself has a magnetic field which is similar to that of a bar magnet (see the picture below). The compass needle aligns with the earth's magnetic field direction and points north-south. Once you know where north is, you can figure out any other direction. A picture of a compass is shown below:



Some animals can detect magnetic fields, which helps them orientate themselves and navigate. Animals which can do this include pigeons, bees, Monarch butterflies, sea turtles and certain fish.

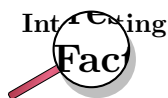
### 16.4.1 The earth's magnetic field

In the picture below, you can see a representation of the earth's magnetic field which is very similar to the magnetic field of a giant bar magnet like the one on the right of the picture. So the earth has two sets of north poles and south poles: **geographic poles** and **magnetic poles**.



The earth's magnetic field is thought to be caused by flowing liquid metals in the outer core which causes electric currents and a magnetic field. From the picture you can see that the direction of magnetic north and true north are not identical. The **geographic north pole**, which is the point through which the earth's rotation axis goes, is about  $11,5^\circ$  away from the direction of the **magnetic north pole** (which is where a compass will point). 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!



The direction of the earth's magnetic field flips direction about once every 200 000 years! You can picture this as a bar magnet whose north and south pole periodically switch sides. The reason for this is still not fully understood.

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The earth's magnetic field is very important for humans and other animals on earth because it stops electrically charged particles emitted by the sun from hitting the earth and us. Charged particles can also damage and cause interference with telecommunications (such as cell phones). The stream of charged particles (mainly protons and electrons) coming from the sun is called the solar wind. These particles spiral in the earth's magnetic field towards the poles. If they collide with particles in the earth's atmosphere they sometimes cause red or green lights or a glow in the sky which is called the aurora. This happens close to the north and south pole and so we cannot see the aurora from South Africa.

## 16.5 Summary

1. Magnets have two poles - North and South.
2. Some substances can be easily magnetised.
3. Like poles repel each other and unlike poles attract each other.
4. The Earth also has a magnetic field.
5. A compass can be used to find the magnetic north pole and help us find our direction.

## 16.6 End of chapter exercises

1. Describe what is meant by the term *magnetic field*.
2. Use words and pictures to explain why permanent magnets have a magnetic field around them. Refer to *domains* in your explanation.
3. What is a magnet?
4. What happens to the poles of a magnet if it is cut into pieces?
5. What happens when like magnetic poles are brought close together?
6. What happens when unlike magnetic poles are brought close together?
7. Draw the shape of the magnetic field around a bar magnet.
8. Explain how a compass indicates the direction of a magnetic field.
9. Compare the magnetic field of the Earth to the magnetic field of a bar magnet using words and diagrams.
10. Explain the difference between the geographical north pole and the magnetic north pole of the Earth.
11. Give examples of phenomena that are affected by Earth's magnetic field.
12. Draw a diagram showing the magnetic field around the Earth.



# Chapter 17

## Electrostatics - Grade 10

### 17.1 Introduction

Electrostatics is the study of electric charge which is static (not moving).

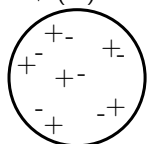
### 17.2 Two kinds of charge

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 brought together, they neutralise each other and there is *no net charge*. **Neutral** objects are objects which contain equal amounts of positive and negative charges. However, if there is a little bit more of one type of charge than the other on the object then the object is said to be **electrically charged**. The picture below shows what the distribution of charges might look like for a neutral, positively charged and negatively charged object.

There are:

6 positive charges and  
6 negative charges

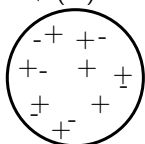
$$6 + (-6) = 0$$



There is zero net charge:  
The object is neutral

8 positive charges and  
6 negative charges

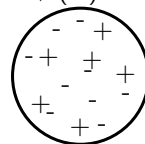
$$8 + (-6) = 2$$



The net charge is +2  
The object is positively charged

6 positive charges and  
9 negative charges

$$6 + (-9) = -3$$



The net charge is -3

The object is negatively charged

### 17.3 Unit of charge

Charge is measured in units called **coulombs (C)**. A coulomb of charge is a very large charge. In electrostatics we therefore often work with charge in microcoulombs ( $1 \mu\text{C} = 1 \times 10^{-6} \text{ C}$ ) and nanocoulombs ( $1 \text{ nC} = 1 \times 10^{-9} \text{ C}$ ).

### 17.4 Conservation of charge

Objects may become charged in many ways, including by contact with or being rubbed by other objects. This means that they can gain extra negative or positive charge. Charging happens when you, for example, rub your feet against the carpet. When you then touch something metallic or another person, you feel a shock as the excess charge that you have collected is *discharged*.

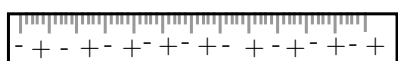


**Important:** Charge, like energy, cannot be created or destroyed. We say that charge is **conserved**.

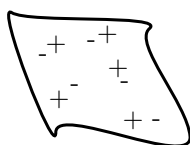
When you rub your feet against the carpet, negative charge is transferred to you from the carpet. The carpet will then become positively charged by the *same amount*.

Another example is to take two *neutral* objects such as a plastic ruler and a cotton cloth (handkerchief). To begin, the two objects are neutral (i.e. have the same amounts of positive and negative charge).

BEFORE rubbing:



The ruler has 9 positive charges and 9 negative charges



The neutral cotton cloth has 5 positive charges and 5 negative charges

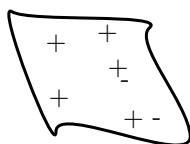
The total number of charges is:  
 $(9+5)=14$  positive charges  
 $(9+5)=14$  negative charges

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 and the cloth is *positively* charged. 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*!

AFTER rubbing:



The ruler has 9 positive charges and 12 negative charges  
 It is now negatively charged.



The cotton cloth has 5 positive charges and 2 negative charges.  
 It is now positively charged.

The total number of charges is:  
 $(9+5)=14$  positive charges  
 $(12+2)=14$  negative charges

Charges have been transferred from the cloth to the ruler BUT total charge has been conserved!

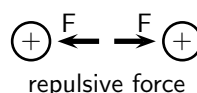
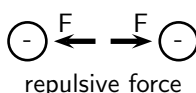
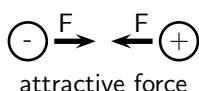
Note that in this example the numbers are made up to be easy to calculate. In the real world only a tiny fraction of the charges would move from one object to the other, but the total charge would still be conserved.

## 17.5 Force between Charges

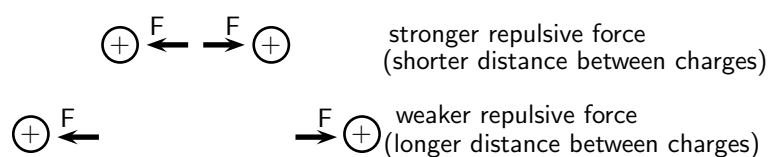
The force exerted by non-moving (static) charges on each other is called the **electrostatic force**. The electrostatic force between:

- **like** charges are **repulsive**
- **opposite** (unlike) charges are **attractive**.

In other words, like charges repel each other while opposite charges attract each other. This is different to the gravitational force which is only attractive.



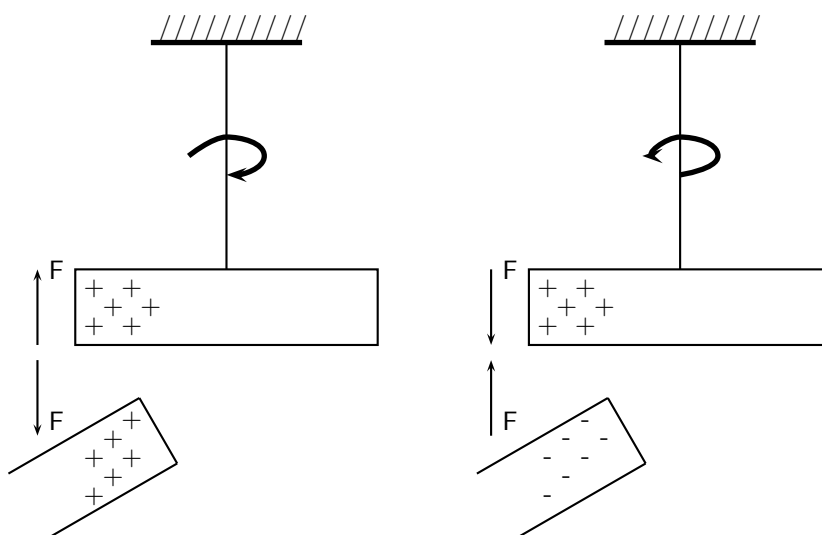
The *closer* together the charges are, the *stronger* the electrostatic force between them.



### Activity :: Experiment : Electrostatic Force

You can easily test that like charges repel and unlike charges attract each other by doing a very simple experiment.

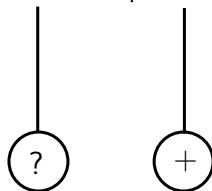
Take a glass rod and rub it with a piece of silk, then hang it from its middle with a piece string so that it is free to move. If you then bring another glass rod which you have also charged in the same way next to it, you will see the rod on the string turn **away** from the rod in your hand i.e. it is **repelled**. If, however, you take a plastic rod, rub it with a piece of fur and then bring it close to the rod on the string, you will see the rod on the string turn **towards** the rod in your hand i.e. it is **attracted**.



This happens because when you rub the glass with silk, tiny amounts of negative charge are transferred from the glass onto the silk, which causes the glass to have less negative charge than positive charge, making it **positively charged**. When you rub the plastic rod with the fur, you transfer tiny amounts of negative charge onto the rod and so it has more negative charge than positive charge on it, making it **negatively charged**.


**Worked Example 57: Application of electrostatic forces**

**Question:** Two charged 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 hand sphere swings towards the right hand sphere, what can you say about the charge on the left sphere and why?
2. If the left hand sphere swings away from the right hand sphere, what can you say about the charge on the left sphere and why?

**Answer**

**Step 1 : Identify what is known and what question you need to answer:**

In the first case, we have a sphere with positive charge which is *attracting* the left charged sphere. We need to find the charge on the left sphere.

**Step 2 : What concept is being used?**

We are dealing with electrostatic forces between charged objects. Therefore, we know that *like* charges *repel* each other and *opposite* charges *attract* each other.

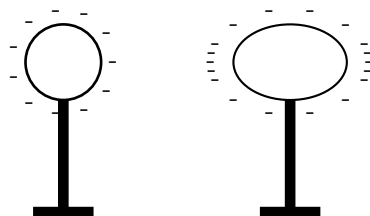
**Step 3 : Use the concept to find the solution**

1. In the first case, the positively charged sphere is attracting the left sphere. Since an electrostatic force between unlike charges is attractive, the left sphere must be *negatively* charged.
2. In the second case, the positively charged sphere repels the left sphere. Like charges repel each other. Therefore, the left sphere must now also be *positively* charged.



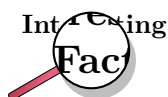
*Extension: Electrostatic Force*

The electrostatic force determines the arrangement of charge on the surface of conductors. This is possible because charges can move inside a conductive material. When we place a charge on a spherical conductor the repulsive forces between the individual like charges cause them to spread uniformly over the surface of the sphere. However, for conductors with non-regular shapes, there is a concentration of charge near the point or points of the object.





This collection of charge can actually 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 “spreading out” of charge would not occur if we were to place the charge on an insulator since charge cannot move in insulators.



The word ‘electron’ comes from the Greek word for amber. The ancient Greeks observed that if you rubbed a piece of amber, you could use it to pick up bits of straw.

## 17.6 Conductors and insulators

All atoms are electrically neutral i.e. they have the same amounts of negative and positive charge inside them. By convention, the electrons carry negative charge and the protons carry positive charge. The basic unit of charge, called the elementary charge,  $e$ , is the amount of charge carried by one electron.

All the matter and materials on earth are made up of atoms. Some materials allow electrons to move relatively freely through them (e.g. most metals, 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, 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 like charges will repel each other and spread out over the outside surface of the object. When two conductors are made to touch, the total charge on them is shared between the two. If the two conductors are identical, then each conductor will be left with half of the total charge.



### *Extension: Charge and electrons*

The basic unit of charge, namely the elementary charge is carried by the electron (equal to  $1.602 \times 10^{-19}$  C!). In a conducting material (e.g. copper), when the atoms bond to form the material, some of the outermost, loosely bound electrons become detached from the individual atoms and so become free to move around. The charge carried by these electrons can move around in the material. In insulators, there are very few, if any, free electrons and so the charge cannot move around in the material.



**Worked Example 58: Conducting spheres and movement of charge**

**Question:** I have 2 charged metal conducting spheres which are identical except for having different charge. Sphere A has a charge of  $-5\text{ nC}$  and sphere B has a charge of  $-3\text{ nC}$ . I then bring the spheres together so that they touch each other. Afterwards I move the two spheres apart so that they are no longer touching.

1. What happens to the charge on the two spheres?
2. What is the final charge on each sphere?

**Answer**

**Step 1 : Identify what is known and what question/s we need to answer:**

We have two identical negatively charged conducting spheres which are brought together to touch each other and then taken apart again. We need to explain what happens to the charge on each sphere and what the final charge on each sphere is after they are moved apart.

**Step 2 : What concept is being used?**

We know that the charge carriers in conductors are free to move around and that charge on a conductor spreads itself out on the surface of the conductor.

**Step 3 : Use the concept to find the answer**

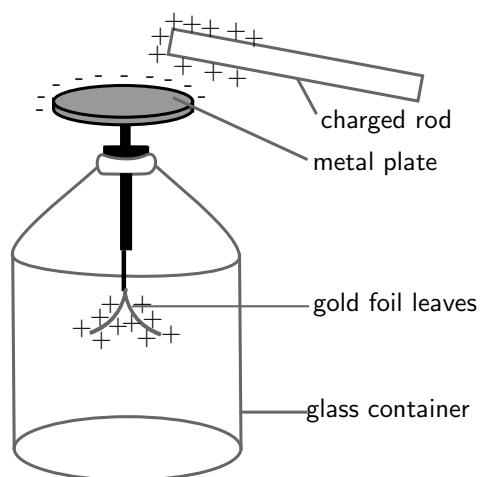
1. When the two conducting spheres are brought together to touch, it is as though they become one single big conductor and the total charge of the two spheres spreads out across the whole surface of the touching spheres. When the spheres are moved apart again, each one is left with half of the total original charge.
2. Before the spheres touch, the total charge is:  $-5\text{ nC} + (-3)\text{ nC} = -8\text{ nC}$ . When they touch they share out the  $-8\text{ nC}$  across their whole surface. When they are removed from each other, each is left with half of the original charge:

$$-8\text{ nC} / 2 = -4\text{ nC}$$

on each sphere.

### 17.6.1 The electroscope

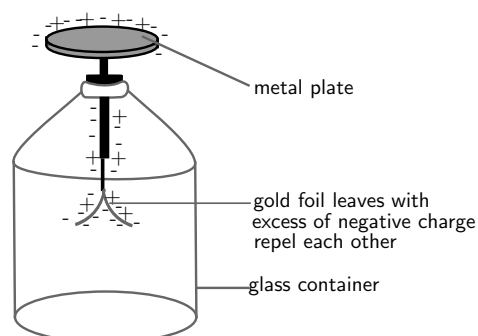
The electroscope is a very sensitive instrument which can be used to detect electric charge. A diagram of a gold leaf electroscope is shown in the figure below. The electroscope consists of a glass container with a metal rod inside which has 2 thin pieces of gold foil attached. The other end of the metal rod has a metal plate attached to it outside the glass container.



The electroscope detects charge in the following way: A charged object, like the positively charged rod in the picture, is brought close to (but not touching) the neutral metal plate of the electroscope. This causes negative charge in the gold foil, metal rod, and metal plate, to be attracted to the positive rod. Because the metal (gold is a metal too!) is a conductor, the charge can move freely from the foil up the metal rod and onto the metal plate. There is now more negative charge on the plate and more positive charge on the gold foil leaves. This is called *inducing* a charge on the metal plate. It is important to remember that the electroscope is still neutral (the total positive and negative charges are the same), the charges have just been induced to *move* to different parts of the instrument! The induced positive charge on the gold leaves forces them apart since like charges repel! This is how we can tell that the rod is charged. If the rod is now moved away from the metal plate, the charge in the electroscope will spread itself out evenly again and the leaves will fall down because there will no longer be an induced charge on them.

### Grounding

If you were to bring the charged rod close to the uncharged electroscope, and then you touched the metal plate with your finger at the same time, this would cause charge to flow up from the ground (the earth), through your body onto the metal plate. Connecting to the earth so charge flows is called **grounding**. The charge flowing onto the plate is opposite to the charge on the rod, since it is attracted to the charge on the rod. Therefore, for our picture, the charge flowing onto the plate would be negative. Now that charge has been added to the electroscope, it is no longer neutral, but has an excess of negative charge. Now if we move the rod away, the leaves will remain apart because they have an excess of negative charge and they repel each other. If we ground the electroscope again (this time without the charged rod nearby), the excess charge will flow back into the earth, leaving it neutral.

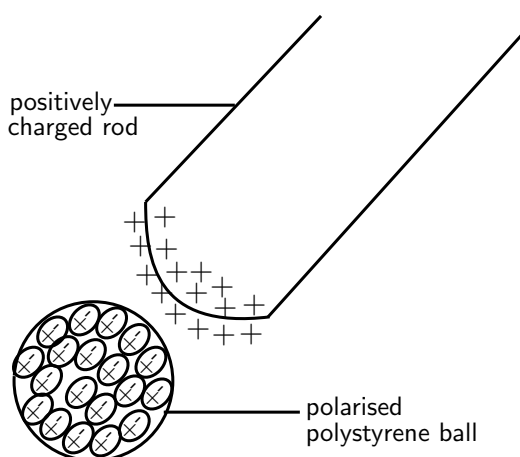


## 17.7 Attraction between charged and uncharged objects

### 17.7.1 Polarisation of Insulators

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**.

If a positively charged rod is brought close to a neutral insulator such as polystyrene, 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:



Some materials are made up of molecules which are already polarised. These are molecules which 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.

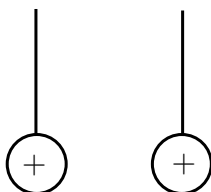
Water is an example of a substance which is made of polarised molecules. If a positively charged rod is brought close to a stream of water, the molecules can rotate so that the negative sides all line up towards the rod. The stream of water will then be attracted to the rod since opposite charges attract.

## 17.8 Summary

1. Objects can be **positively** charged, **negatively** charged or **neutral**.
2. Objects that are neutral have equal numbers of positive and negative charge.
3. Unlike charges are attracted to each other and like charges are repelled from each other.
4. Charge is neither created nor destroyed, it can only be transferred.
5. Charge is measured in coulombs (C).
6. Conductors allow charge to move through them easily.
7. Insulators do not allow charge to move through them easily.

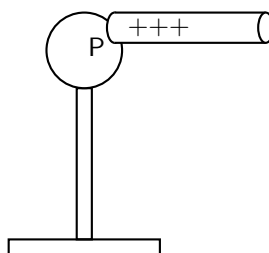
## 17.9 End of chapter exercise

1. What are the two types of charge called?
2. Provide evidence for the existence of two types of charge.
3. Fill in the blanks: The electrostatic force between like charges is \_\_\_\_\_ while the electrostatic force between opposite charges is \_\_\_\_\_.
4. I have two positively charged metal balls placed 2 m apart.
  - 4.1 Is the electrostatic force between the balls attractive or repulsive?
  - 4.2 If I now move the balls so that they are 1 m apart, what happens to the strength of the electrostatic force between them?
5. I have 2 charged spheres each hanging from string as shown in the picture below.



Choose the correct answer from the options below: The spheres will

- 5.1 swing towards each other due to the attractive electrostatic force between them.
- 5.2 swing away from each other due to the attractive electrostatic force between them.
- 5.3 swing towards each other due to the repulsive electrostatic force between them.
- 5.4 swing away from each other due to the repulsive electrostatic force between them.
6. Describe how objects (insulators) can be charged by contact or rubbing.
7. You are given a perspex ruler and a piece of cloth.
  - 7.1 How would you charge the perspex ruler?
  - 7.2 Explain how the ruler becomes charged in terms of charge.
  - 7.3 How does the charged ruler attract small pieces of paper?
8. [IEB 2005/11 HG] An uncharged hollow metal sphere is placed on an insulating stand. A positively charged rod is brought up to touch the hollow metal sphere at P as shown in the diagram below. It is then moved away from the sphere.



Where is the excess charge distributed on the sphere after the rod has been removed?

- 8.1 It is still located at point P where the rod touched the sphere.
- 8.2 It is evenly distributed over the outer surface of the hollow sphere.
- 8.3 It is evenly distributed over the outer and inner surfaces of the hollow sphere.
- 8.4 No charge remains on the hollow sphere.
9. What is the process called where molecules in an uncharged object are caused to align in a particular direction due to an external charge?
10. Explain how an uncharged object can be attracted to a charged object. You should use diagrams to illustrate your answer.
11. Explain how a stream of water can be attracted to a charged rod.



## Chapter 18

# Electric Circuits - Grade 10

### 18.1 Electric Circuits

People all over the world depend on electricity to provide power for most appliances in the home and at work. For example, fluorescent lights, electric heating and cooking (on electric stoves), all depend on electricity to work. To realise just how big an impact electricity has on our daily lives, just think about what happens when there is a power failure or load shedding.

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#### Activity :: Discussion : Uses of electricity

With a partner, take the following topics and, for each topic, write down at least 5 items/appliances/machines which need electricity to work. Try not to use the same item more than once.

- At home
- At school
- At the hospital
- In the city

Once you have finished making your lists, compare with the lists of other people in your class. (Save your lists somewhere safe for later because there will be another activity for which you'll need them.)

When you start comparing, you should notice that there are many different items which we use in our daily lives which rely on electricity to work!

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**Important: Safety Warning:** We believe in experimenting and learning about physics at every opportunity, BUT playing with electricity and electrical appliances can be **EXTREMELY DANGEROUS!** Do not try to build home made circuits alone. Make sure you have someone with you who knows if what you are doing is safe. Normal electrical outlets are dangerous. Treat electricity with respect in your everyday life. Do not touch exposed wires and do not approach downed power lines.

#### 18.1.1 Closed circuits

In the following activity we will investigate what is needed to cause charge to flow in an electric circuit.

**Activity :: Experiment : Closed circuits****Aim:**

To determine what is required to make electrical charges flow. In this experiment, we will use a lightbulb to check whether electrical charge is flowing in the circuit or not. If charge is flowing, the lightbulb should glow. On the other hand, if no charge is flowing, the lightbulb will not glow.

**Apparatus:**

You will need a small lightbulb which is attached to a metal conductor (e.g. a bulb from a school electrical kit), some connecting wires and a battery.

**Method:**

Take the apparatus items and try to connect them in a way that you cause the light bulb to glow (i.e. charge flows in the circuit).

**Questions:**

1. Once you have arranged your circuit elements to make the lightbulb glow, draw your circuit.
2. What can you say about how the battery is connected? (i.e. does it have one or two connecting leads attached? Where are they attached?)
3. What can you say about how the light bulb is connected in your circuit? (i.e. does it connect to one or two connecting leads, and where are they attached?)
4. Are there any items in your circuit which are not attached to something? In other words, are there any gaps in your circuit?

Write down your conclusion about what is needed to make an electric circuit work and charge to flow.

In the experiment above, you will have seen that the light bulb only glows when there is a *closed* circuit i.e. there are no gaps in the circuit and all the circuit elements are connected in a *closed loop*. Therefore, in order for charges to flow, a closed circuit and an energy source (in this case the battery) are needed. (Note: you do not have to have a lightbulb in the circuit! We used this as a check that charge was flowing.)

**Definition: Electric circuit**

An electric circuit is a closed path (with no breaks or gaps) along which electrical charges (electrons) flow powered by an energy source.

**18.1.2 Representing electric circuits****Components of electrical circuits**

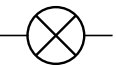
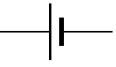
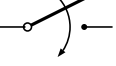
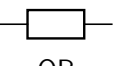

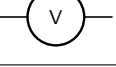
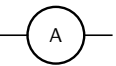
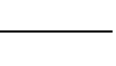
Some common elements (components) which can be found in electrical circuits include light bulbs, batteries, connecting leads, switches, resistors, voltmeters and ammeters. You will learn more about these items in later sections, but it is important to know what their symbols are and how to represent them in circuit diagrams. Below is a table with the items and their symbols:

**Circuit diagrams****Definition: Representing circuits**

A **physical circuit** is the electric circuit you create with real components.

A **circuit diagram** is a drawing which uses symbols to represent the different components in the physical circuit.



Component	Symbol	Usage
light bulb		glows when charge moves through it
battery		provides energy for charge to move
switch		allows a circuit to be open or closed
resistor	 OR 	resists the flow of charge
voltmeter		measures potential difference
ammeter		measures current in a circuit
connecting lead		connects circuit elements together

We use circuit diagrams to represent circuits because they are much simpler and more general than drawing the physical circuit because they only show the workings of the electrical components. You can see this in the two pictures below. The first picture shows the *physical circuit* for an electric torch. You can see the light bulb, the batteries, the switch and the outside plastic casing of the torch. The picture is actually a *cross-section* of the torch so that we can see inside it.

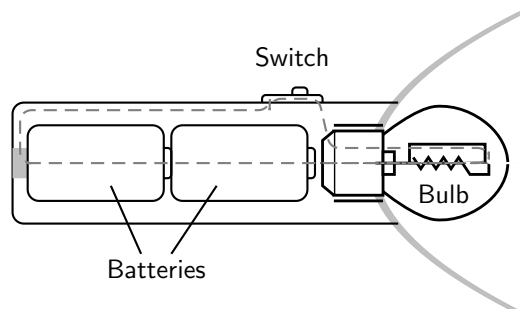


Figure 18.1: Physical components of an electric torch. The dotted line shows the path of the electrical circuit.

Below is the *circuit diagram* for the electric torch. Now the light bulb is represented by its symbol, as are the batteries, the switch and the connecting wires. It is not necessary to show the plastic casing of the torch since it has nothing to do with the electric workings of the torch. You can see that the circuit diagram is much simpler than the physical circuit drawing!

### Series and parallel circuits

There are two ways to connect electrical components in a circuit: **in series** or **in parallel**.

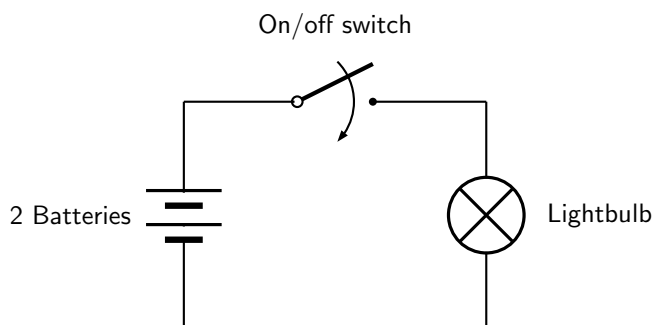


Figure 18.2: Circuit diagram of an electric torch.

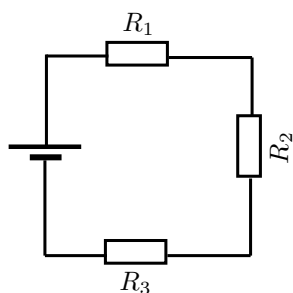
**Definition: Series circuit**

In a series circuit, the charge flowing from the battery can only flow along a **single** path to return to the battery.

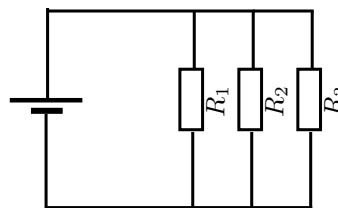
**Definition: Parallel circuit**

In a parallel circuit, the charge flowing from the battery can flow along **multiple** paths to return to the battery.

The picture below shows a circuit with three resistors connected *in series* on the left and a circuit with three resistors connected *in parallel* on the right. In the series circuit, the charge path from the battery goes through every component before returning to the battery. In the parallel circuit, there is more than one path for the charge to flow from the battery through one of the components and back to the battery.



3 resistors in a series circuit



3 resistors in a parallel circuit

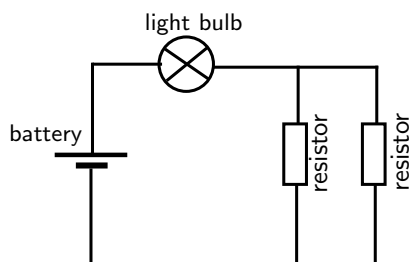
**Worked Example 59: Drawing circuits I**

**Question:** Draw the circuit diagram for a circuit which has the following components:

1. 1 battery
2. 1 lightbulb connected in series
3. 2 resistors connected in parallel

**Answer**

**Step 1 :** Identify the components and their symbols and draw according to the instructions:

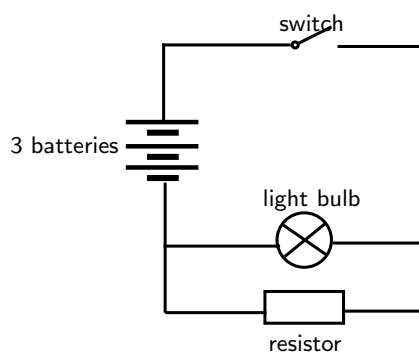
**Worked Example 60: Drawing circuits II**

**Question:** Draw the circuit diagram for a circuit which has the following components:

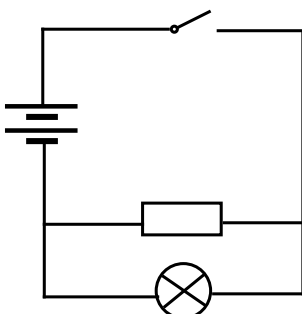
1. 3 batteries in series
2. 1 lightbulb connected in parallel with 1 resistor
3. a switch in series with the batteries

**Answer**

**Step 1 : Identify the symbol for each component and draw according to the instructions:**

**Exercise: Circuits**

1. Using physical components, set up the physical circuit which is described by the circuit diagram below:



2. Using physical components, set up a closed circuit which has one battery and a light bulb in series with a resistor.
    - 2.1 Draw the physical circuit.
    - 2.2 Draw the resulting circuit diagram.
    - 2.3 How do you know that you have built a closed circuit? (What happens to the light bulb?)
    - 2.4 If you add one more resistor to your circuit (also in series), what do you notice? (What happens to the light from the light bulb?)
    - 2.5 Draw the new circuit diagram which includes the second resistor.
  3. Draw the circuit diagram for the following circuit: 2 batteries and a switch in series, and 1 lightbulb which is in parallel with two resistors.
    - 3.1 Now use physical components to set up the circuit.
    - 3.2 What happens when you close the switch? What does this mean about the circuit?
    - 3.3 Draw the physical circuit.
- 

### Activity :: Discussion : Alternative Energy

At the moment, most electric power is produced by burning fossil fuels such as coal and oil. In South Africa, our main source of electric power is coal burning power stations. (We also have one nuclear power plant called Koeberg in the Western Cape). However, burning fossil fuels releases large amounts of pollution into the earth's atmosphere and contributes to global warming. Also, the earth's fossil fuel reserves (especially oil) are starting to run low. For these reasons, people all across the world are working to find *alternative*/other sources of energy and on ways to *conserve*/save energy. Other sources of energy include wind power, solar power (from the sun), hydro-electric power (from water, e.g. dammed rivers) among others. With a partner, take out the lists you made earlier of the item/appliances/machines which used electricity in the following environments. For each item, try to think of an *alternative* AND a way to *conserve* or save power.

For example, if you had a fluorescent light as an item used in the home, then:

- Alternative: use candles at supper time to reduce electricity consumption
- Conservation: turn off lights when not in a room, or during the day.

#### Topics:

- At home
- At school
- At the hospital
- In the city

Once you have finished making your lists, compare with the lists of other people in your class.

---

## 18.2 Potential Difference

### 18.2.1 Potential Difference

When a circuit is connected and complete, charge can move through the circuit. Charge will not move unless there is a reason, a force. 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.

We call the moving charge "current" and we will talk about this later.

The position of the charge in the circuit tells you how much potential energy it has because of the force being exerted on it. This is like the force from gravity, the higher an object is above the ground (position) the more potential energy it has.

The amount of work to move a charge from one point to another point is how much the potential energy has changed. This is the difference in potential energy, called potential difference. Notice that it is a difference between the value of potential energy at two points so we say that potential difference is measured between or across two points. We do not say potential difference through something.



#### Definition: Potential Difference

Electrical potential difference as the difference in electrical potential energy per unit charge between two points. The units of potential difference are the volt<sup>a</sup> (V).

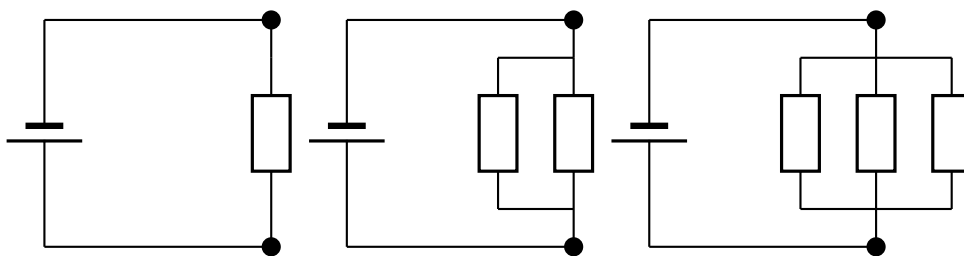
<sup>a</sup>named after the Italian physicist Alessandro Volta (1745–1827)

The units are volt (V), which is the same as joule per coulomb, the amount of work done per unit charge. Electrical potential difference is also called voltage.

### 18.2.2 Potential Difference and Parallel Resistors

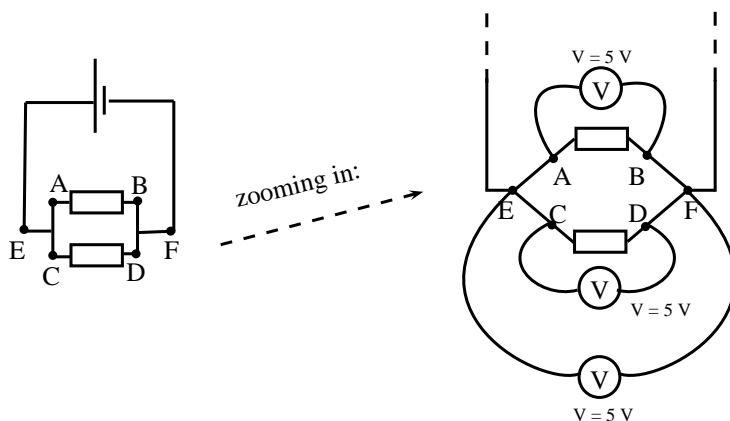
When resistors are connected in parallel the start and end points for all the resistors are the same. These points have the same potential energy and so the potential difference between them is the same no matter what is put in between them. You can have one, two or many resistors between the two points, the potential difference will not change. You can ignore whatever components are between two points in a circuit when calculating the difference between the two points.

Look at the following circuit diagrams. The battery is the same in all cases, all that changes is more resistors are added between the points marked by the black dots. If we were to measure the potential difference between the two dots in these circuits we would get the same answer for all three cases.



Lets look at two resistors in parallel more closely. When you construct a circuit you use wires and you might think that measuring the voltage in different places on the wires will make a difference. This is not true. The potential difference or voltage measurement will only be different if you measure a different set of components. All points on the wires that have no circuit components between them will give you the same measurements.

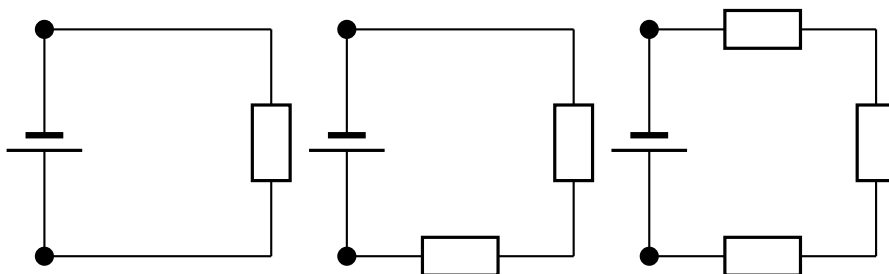
All three of the measurements shown in the picture below (i.e. A–B, C–D and E–F) will give you the same voltage. The different measurement points on the left have no components between them so there is no change in potential energy. Exactly the same applies to the different points on the right. When you measure the potential difference between the points on the left and right you will get the same answer.



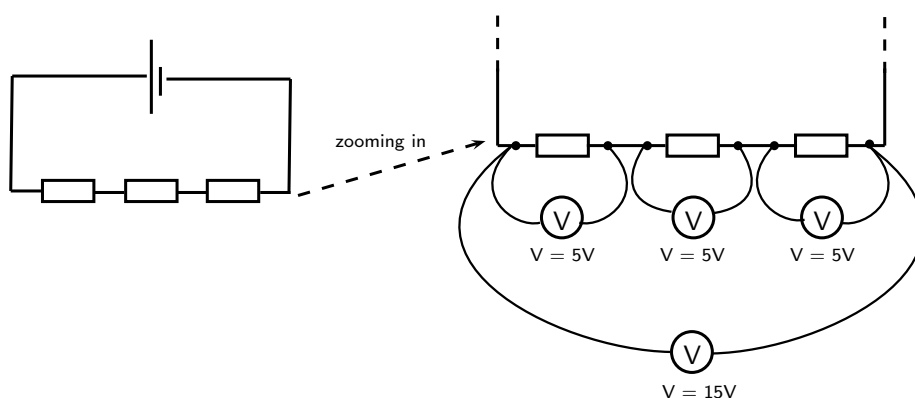
### 18.2.3 Potential Difference and Series Resistors

When resistors are in series, one after the other, there is a potential difference across each resistor. The total potential difference across a set of resistors in series is the sum of the potential differences across each of the resistors in the set. This is the same as falling a large distance under gravity or falling that same distance (difference) in many smaller steps. The total distance (difference) is the same.

Look at the circuits below. If we measured the potential difference between the black dots in all of these circuits it would be the same just like we saw above. So we now know the total potential difference is the same across one, two or three resistors. We also know that some work is required to make charge flow through each one, each is a step down in potential energy. These steps add up to the total drop which we know is the difference between the two dots.



Let us look at this in a bit more detail. In the picture below you can see what the different measurements for 3 identical resistors in series could look like. The total voltage across all three resistors is the sum of the voltages across the individual resistors.



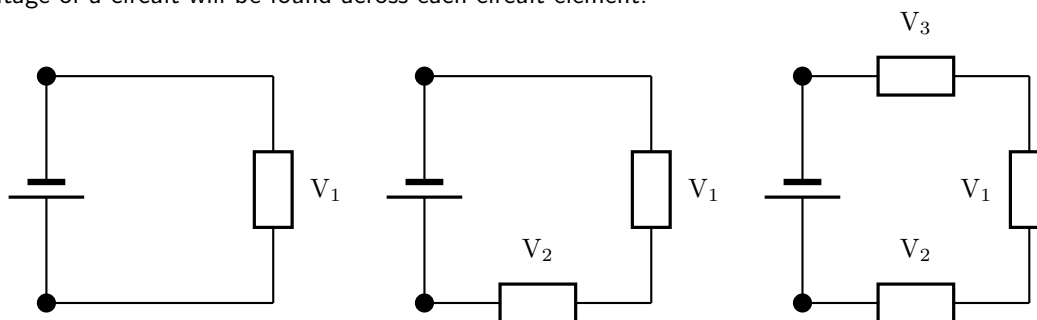
### 18.2.4 Ohm's Law

The voltage is the change in potential energy or work done when charge moves between two points in the circuit. The greater the resistance to charge moving the more work that needs to be done. The work done or voltage thus depends on the resistance. The potential difference is proportional to the resistance.


**Definition: Ohm's Law**

Voltage across a circuit component is proportional to the resistance of the component.

Use the fact that voltage is proportional to resistance to calculate what proportion of the total voltage of a circuit will be found across each circuit element.



We know that the total voltage is equal to  $V_1$  in the first circuit, to  $V_1 + V_2$  in the second circuit and  $V_1 + V_2 + V_3$  in the third circuit.

We know that the potential energy lost across a resistor is proportional to the resistance of the component. The total potential difference is shared evenly across the total resistance of the circuit. This means that the potential difference per unit of resistance is

$$V_{\text{per unit of resistance}} = \frac{V_{\text{total}}}{R_{\text{total}}}$$

Then the voltage across a resistor is just the resistance times the potential difference per unit of resistance

$$V_{\text{resistor}} = R_{\text{resistor}} \cdot \frac{V_{\text{total}}}{R_{\text{total}}}$$

### 18.2.5 EMF

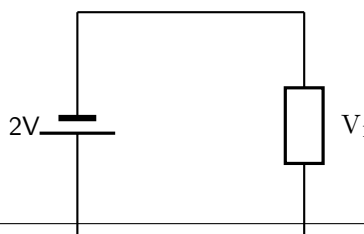
When you measure the potential difference across (or between) the terminals of a battery you are measuring the “electromotive force” (emf) of the battery. This is how much potential energy the battery has to make charges move through the circuit. This driving potential energy is equal to the total potential energy drops in the circuit. This means that the voltage across the battery is equal to the sum of the voltages in the circuit.

We can use this information to solve problems in which the voltages across elements in a circuit add up to the emf.

$$EMF = V_{\text{total}}$$


**Worked Example 61: Voltages I**

**Question:** What is the voltage across the resistor in the circuit shown?



**Answer****Step 1 : Check what you have and the units**

We have a circuit with a battery and one resistor. We know the voltage across the battery. We want to find that voltage across the resistor.

$$V_{\text{battery}} = 2\text{V}$$

**Step 2 : Applicable principles**

We know that the voltage across the battery must be equal to the total voltage across all other circuit components.

$$V_{\text{battery}} = V_{\text{total}}$$

There is only one other circuit component, the resistor.

$$V_{\text{total}} = V_1$$

This means that the voltage across the battery is the same as the voltage across the resistor.

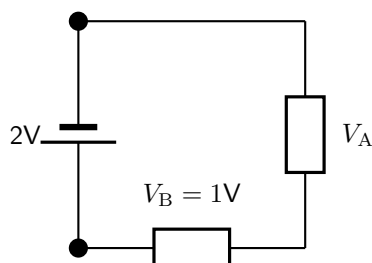
$$V_{\text{battery}} = V_{\text{total}} = V_1$$

$$V_{\text{battery}} = V_{\text{total}} = V_1$$

$$V_1 = 2\text{V}$$

**Worked Example 62: Voltages II****Question:**

What is the voltage across the unknown resistor in the circuit shown?

**Answer****Step 1 : Check what you have and the units**

We have a circuit with a battery and two resistors. We know the voltage across the battery and one of the resistors. We want to find that voltage across the resistor.

$$V_{\text{battery}} = 2\text{V}$$

$$V_A = 1\text{V}$$

**Step 2 : Applicable principles**

We know that the voltage across the battery must be equal to the total voltage across all other circuit components that are in series.

$$V_{\text{battery}} = V_{\text{total}}$$

The total voltage in the circuit is the sum of the voltages across the individual resistors

$$V_{\text{total}} = V_A + V_B$$

Using the relationship between the voltage across the battery and total voltage across the resistors

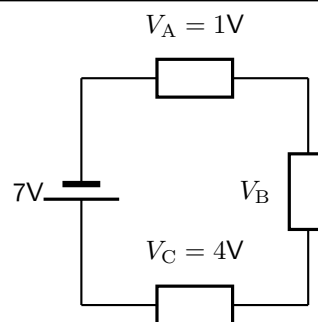
$$V_{\text{battery}} = V_{\text{total}}$$



$$\begin{aligned}
 V_{battery} &= V_1 + V_{resistor} \\
 2V &= V_1 + 1V \\
 V_1 &= 1V
 \end{aligned}$$

**Worked Example 63: Voltages III**

**Question:** What is the voltage across the unknown resistor in the circuit shown?

**Answer****Step 1 : Check what you have and the units**

We have a circuit with a battery and three resistors. We know the voltage across the battery and two of the resistors. We want to find that voltage across the unknown resistor.

$$V_{battery} = 7V$$

$$\begin{aligned}
 V_{known} &= V_A + V_C \\
 &= 1V + 4V
 \end{aligned}$$

**Step 2 : Applicable principles**

We know that the voltage across the battery must be equal to the total voltage across all other circuit components that are in series.

$$V_{battery} = V_{total}$$

The total voltage in the circuit is the sum of the voltages across the individual resistors

$$V_{total} = V_B + V_{known}$$

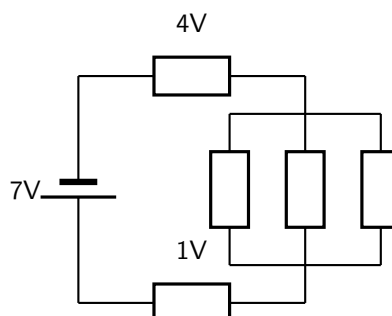
Using the relationship between the voltage across the battery and total voltage across the resistors

$$V_{battery} = V_{total}$$

$$\begin{aligned}
 V_{battery} &= V_B + V_{known} \\
 7V &= V_B + 5V \\
 V_B &= 2V
 \end{aligned}$$


**Worked Example 64: Voltages IV**

**Question:** What is the voltage across the parallel resistor combination in the circuit shown?  
Hint: the rest of the circuit is the same as the previous problem.


**Answer**
**Step 1 : Quick Answer**

The circuit is the same as the previous example and we know that the voltage difference between two points in a circuit does not depend on what is between them so the answer is the same as above  $V_{parallel} = 2V$ .

**Step 2 : Check what you have and the units - long answer**

We have a circuit with a battery and five resistors (two in series and three in parallel). We know the voltage across the battery and two of the resistors. We want to find that voltage across the parallel resistors,  $V_{parallel}$ .

$$V_{battery} = 7V$$

$$V_{known} = 1V + 4V$$

**Step 3 : Applicable principles**

We know that the voltage across the battery must be equal to the total voltage across all other circuit components.

$$V_{battery} = V_{total}$$

Voltages only add for components in series. The resistors in parallel can be thought of as a single component which is in series with the other components and then the voltages can be added.

$$V_{total} = V_{parallel} + V_{known}$$

Using the relationship between the voltage across the battery and total voltage across the resistors

$$V_{battery} = V_{total}$$

$$V_{battery} = V_{parallel} + V_{known}$$

$$7V = V_1 + 5V$$

$$V_{parallel} = 2V$$

## 18.3 Current

### 18.3.1 Flow of Charge

We have been talking about moving charge. We need to be able to deal with numbers. How much charge is moving, how fast is it moving? The concept that represents this information is called *current*. Current allows us to quantify the movement of charge.

When we talk about current we talk about how much charge moves past a fixed point in circuit in one second. Think of charges being pushed around the circuit by the battery, there are charges in the wires but unless there is a battery they won't move. When one charge moves the charges next to it also move. They keep their spacing as if you had a tube of marbles like in this picture.



If you push one marble into the tube one must come out the other side. If you look at any point in the tube and push one marble into the tube, one marble will move past the point you are looking at. This is similar to charges in the wires of a circuit.

If one charge moves they all move and the same number move at every point in the circuit. This is due to the conservation of charge.

### 18.3.2 Current

Now that we've thought about the moving charges and visualised what is happening we need to get back to quantifying moving charge. I've already told you that we call moving charge current but we still need to define it precisely.



**Definition: Current**

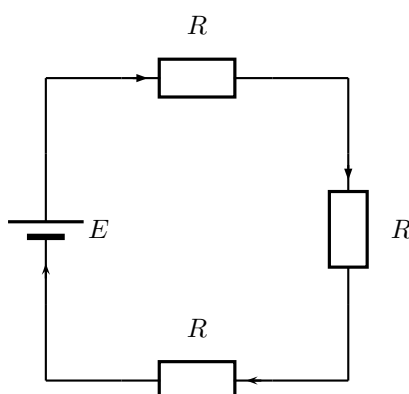
Current is the rate at which charges moves past a fixed point in a circuit. We use the symbol  $I$  to show current and it is measured in amperes (A). One ampere is one coulomb of charge moving in one second.

$$I = \frac{Q}{\Delta t}$$

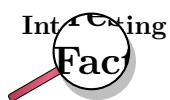
When current flows in a circuit we show this on a diagram by adding arrows. The arrows show the direction of flow in a circuit. By convention we say that charge flows from the positive terminal on a battery to the negative terminal. We measure current with an *ammeter*

### 18.3.3 Series Circuits

In a series circuit, the charge has a single path from the battery, returning to the battery.



The arrows in this picture show you the direction that charge will flow in the circuit. They don't show you much charge will flow, only the direction.



Benjamin Franklin made a guess about the direction of charge flow when rubbing smooth wax with rough wool. He thought that the charges flowed from the wax to the wool (i.e. from positive to negative) which was opposite to the real direction. Due to this, electrons are said to have a *negative* charge and so objects which Ben Franklin called “negative” (meaning a shortage of charge) really have an excess of electrons. By the time the true direction of electron flow was discovered, the convention of “positive” and “negative” had already been so well accepted in the scientific world that no effort was made to change it.



**Important:** A battery **does not** produce the same amount of current no matter what is connected to it. While the voltage produced by a battery is constant, the amount of current supplied depends on what is in the circuit.

How does the current through the battery in a circuit with several resistors in series compare to the current in a circuit with a single resistor (assuming all the resistors are the same)?

### Activity :: Experiment : Current in Series Circuits

#### Aim:

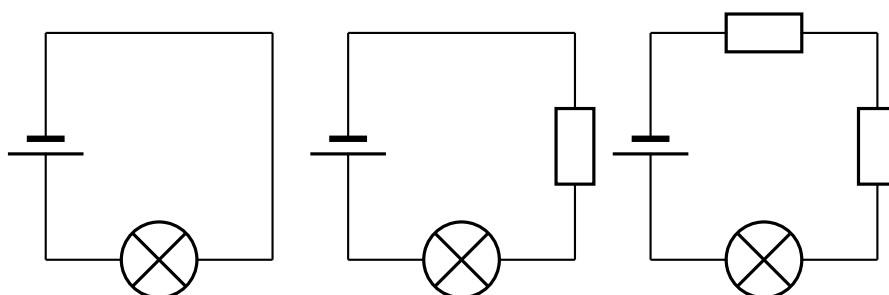
To determine the effect of multiple resistors on current in a circuit

#### Apparatus:

- Battery
- Resistors
- Light bulb
- Wires

#### Method:

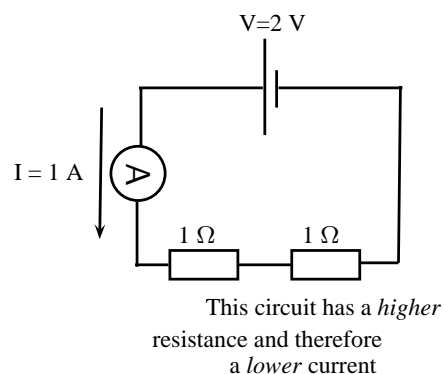
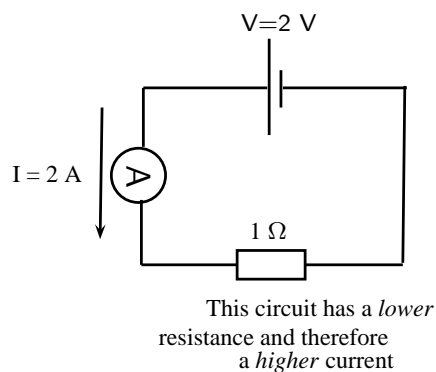
1. Construct the following circuits



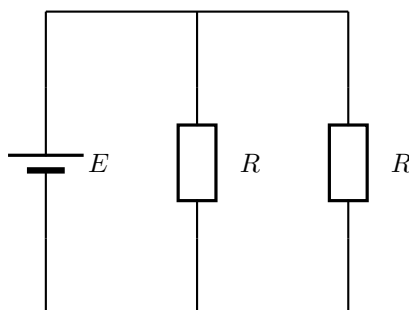
2. Rank the three circuits in terms of the brightness of the bulb.

#### Conclusions:

The brightness of the bulb is an indicator of how much current is flowing. If the bulb gets brighter because of a change then more current is flowing. If the bulb gets dimmer less current is flowing. You will find that the more resistors you have the dimmer the bulb.



### 18.3.4 Parallel Circuits



How does the current through the battery in a circuit with several resistors in parallel compare to the current in a circuit with a single resistor?

#### Activity :: Experiment : Current in Series Circuits

##### Aim:

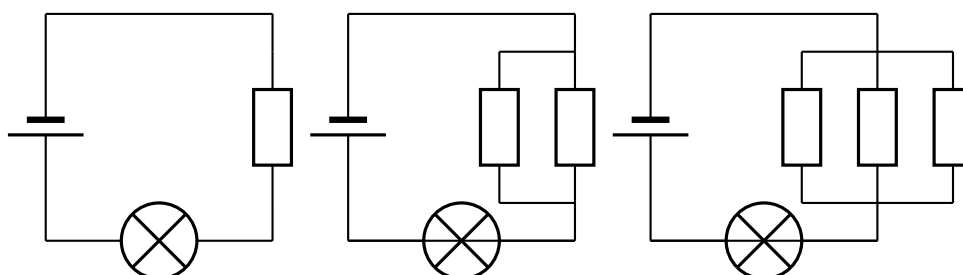
To determine the effect of multiple resistors on current in a circuit

##### Apparatus:

- Battery
- Resistors
- Light bulb
- Wires

##### Method:

1. Construct the following circuits

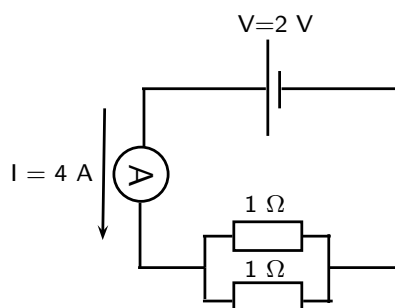
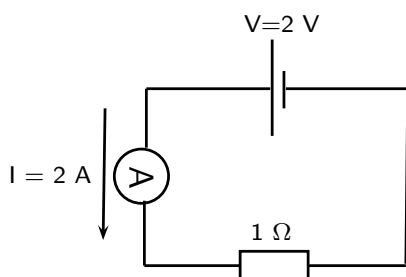


2. Rank the three circuits in terms of the brightness of the bulb.

### Conclusions:

The brightness of the bulb is an indicator of how much current is flowing. If the bulb gets brighter because of a change then more current is flowing. If the bulb gets dimmer less current is flowing. You will find that the more resistors you have the brighter the bulb.

Why is this the case? Why do more resistors make it easier for charge to flow in the circuit? It is because they are in parallel so there are more paths for charge to take to move. You can think of it like a highway with more lanes, or the tube of marbles splitting into multiple parallel tubes. The more branches there are, the easier it is for charge to flow. You will learn more about the total resistance of parallel resistors later but always remember that more resistors in parallel mean more pathways. In series the pathways come one after the other so it does not make it easier for charge to flow.



the 2 resistors in parallel result in a  
*lower* total resistance and therefore  
a *higher* current in the circuit

## 18.4 Resistance

### 18.4.1 What causes resistance?

We have spoken about resistors that reduce the flow of charge in a conductor. On a microscopic level, electrons moving through the conductor collide with the particles of which the conductor (metal) is made. When they collide, they transfer kinetic energy. The electrons therefore lose kinetic energy and slow down. This leads to resistance. The transferred energy causes the resistor to heat up. You can feel this directly if you touch a cellphone charger when you are charging a cell phone - the charger gets warm because its circuits have some resistors in them!



#### Definition: Resistance

Resistance slows down the flow of charge in a circuit. We use the symbol **R** to show resistance and it is measured in units called **Ohms** with the symbol  $\Omega$ .

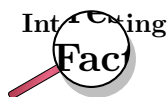
$$1\text{ Ohm} = 1 \frac{\text{Volt}}{\text{Ampere}}.$$

All conductors have some resistance. For example, a piece of wire has less resistance than a light bulb, but both have resistance. A lightbulb is a very thin wire surrounded by a glass housing. The high resistance of the filament (small wire) in a lightbulb causes the electrons to transfer a lot of their kinetic energy in the form of heat<sup>1</sup>. The heat energy is enough to cause the filament

<sup>1</sup>Flourescent lightbulbs do not use thin wires; they use the fact that certain gases glow when a current flows through them. They are much more efficient (much less resistance) than lightbulbs.

to glow white-hot which produces light. The wires connecting the lamp to the cell or battery hardly even get warm while conducting the same amount of current. This is because of their much lower resistance due to their larger cross-section (they are thicker).

An important effect of a resistor is that it *converts* electrical energy into other forms of **heat** energy. **Light** energy is a by-product of the heat that is produced.



There is a special type of conductor, called a **superconductor** that has no resistance, but the materials that make up all known superconductors only start superconducting at very low temperatures (approximately  $-170^{\circ}\text{C}$ ).

### Why do batteries go flat?

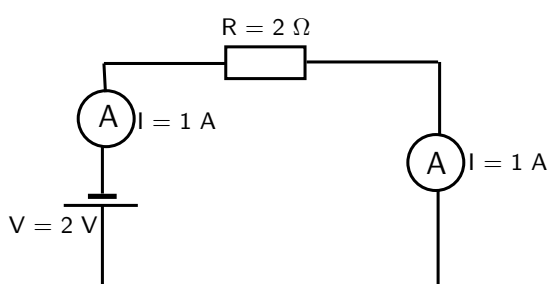
A battery stores chemical potential energy. When it is connected in a circuit, a chemical reaction takes place inside the battery which converts chemical potential energy to electrical energy which powers the electrons to move through the circuit. All the circuit elements (such as the conducting leads, resistors and lightbulbs) have some resistance to the flow of charge and convert the electrical energy to heat and, in the case of the lightbulb, light. Since energy is always conserved, the battery goes flat when all its chemical potential energy has been converted into other forms of energy.

## 18.4.2 Resistors in electric circuits

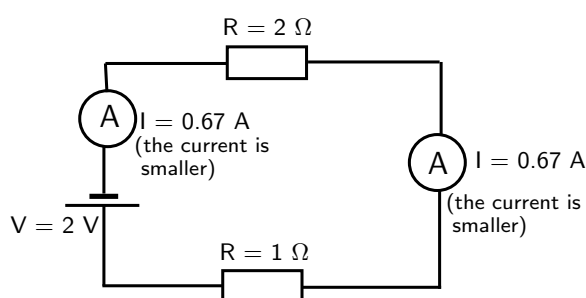
It is important to understand what effect adding resistors to a circuit has on the *total* resistance of a circuit and on the current that can flow in the circuit.

### Resistors in series

When we add resistors in series to a circuit, we *increase* the resistance to the flow of current. There is only **one path** that the current can flow down and the current is the same at all places in the series circuit. Take a look at the diagram below: On the left there is a circuit with a single resistor and a battery. No matter where we measure the current, it is the same in a series circuit. On the right, we have added a second resistor in series to the circuit. The *total* resistance of the circuit has *increased* and you can see from the reading on the ammeter that the current in the circuit has decreased.



The current in a series circuit is the same everywhere

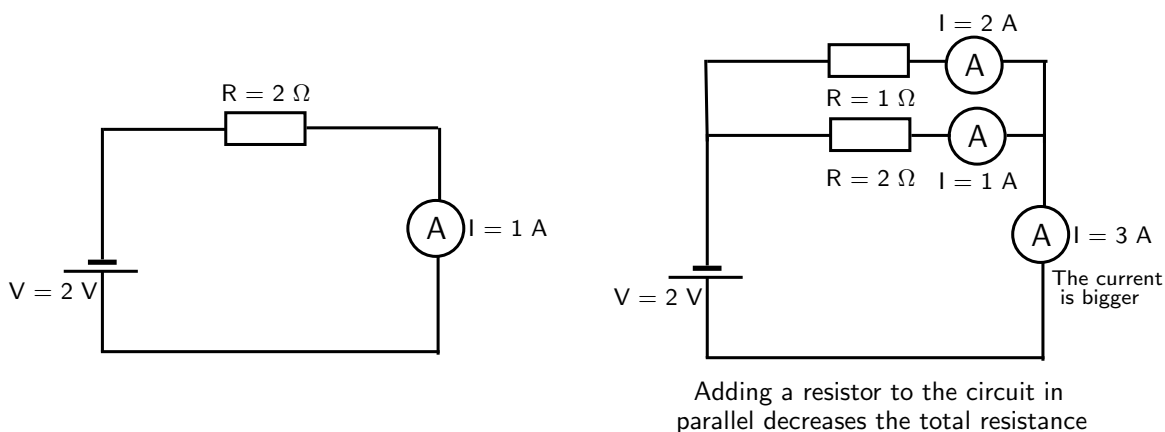


Adding a resistor to the circuit increases the total resistance

### Resistors in parallel

In contrast to the series case, when we add resistors in parallel, we create **more paths** along which current can flow. By doing this we *decrease* the total resistance of the circuit!

Take a look at the diagram below. On the left we have the same circuit as in the previous diagram with a battery and a resistor. The ammeter shows a current of 1 ampere. On the right we have added a second resistor in parallel to the first resistor. This has increased the number of paths (branches) the charge can take through the circuit - the total resistance has decreased. You can see that the current in the circuit has increased. Also notice that the current in the different branches can be different.



#### Exercise: Resistance

1. What is the unit of resistance called and what is its symbol?
2. Explain what happens to the total resistance of a circuit when resistors are added in series?
3. Explain what happens to the total resistance of a circuit when resistors are added in parallel?
4. Why do batteries go flat?

## 18.5 Instruments to Measure voltage, current and resistance

As we have seen in previous sections, an electric circuit is made up of a number of different components such as batteries, resistors and light bulbs. There are devices to measure the properties of these components. These devices are called meters.

For example, one may be interested in measuring the amount of current flowing through a circuit using an *ammeter* or measuring the voltage provided by a battery using a *voltmeter*. In this section we will discuss the practical usage of voltmeters, ammeters, and *ohmmeters*.



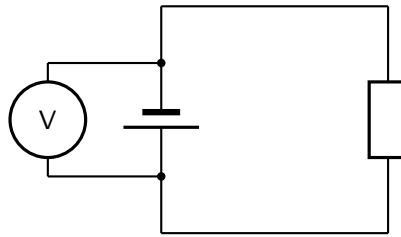


Figure 18.3: A voltmeter should be connected in parallel in a circuit.

### 18.5.1 Voltmeter

A voltmeter is an instrument for measuring the voltage between two points in an electric circuit. In analogy with a water circuit, a voltmeter is like a meter designed to measure pressure difference. Since one is interested in measuring the voltage between two points in a circuit, a voltmeter must be connected in *parallel* with the portion of the circuit on which the measurement is made.

Figure 18.3 shows a voltmeter connected in parallel with a battery. One lead of the voltmeter is connected to one end of the battery and the other lead is connected to the opposite end. The voltmeter may also be used to measure the voltage across a resistor or any other component of a circuit that has a voltage drop.

### 18.5.2 Ammeter

An ammeter is an instrument used to measure the flow of electric current in a circuit. Since one is interested in measuring the current flowing *through* a circuit component, the ammeter must be connected in *series* with the measured circuit component (Figure 18.4).

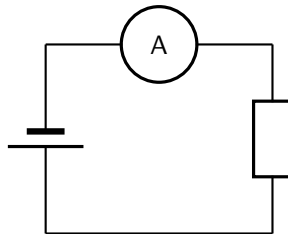


Figure 18.4: An ammeter should be connected in series in a circuit.

### 18.5.3 Ohmmeter

An ohmmeter is an instrument for measuring electrical resistance. The basic ohmmeter can function much like an ammeter. The ohmmeter works by supplying a constant voltage to the resistor and measuring the current flowing through it. The measured current is then converted into a corresponding resistance reading through Ohm's Law. Ohmmeters only function correctly when measuring resistance over a component that is not being powered by a voltage or current source. In other words, you cannot measure the resistance of a component that is already connected to a live circuit. This is because the ohmmeter's accurate indication depends only on its own source of voltage. The presence of **any other** voltage across the measured circuit component interferes with the ohmmeter's operation. Figure 18.5 shows an ohmmeter connected with a resistor.

### 18.5.4 Meters Impact on Circuit

A good quality meter used correctly will not significantly change the values it is used to measure. This means that an ammeter has very low resistance to not slow down the flow of charge. A

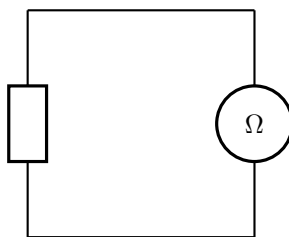


Figure 18.5: An ohmmeter should be used when there are no voltages present in the circuit.

voltmeter has a very high resistance so that it does not add another parallel pathway to the circuit for the charge to flow along.

---

### Activity :: Investigation : Using meters

If possible, connect meters in circuits to get used to the use of meters to measure electrical quantities. If the meters have more than one scale, always connect to the **largest scale** first so that the meter will not be damaged by having to measure values that exceed its limits.

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The table below summarises the use of each measuring instrument that we discussed and the way it should be connected to a circuit component.

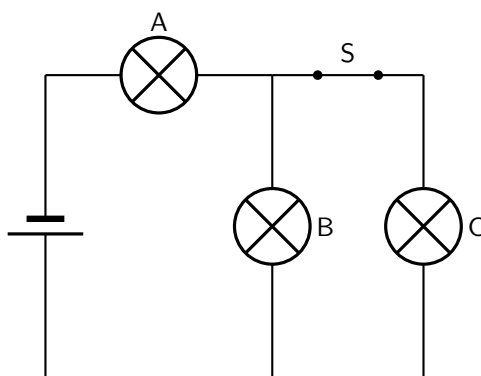
Instrument	Measured Quantity	Proper Connection
Voltmeter	Voltage	In Parallel
Ammeter	Current	In Series
Ohmmeter	Resistance	Only with Resistor

## 18.6 Exercises - Electric circuits

1. Write definitions for each of the following:
  - 1.1 resistor
  - 1.2 coulomb
  - 1.3 voltmeter
2. Draw a circuit diagram which consists of the following components:
  - 2.1 2 batteries in parallel
  - 2.2 an open switch
  - 2.3 2 resistors in parallel
  - 2.4 an ammeter measuring total current
  - 2.5 a voltmeter measuring potential difference across one of the parallel resistors
3. Complete the table below:

Quantity	Symbol	Unit of measurement	Symbol of unit
e.g. Distance	e.g. d	e.g. kilometer	e.g. km
Resistance			
Current			
Potential difference			

4. [SC 2003/11] The emf of a battery can best be explained as the ...
- 4.1 rate of energy delivered per unit current
  - 4.2 rate at which charge is delivered
  - 4.3 rate at which energy is delivered
  - 4.4 charge per unit of energy delivered by the battery
5. [IEB 2002/11 HG1] Which of the following is the correct definition of the emf of a battery?
- 5.1 It is the product of current and the external resistance of the circuit.
  - 5.2 It is a measure of the cell's ability to conduct an electric current.
  - 5.3 It is equal to the "lost volts" in the internal resistance of the circuit.
  - 5.4 It is the power supplied by the battery per unit current passing through the battery.
6. [IEB 2005/11 HG] Three identical light bulbs A, B and C are connected in an electric circuit as shown in the diagram below.



- 6.1 How bright is bulb A compared to B and C?
- 6.2 How bright are the bulbs after switch S has been opened?
- 6.3 How do the currents in bulbs A and B change when switch S is opened?

	Current in A	Current in B
(a)	decreases	increases
(b)	decreases	decreases
(c)	increases	increases
(d)	increases	decreases

7. [IEB 2004/11 HG1] When a current  $I$  is maintained in a conductor for a time of  $t$ , how many electrons with charge  $e$  pass any cross-section of the conductor per second?
- 7.1  $It$
  - 7.2  $It/e$
  - 7.3  $Ite$
  - 7.4  $e/It$



## Appendix A

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