How the ideas in this topic link together

All the materials around us are made from smaller building blocks. Using light microscopes, we can see that living organisms are made from cells. Using electron microscopes we can see that cells are made up of even smaller components, and that these are composed of tinier and tinier particles, until it is not possible to see them even with the most powerful microscope. The particle model of matter was developed to explain the behaviour of these building blocks. Using ideas of scale helps us to relate the behaviour of these tiny particles to the real world of objects we can see and hold.

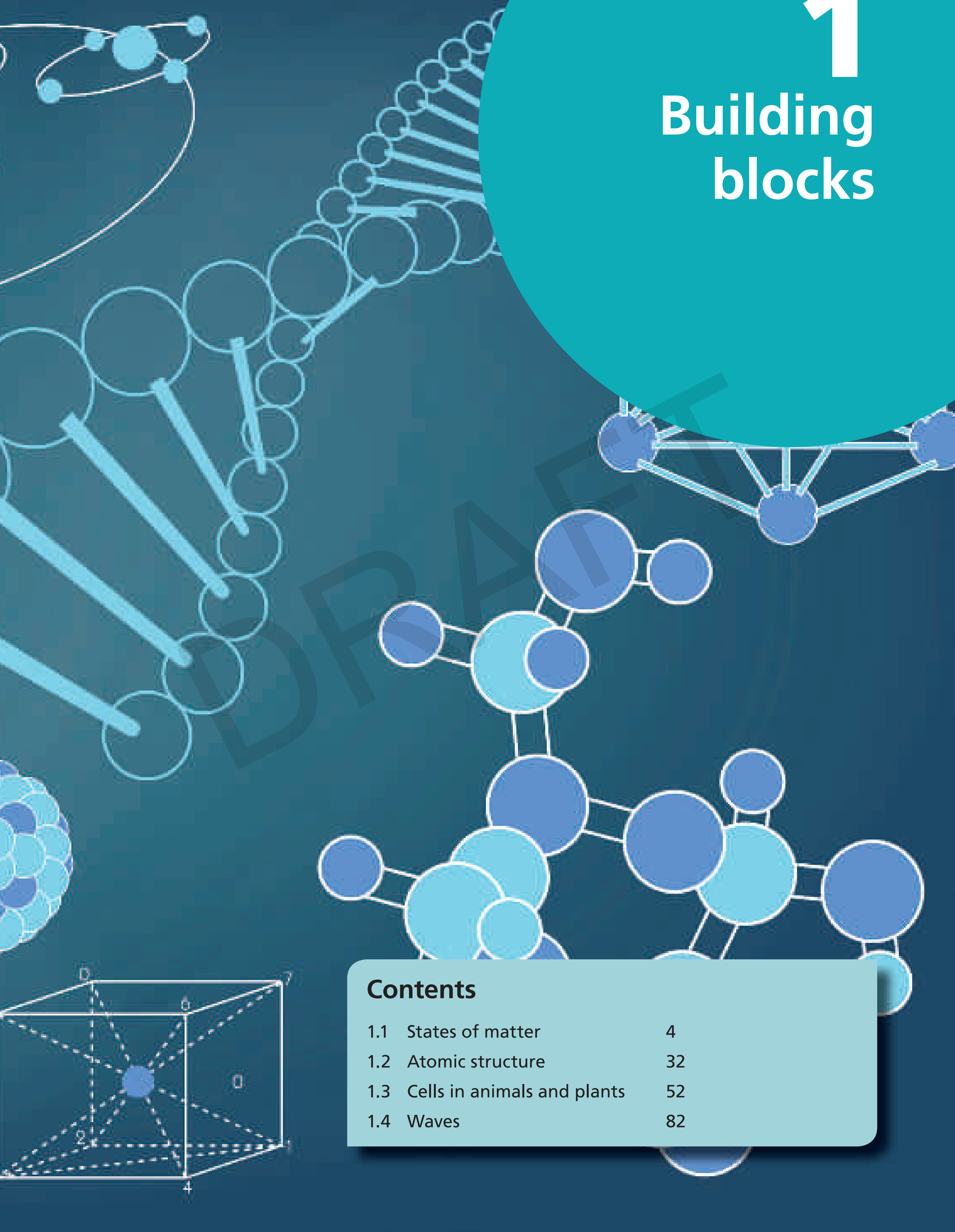
According to the particle model, particles are arranged in such a way that they form solids, liquids or gases. Each state of matter has different properties. The behaviour of particles as liquids and gases can explain how substances move into cells and across membranes in living organisms. The universal genetic code is a particle pattern that can build amino acids into proteins to build living cells, which can then replicate.

Energy is transferred over small distances and large distances in different ways in living and non-living systems. The idea of waves helps to explain transfer of energy over long distances, and some of the interactions between living and non-living systems.

Working Scientifically Focus

- Understand how scientific methods and theories develop over time
- Using models, including representational drawings
- Using SI units, SI prefixes and interconverting units
- Using significant figures

1 Building blocks



Contents

STATES OF MATTER

IDEAS YOU HAVE MET BEFORE:

PARTICLE MODEL AND STATES OF MATTER

- All matter is made up of particles.
- The particle model represents the particles of matter as solid spheres.
- Ice and other solids can turn to liquids and gases.
- Solids melt into liquids at the melting point.
- Liquids turn into gases at the boiling point.

DENSITY

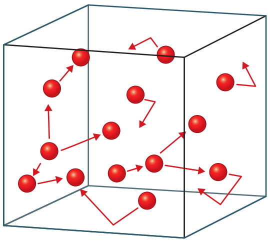
- Density is equal to mass/volume. The unit is kg/m^3.
- Solids usually have a larger density than liquids and gases. The particles are closer together.
- In a gas the particles are far apart and move freely.
- The particles in a gas fill the space available.

TEMPERATURE AND ENERGY TRANSFER

- When there is a difference in temperature between two objects, energy is transferred from the hotter object to the colder one.
- Energy is measured in joules (J) or kilojoules (kJ).
- The amount of energy involved in a temperature change can be calculated.

PARTICLE MODEL AND PRESSURE OF A GAS

- Every material is made of tiny moving particles.
- In a gas the particles are far apart and move freely.
- The higher the temperature the more kinetic energy the particles have and the faster they move.
- The pressure in a container of gas is caused by the particles colliding with the walls of the container.

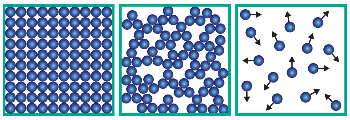


1.1

IN THIS CHAPTER YOU WILL FIND OUT ABOUT:

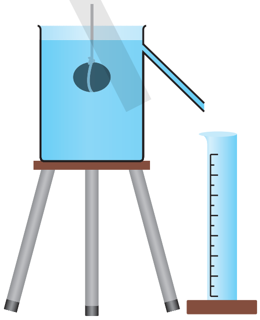
WHAT HAPPENS TO PARTICLES AS SUBSTANCES CHANGE STATE?

- The particles in a system store energy, called internal energy.
- In solids and liquids there are forces between particles that hold them together.
- An increase in internal energy can increase the temperature of the system or change its state.
- The amount of energy needed to change state from solid to liquid or liquid to gas depends on how strong the forces are between the particles.



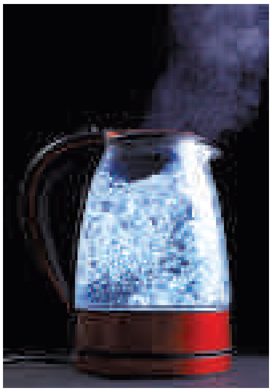
HOW CAN WE FIND THE DENSITY OF LIQUIDS AND SOLIDS?

- The density of a liquid can be found by weighing a known volume.
- The density of a solid can be found from measurements of its mass and measured volume.
- The volume of a solid with a regular shape can be found by accurate measurement.
- The volume of an irregular solid can be found by a displacement method.



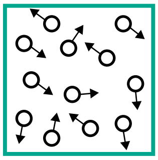
HOW DOES ENERGY TRANSFER BY HEATING CHANGE THE TEMPERATURE OR STATE OF AN OBJECT?

- The increase in temperature of a system depends on the mass of the substance, the type of material and the energy input.
- The specific heat capacity, *c*, is the energy required to raise the temperature of 1 kg of an object by 1 °C. The unit for *c* is J/kg °C.
- The specific latent heat of fusion is the energy required to change 1 kg of an object from a solid to a liquid without a change in temperature.
- The specific latent heat of vaporisation is the energy required to change 1 kg of an object from a liquid to a gas without a change in temperature.

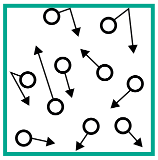


WHAT HAPPENS TO THE PRESSURE OF A GAS WHEN IT IS HEATED, KEEPING THE VOLUME CONSTANT?

- An increase in temperature increases the kinetic energy of the gas particles.
- The particles move faster, colliding more often and with greater force on the walls of their container. The pressure of the gas increases.



Cool gas, fewer and less energetic collisions



Hot gas, more and more energetic collisions

1.1a The particle model

Learning objectives:

- describe and explain the properties of solids, liquids and gases using the particle model
- relate the size and scale of atoms to objects in the physical world
- identify the strengths and limitations of the particle model.

KEY WORDS

model
particle model
physical change

In science we often use models to help us think about situations in which what we are looking at is too big or too small to see. The particle model is one of the most important concepts in science, because we use it to explain so many different things.

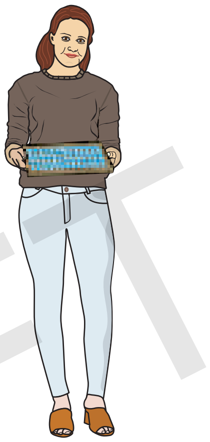


Figure 1.1.1 Modelling a solid by gently shaking a tray of marbles and allowing the marbles to settle

The states of matter

The particle model says that all matter is made from tiny particles. This simple model uses small solid spheres to represent the particles.

There are three states of matter: solid, liquid and gas.

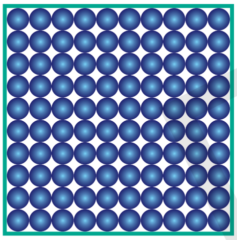
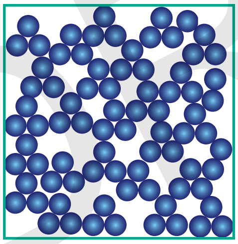
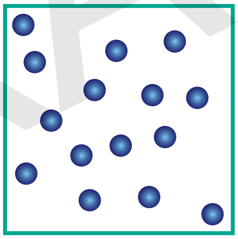
Solid	Liquid	Gas
		
• particles very close together in an ordered pattern • particles vibrate to and fro but cannot change their positions • fixed shape and volume	• particles close together but not in a regular pattern • particles slide past each other • fixed volume but not a fixed shape	• particles spaced far apart • particles move fast in all directions • no fixed shape or volume

Figure 1.1.2 The three states of matter

DID YOU KNOW?

Atoms are so small that they cannot be seen, even with the most powerful light microscope. If you imagine an atom to be the size of a golf ball, then an actual golf ball would represent the size of the Earth.

1 Which state does each of the following describe?

a fixed shape and volume

b particles move around freely at high speed

c fixed volume but no fixed shape

2 **Explain why it is possible to squash a gas but not a solid or a liquid.**

Changes of state

When substances change state the arrangement and movement of the particles changes.

- Melting and freezing both take place at the melting point.
- Boiling and condensing both take place at the boiling point.

Changes of state are **physical changes**. The change is reversible, as the substance does not change its composition.

Substance	Melting point (°C)	Boiling point (°C)	State at room temperature
W	–18	42	liquid
X	150	875	
Y	–190	–84	
Z	–56	16	

Substance W in the table will have melted at –18°C but will not have boiled at room temperature, so it is a liquid.

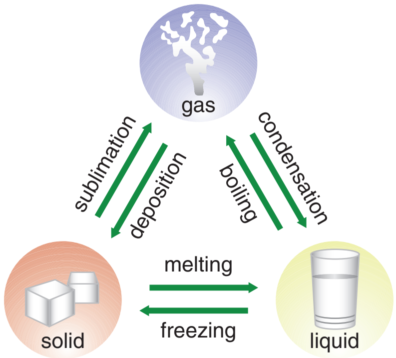


Figure 1.1.3 Energy must be supplied to change state from solid to liquid, and from liquid to gas. Energy is given out when the change happens in the reverse direction

3 **Look at the table above. What are the states of substances X, Y and Z at room temperature?**

HIGHER TIER ONLY

Limitations of models

This simple particle model of solid spheres has limitations, as:

- there are no forces of attraction between the spheres
- the particles are all solid spheres of the same size.

This means that interactions between particles as they get closer together or further apart cannot be represented fully. We also cannot properly model the distance between atoms, molecules and ions.

4 **State with reasons one way in which a tray of marbles is a good model for a solid and one way in which it is not.**

5 **Water vapour condenses to form liquid water. Explain how the limitations of the model relate to the process of condensation.**

REMEMBER!

Particle diagrams are a model, not the real situation. In the model of a solid the individual spheres represent particles that are themselves not solid. It is only when lots of these particles are arranged closely in a regular pattern that they represent a solid.

1.1b Density

Learning objectives:

- define density
- explain the differences in density between different states of matter using the particle model
- calculate densities of different materials.

KEY WORDS

density
gas
liquid
solid

Identical volumes of marbles and feathers will not have the same mass. A box of marbles has more mass for the same volume (or *per volume*) than the feathers. The marbles are more dense.

Density

When people say 'lead is heavier than iron', what they mean is that a piece of lead is heavier than a piece of iron of the same volume.

Density compares the mass of materials with the same volume. It is defined as the mass of unit volume of a substance:

density (in kg/m^3) = mass (in kg) ÷ volume (in m^3)

Gold has a density of 19 000 kg/m^3. That means a volume of 1 m^3 of gold has a mass of 19 000 kg. The densities of a range of materials are shown in the table.

Substance	Physical state at room temperature	Density in kg/m^3
gold	solid	19 000
iron	solid	8000
lead	solid	11 000
cork	solid	200
mercury	liquid	13 600
water	liquid	1000
petrol	liquid	800
air	gas	1.3

1. **Which material in the table has the smallest density? What is its physical state at room temperature?**
2. **What state of matter has the greatest density?**

Figure 1.1.4 A standard gold bar has a mass of 12.4 kg. A gold bar the size of a brick would have a mass of 20.9 kg. Could you lift that with one hand?

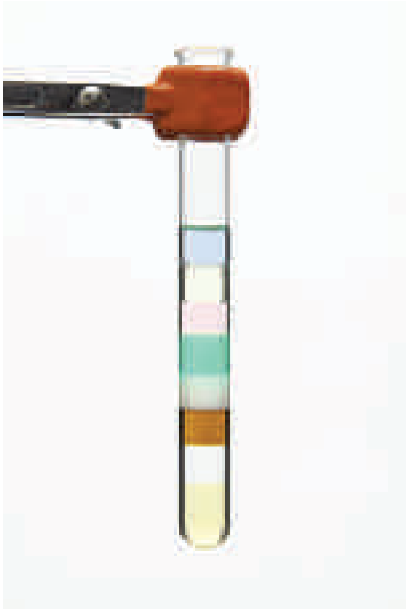


Figure 1.1.5 Liquids with different densities will form layers, but only if the liquids do not mix freely

Density and the particle model

The particle model can help to explain the different densities of solids, liquids and gases.

In a **solid** the particles are very close together. When a solid melts it becomes a **liquid**. The particles are still very close together, but they are not quite as tightly packed as in a solid. So the density of a liquid is usually less than the solid. For example, the density of solid aluminium is 2720 kg/m³ and the density of liquid aluminium is 2380 kg/m³.

When a liquid boils it becomes a **gas**. The particles are very far apart so the density is small.

1.1b

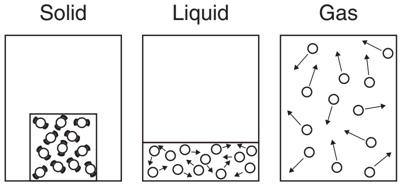


Figure 1.1.6 Particles in a solid, liquid and gas

3 **Use the particle model to explain why solids usually have a higher density than liquids and gases.**

4 **Draw a particle model of a gas, and annotate it to show why gases have low density.**

DID YOU KNOW?

Water vapour has a density of about 0.8 kg/m³. Boiling away 100 g (100 cm³) of water would produce about 100 000 cm³ (100 litres) of water vapour.

Calculations with density

Another way of writing the equation for density is with symbols:

$$\rho = m \div V$$

where ρ is density in kg/m³, m is mass in kg and V is volume in m³.

Density is also given in g/cm³, where mass is in g and volume is in cm³.

$$1 \text{ g/cm}^3 = 1000 \text{ kg/m}^3$$

Example:

Calculate the mass of 3 m³ of water. The density of water is 1000 kg/m³.

$$\rho = m \div V$$

Rearrange the equation to give

$$m = \rho V$$
$$= 1000 \text{ kg/m}^3 \times 3 \text{ m}^3$$
$$= 3000 \text{ kg}$$

Figure 1.1.7 Materials used in aeroplanes have to be light but strong

DID YOU KNOW?

Osmium is the densest substance found on Earth. Its density is 22 600 kg/m³.

5 a **Calculate the density of a 5400 kg block of aluminium with a volume of 2 m³.**

b **Calculate the mass of steel having the same volume as the aluminium block. Density of steel = 7700 kg/m³.**

c **Explain why aluminium is used to build aeroplanes rather than steel (Figure 1.1.7).**

6 **Calculate the mass of air in a room 5 m by 4 m by 3 m. The density of air is 1.3 kg/m³.**

7 **Suggest why cork floats in water, but iron sinks.**

REQUIRED PRACTICAL

1.1c To investigate the densities of regular and irregular solid objects and liquids

Learning objectives:

- interpret observations and data
- use spatial models to solve problems
- plan experiments and devise procedures
- use an appropriate number of significant figures in measurements and calculations.

KEY WORD

displace
Eureka can
significant figures

Density is worked out knowing the mass of an object and the volume it occupies. Measuring the volume is easy enough if the object is a regular shape such as a cube but what if it was, say, a crown?

This problem was given to Archimedes, a clever man who lived thousands of years ago in Greece. The king had ordered a new crown to be made but suspected the craftsman had mixed a cheaper metal with the gold. Measuring the density would reveal if the gold was pure, but how could the volume be found? Archimedes realised that by carefully immersing the crown in a full can of water, the water that overflowed would have the same volume as the crown.

Apparently he shouted "Eureka!" ("I have found it!") and the cans used in practical investigations are known as Eureka cans in recognition of this.

These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

Figure 1.1.8 Archimedes making his discovery

Measuring the density of a liquid

The density of any substance can be worked out using the formula:

density = mass/volume

If mass is measured in grams (g) and volume in cubic centimetres (cm^3) then the density will be in g/cm^3.

Measuring the density of a liquid can be done by pouring the liquid into a measuring cylinder to find its volume and using a balance to find the mass. The results might look rather like those in the table.

Liquid	Mass (g)	Volume (cm^3)
coconut oil	18.5	20
acetone	19.6	25
sea water	51.3	50

1. **Explain why you would not get the mass of the liquid by just putting the measuring cylinder with the liquid on the balance and recording the reading.**

Link: 1.1c ⟶ 1.1d

2. **Suggest what you could do to get the mass of the liquid.**
3. **Calculate the density of each of the liquids in the table on the previous page.**

Measuring the density of a regular solid

Solids, of course, have their own shape. If that shape is a regular one, we can calculate the volume by measuring dimensions and then using the correct formula. For example, if the solid was a cuboid, the volume would be length multiplied by width multiplied by height. The mass would be divided by this to get the density.

For example, if a 2.0 cm cube of soft rubber had a mass of 8.82 g, its volume would be 2.0 cm × 2.0 cm × 2.0 cm, which is 8.0 cm^3 and the density would be 8.82 g/8.0 cm^3 which is 1.1 g/cm^3.

The answer can only have the same number of significant figures as the component with the least number of significant figures (8.0 – it has two significant figures).

Material	Mass (g)	Length (cm)	Width (cm)	Height (cm)
cork	3	2.0	2.0	3.0
oak	17	2.0	3.0	4.0
tin	364	2.5	2.5	8.0

Figure 1.1.9 Assortment of cubes of different materials

4. **Look at the table above. What is the volume of the piece of cork?**
5. **What is its density?**
6. **What are the densities of the other two materials?**
7. **The dimensions of the oak were measured using Vernier calipers. Why is it incorrect to use 0.68106 g/cm^3 as the answer for the density of oak?**

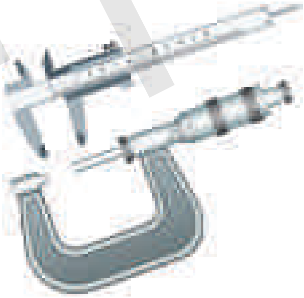


Figure 1.1.10 Precise measuring instruments. Vernier calipers (top) measure to 0.1 mm and micrometers (below) measure to 0.01 mm. Which is more precise?

Measuring the density of an irregular solid

This is, of course, the problem that Archimedes was trying to solve and his solution (apparently inspired by getting into a bath tub that was too full) was to use the idea of displacement. The solid will displace the same volume of water as its own volume. If there's room in the container, it rises. If not, it overflows.

Imagine trying to see if a gold necklace was pure. Knowing that the density of gold is 19.29 g/cm^3, being able to dangle the necklace on a thread and having a glass of water full to the brim, you could carry out a simple experiment.

Figure 1.1.11 How could you find out if this is pure gold?

8. **What procedure would you follow?**
9. **What measurements would you need to take?**
10. **What calculation would you then perform?**
11. **Why might this experiment probably not be very accurate?**

KEY CONCEPT

1.1d Particle theory

Learning objectives:

- use the particle model to explain states of matter
- use ideas about energy and bonds to explain changes of state
- explain the relationship between temperature and energy

KEY WORDS

specific latent heat of fusion
specific latent heat of vaporisation

The physical state of a substance is determined by the way in which its particles are arranged. Using the idea of forces between particles, the particle theory can explain why substances have different melting and boiling points, and what happens when a substance changes state.

Solids, liquids and gases

All matter is made up from atoms and molecules, but it is the way these atoms and molecules are held together that determines whether a substance is solid, liquid or gas. In a solid the atoms are held tightly together forming strong regular shapes. In a liquid the atoms are held much more loosely, which is why liquids can flow. In a gas the atoms and molecules are free to move about on their own.

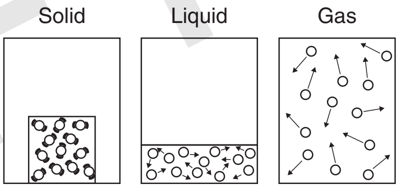


Figure 1.1.12 Movement of particles in the three states of matter

What determines the state of matter is the strength with which the atoms and molecules are held together by their bonds. All atoms also vibrate. Even in a solid, where the atoms are held together in a tight structure, every single atom is moving backwards and forwards next to its neighbour.

To get a solid to become a liquid, energy has to be added to the substance. Energy increases the vibrations of the atoms. As the vibrations increase, the bonds that hold the atoms are stretched and the atoms are pushed further apart from each other (Figures 1.1.12 and 1.1.13).

Adding more energy to the solid increases the vibrations even more until comes a point where the bonds can no longer hold together. Many bonds break and the atoms are free to move – the solid has become a liquid. Adding yet more energy breaks the bonds completely and the atoms escape into the atmosphere. The liquid becomes a gas. The amount of energy needed to change state from solid to liquid and from liquid to gas depends on the strength of the forces between the particles of the substance.

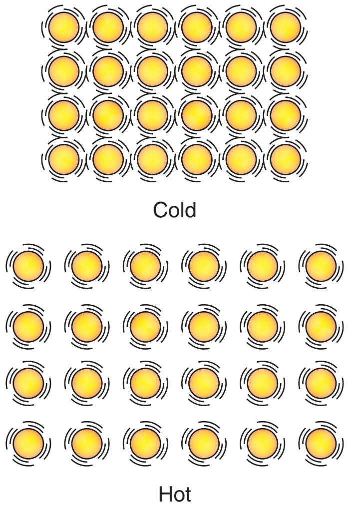


Figure 1.1.13 This particle diagram is exaggerated to show the increased vibration of particles at a higher temperature. Note that the particles do not get bigger

1. **State the difference between a solid and a liquid.**
2. **Explain why solids expand as they are heated.**

Change of state and change in temperature

The state of matter depends on the amount of energy inside it. Heating a substance increases the amount of internal energy and this either raises the temperature of the system or produces a change of state. The process also works in reverse. If you take energy out of a substance it will either decrease the temperature of the system or change state from a gas back to a liquid and then to a solid (Figure 1.1.14).

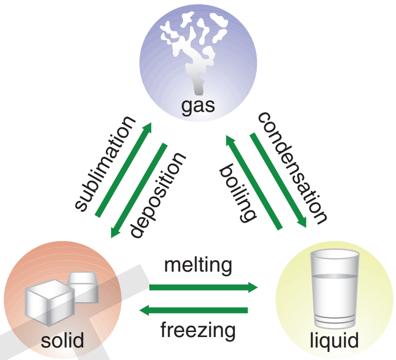


Figure 1.1.14 Changing between states of matter

When you heat a substance there are stages where you just get a rise in temperature and then a stage where you get a change of state.

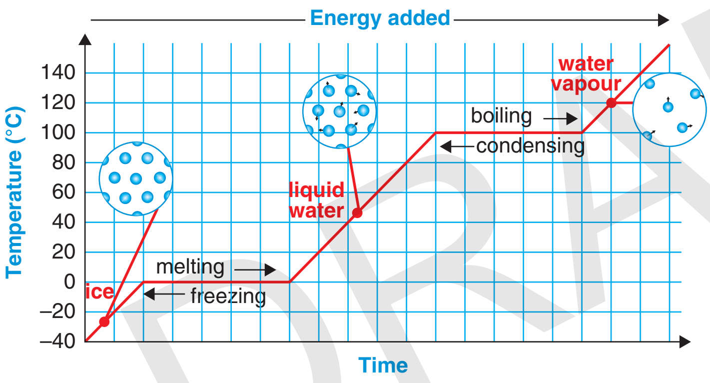


Figure 1.1.15 Temperature–time graph for heating water

Follow the steps on the graph in Figure 1.1.15, which shows how the temperature changes as a block of ice is heated continuously over a period of time.

The ice is initially at –40 °C. As it is heated, the ice gets warmer, but it is still a solid. The upward slope of the graph shows that the temperature is increasing. When the temperature reaches 0 °C energy is still being put into the ice, but there is no increase in temperature. The graph shows a level straight line. This is where the energy is being absorbed by the ice to change it into liquid water. The amount of energy needed to change state from solid to liquid is called the **specific latent heat of fusion**.

Once the ice has melted into water the temperature begins to rise again. The line on the graph is sloping upwards. When the temperature reaches 100 °C we get the second change in state. Energy is absorbed but there is no rise in temperature. The amount of energy required to change the state from liquid to water vapour is called the **specific latent heat of vaporisation**.

3. **Ethanol freezes at –114 °C and boils at 78 °C. Draw a temperature–time diagram for heating ethanol from –120 °C to 100 °C.**
4. **Explain what a line sloping down from left to right on a temperature–time graph means.**

1.1e Gas pressure

Learning objectives:

- use the particle model to relate the temperature of a gas to the average kinetic energy of the particles
- explain how a gas has a pressure.

KEY WORD

randomly

Inside an iron, the hot plate heats up the water, changing it from a liquid to a gas. Gas particles are fast-moving, and collide with the walls of the reservoir to create a force. The steam then escapes from the iron as a jet of gas under pressure.

Figure 1.1.16 Steam escaping under pressure from a steam iron

Temperature and pressure of a gas

The particles in a gas move around **randomly**. These particles have kinetic energy (the energy of moving objects). They move about freely at high speed.

The higher the temperature the faster the particles move and the more kinetic energy they have. The temperature of a gas is related to the average kinetic energy of the molecules. As the temperature increases, the particles move faster. They gain more kinetic energy.

1. **What happens to the molecules of a gas when the gas is heated?**
2. **How does the particle model explain temperature?**

The molecules of a gas collide with each other as well as with the walls of their container (Figure 1.1.17). When they hit a wall there is a force on the wall. Pressure is equal to the force on the wall divided by the area over which the force acts. The total force exerted by all the molecules inside the container that strike a unit area of the wall is the gas pressure.

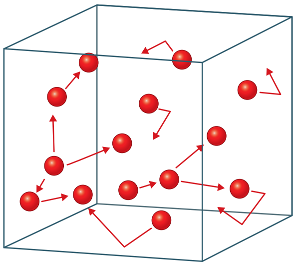


Figure 1.1.17 An expanded model view showing that when gas particles hit a wall of their container there is a force on the wall. This force is the pressure of the gas

3. **When you press on a balloon the pressure inside it increases. How does the particle model explain this?**
4. **Describe, in terms of particles, how a gas exerts a pressure.**

Changing the temperature of a gas

Air is sealed in a container (Figure 1.1.18). If we keep the mass and volume of the air constant, an increase in the temperature will increase the pressure of the gas.

There are the same number of particles because the container is sealed, and there is the same mass of gas. As the container is sealed the volume of gas is also constant. As the particles have more energy, they move faster, hitting the walls more often and with greater force, increasing the pressure.

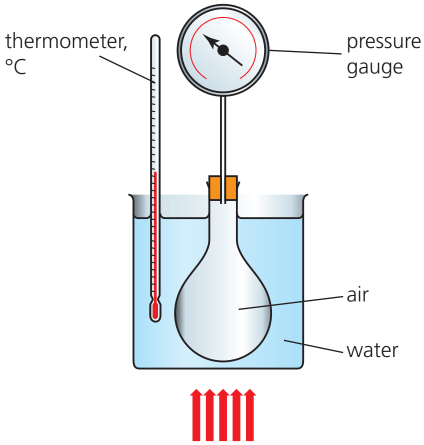


Figure 1.1.18 Heating air in a sealed container

5 **How do we know that the mass of gas is constant?**

6 **Explain, using ideas about energy, why the pressure of gas increases if it gets hotter.**

Linking pressure and volume, at constant temperature

For a fixed amount of gas kept at constant temperature, increasing the volume of the container results in a decrease in pressure. If the volume is doubled, with the same number of particles, there will be fewer collisions between the particles and the walls of the container. The pressure will be halved.

7 **Explain why the pressure is higher in the smaller box in Figure 1.1.19.**

Decreasing the volume of the container results in an increase in pressure. If the volume is halved the pressure will double (figure 1.1.19).

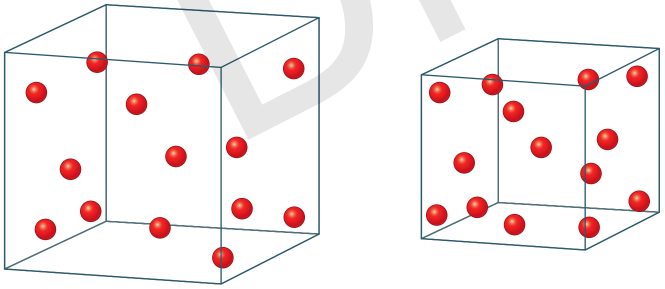


Figure 1.1.19 An expanded model view showing that there is the same number of particles in each box

1.1f Heating and changes of state

Learning objectives:

- describe how mass is conserved when the physical state changes
- describe how heating a system changes its internal energy
- explain that when a change of state occurs the internal energy changes but not the temperature.

KEY WORDS

boiling point
conserved
evaporation
melting point
sublimate

When a substance changes state, energy is transferred to change the arrangement of the particles. There is no change in temperature. To explain this we use the idea that there are forces between particles in the solid and liquid states.

Conservation of mass

Changes of state are physical changes. Unlike a chemical change, the change does not produce a new substance. If the change is reversed the substance recovers its original properties.

When substances change state, the mass is **conserved**. If you start with 1 kg of ice and melt it, you will have 1 kg of water. Nothing has been added or removed. The process is reversible. If you freeze the 1 kg of water, you will end up with 1 kg of ice again.

1. **What is sublimation?**
2. **What mass of iodine gas is produced by heating 45 g of solid iodine?**

DID YOU KNOW?

Dry ice is frozen carbon dioxide, which turns directly from a solid to a gas at a temperature of –78.5 °C. The fog you can see is a mixture of cold carbon dioxide gas and droplets of water vapour, condensed from the air as the dry ice **sublimates.**

Figure 1.1.20 Dry ice sublimates

Explaining changes of state

Heating a solid at its **melting point** transfers energy to the particles which allows them to overcome the forces holding them in position. While a solid is melting, all the energy transferred is used to rearrange the particles, so the temperature does not rise.

Heating a liquid at its **boiling point** transfers energy to the particles so they can escape the forces of attraction and become a gas. The liquid stays at its boiling point until all the particles have broken free.

The amount of energy needed to change state from solid to liquid, or liquid to gas, is different for different substances. The stronger the forces between the particles, the more energy is needed, and the higher the melting point and boiling point.

MAKING LINKS

You will find out more about the forces involved in different types of bonding in topic 6.2 Structure and bonding.

3 **Olive oil melts at –6 °C and coconut oil at 25 °C. Explain which type of oil has stronger forces between its molecules.**

4 **Explain why water in a kettle does not all turn to gas when the water first reaches 100 °C.**

Internal energy

Energy is stored inside a system by the particles that are within it. This is called the **internal** energy.

Heating changes the internal energy of a system by increasing the energy of the particles that make it up. The hotter a material is, the faster its particles move and the more internal energy it has.

As a liquid warms up the average speed of the particles in it increases. But not all the particles of the liquid will be travelling at the same speed. The faster particles with more energy can escape, leaving behind the slower particles with less energy. This is **evaporation**.

When the faster particles escape, the total internal energy left behind decreases. This has a cooling effect on the material left behind.

KEY INFORMATION

Energy transfer by heating will *either* increase the temperature of a system *or* change its state.

5 **What happens to the internal energy of a system when thermal energy is supplied?**

6 **Suggest why being burned by steam is worse than being burned by hot water.**

Figure 1.1.21 The sand in this pot is wet. Evaporation takes energy away from the inner pot and keeps the food cool

1.1g Specific heat capacity

Learning objectives:

- define and explain specific heat capacity
- state the factors that are involved in increasing the temperature of a substance
- calculate specific heat capacity and energy changes when a material is heated.

KEY WORDS

joule
specific heat capacity

Different materials need different amounts of energy to raise their temperature by 1°C. The syrup on a sponge pudding absorbs more energy during cooking than the sponge, so stays warmer on the plate.

Figure 1.1.22 The syrup stays hotter than the sponge pudding

Heating up

When a liquid is heated, the particles move faster. They gain kinetic energy and the temperature rises. The particles are close together and attract each other strongly. Their motion opposes the forces of attraction and keeps them separated. As they are moving faster, they also separate a bit more and gain potential energy. So the liquid has more kinetic energy and more potential energy. Its internal energy has increased.

1. **What effect does heating have on a liquid?**
2. **What happens to particles of a gas when it is heated?**

Increasing temperature

When a liquid is heated below its boiling point, its temperature increases. The temperature rise depends on

- the mass of liquid heated
- the particular liquid being heated
- the energy input to the system.

3. **Dan is heating a large saucepan of water to boiling point. Explain why more energy is needed to do this than to heat a cup of water to the same temperature.**
4. **Milk does not need as much energy to raise its temperature by 10 °C as the same mass of water. Will hot milk give out less energy than the same amount of water at the same temperature when it cools down? Explain.**

Specific heat capacity

When an object is heated, energy is transferred to the object and its temperature rises. The amount of energy needed to change the temperature of an object depends on the material the object is made from. The property of a material that determines the energy required is called the **specific heat capacity.**

The specific heat capacity of a substance is the energy needed to raise the temperature of 1 kg of the substance by 1 °C.

It is given by the equation:

change in thermal energy = mass × specific heat capacity × change in temperature

$$\Delta E = m \times c \times \Delta\theta$$

where ΔE = change in thermal energy in J

m = mass in kg

c = specific heat capacity in J/kg °C

$\Delta\theta$ = temperature change in °C.

Example: A change in thermal energy of 18 kJ of energy was supplied to a 2 kg steel block and raised its temperature from 20 °C to 40 °C. Calculate the specific heat capacity of steel.

$\Delta E = mc\Delta\theta$

ΔE = 18 kJ = 18 000 J

m = 2 kg

$\Delta\theta$ = (40 – 20) °C = 20 °C

Specific heat capacity, $c = \dfrac{\Delta E}{m\Delta\theta}$

$$= \frac{18000\ \text{J}}{2\ \text{kg} \times 20\ °\text{C}} = 450\ \text{J/kg °C}$$

Material	Specific heat capacity in J/kg °C
water	4200
ice	2100
aluminium	880
copper	380

Water has a very high specific heat capacity. This means that, for a given volume, it absorbs a lot of energy when it warms up. It also gives out a lot of energy when it cools down (Figure 1.1.23).

5 **Calculate how much energy is needed to heat 100 g of water from 10 °C to 40 °C.**

6 **Water has a very high specific heat capacity. Describe a practical use of this.**

7 **A 2 kW electric heater supplies energy to a 0.5 kg copper kettle containing 1 kg of water.**

a **Calculate the time taken to raise the temperature by 10 °C.**

b **What have you assumed in doing this calculation?**

8 **Suggest why some saucepans are made of copper.**

Figure 1.1.23 A domestic radiator contains water which is heated by a boiler

DID YOU KNOW?

Water needs lots of energy to heat it up and gives out lots of energy when it cools down. This is why a hot-water bottle is so effective in warming a bed. An equal volume of mercury would store only 1/30th as much energy, but would be 13 times heavier!

COMMON MISCONCEPTION

Do not confuse thermal energy transfer and temperature. Temperature is how hot an object is. A change in thermal energy does not always produce the same temperature change.

REQUIRED PRACTICAL

1.1h Investigating specific heat capacity

Learning objectives:

- use theories to develop a hypothesis
- evaluate a method and suggest improvements
- perform calculations to support conclusions.

KEY WORDS

energy store
energy transfer
specific heat capacity

Electric storage heaters store energy by heating up blocks during the night, when electricity is cheap. The energy is released the next day. Engineers can test materials to find those that can store and release the most energy.

> These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

Using scientific ideas to plan an investigation

When a lump of brass is immersed in boiling water its temperature increases. It would end up at 100 °C (if we continued to heat the water). Thermal energy is transferred from the store in the water into the brass. If we then take the brass out of the boiling water and put it into another beaker of water at room temperature, thermal energy would transfer from the store in the brass to the water. The brass would cool down and the water would heat up until they were both at the same temperature.

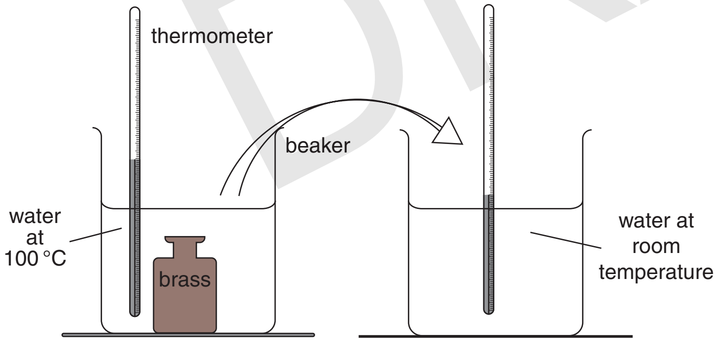


Figure 1.1.24 The lump of brass is transferred from the water at 100 °C to the water at room temperature

1. **How could we find out what the temperature of the water became when the brass was added to it?**
2. **How could we calculate the rise in temperature of the water?**
3. **How could we calculate the temperature drop of the brass?**
4. **What would happen to the temperature of the water and the brass in the second beaker if we left them for a long time (e.g. an hour)?**

SAFETY

It would be advisable to place the beaker in a tray/container that will hold the boiling water in case the brass lump is dropped into the beaker and it cracks, spilling the water. The thermometers should be clamped, and a stirring rod used to agitate the water and therefore obtain more accurate temperature readings.

Link: 1.1h ⟶ 1.1i

Evaluating the method

This experiment is used to find the specific heat capacity of brass by assuming that all the thermal energy transferred from the hot water increases the temperature of the lump of brass.

We are equating the decrease in thermal energy store of the water to the increase in thermal energy store of the brass. If this assumption is not true, the method will not be valid.

5 **The lump of brass has to be moved from one beaker to the other. Consider how this step in the method could affect the accuracy of the results.**

6 **The energy transferred from the brass will cause the water in the second beaker to get hotter. Why will the energy transferred to the water not be stored there permanently?**

7 **What are the implications of your answers to questions 5 and 6 for the way the experiment is carried out?**

8 **Why is it important that the lump of brass is covered in water in the second beaker?**

Using the data to calculate a value for SHC

We find the specific heat capacity of brass by calculating the energy transferred into the water when its temperature increases and equating that to energy transferred out of the brass when its temperature decreases.

Decrease in thermal energy of brass = increase in thermal energy of water

$$m_{water} \times c_{water} \times \text{temperature increase}_{water}$$
$$= m_{brass} \times c_{brass} \times \text{temperature decrease}_{brass}$$

The final temperature of the water and brass is the same (they reach thermal equilibrium). As long as we know the values of the mass of water, mass of brass, specific heat capacity of water and initial temperatures of the water and brass, we can find the unknown value for the specific heat capacity of brass.

9 **There is 250 g of water (c_{water} = 4200 J/kg °C) in the second beaker and its temperature rises from 17 °C to 26 °C. Determine how much energy has been transferred into it.**

10 **How much energy can we assume has been transferred out of the block when it is put into the second beaker?**

11 **If the brass had been in boiling water by how much would its temperature have decreased?**

12 **The brass has a mass of 150 g. Calculate its specific heat capacity.**

13 **Explain why this method is likely to give a lower value for the specific heat capacity than its true value?**

DID YOU KNOW?

Stone Age man, Native American Indians and backwoodsmen all have used hot stones to boil water. Hot stones from a fire are dropped into a wooden bowl of cold water. Thermal energy stored in the stones is transferred to the water making it hot enough to boil. This is an example of a decrease in one energy store producing an increase in another. You can make use of this method to find the specific heat capacity of different materials.

KEY INFORMATION

When thinking about this experiment remember that energy tends to move from hotter areas to cooler ones.

1.1i Changes of state and specific latent heat

Learning objectives

- explain what is meant by latent heat and distinguish it from specific heat capacity
- perform calculations involving specific latent heat.

KEY WORDS

latent heat
specific latent heat
specific latent heat of fusion
specific latent heat of vaporisation

When a substance is heated, at certain temperatures the thermal energy transferred by heating goes into changing the state of the substance rather than continuing to increase the temperature. This can be shown on very characteristic graphs.

Latent heat

When you heat a solid, such as a lump of ice, its temperature rises until it starts to change to a liquid. At its melting point, the temperature stays the same until all the ice has melted (Figure 1.1.25).

The temperature of the liquid then rises until it starts to change into a gas. At its boiling point, the temperature stays the same until all the liquid has turned into a gas. If you continued to heat the gas, the temperature would start to rise again.

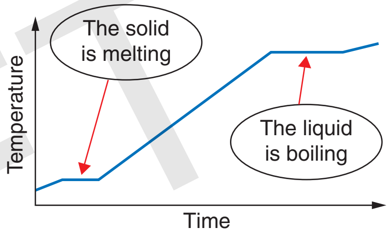


Figure 1.1.25 Temperature–time graph for heating a substance

Latent heat is the energy needed to change the state of a substance without a change in temperature.

1. **Describe is happening when the graph flattens out.**
2. **Energy is needed to turn water into steam. Suggest how the particle model explains this.**

MAKING LINKS

Look back to topic 1.1d to remind yourself about particle theory.

Changes of state

The amount of energy needed to change the state of a sample of a substance, without a change in temperature, depends on the mass of the sample and the type of substance. All substances have a property called **specific latent heat.**

The specific latent heat is the amount of energy needed to change the state of 1 kg of a substance without a change in temperature. Its unit is J/kg.

It is given by the equation:

$$E = mL$$

where E = energy for a change of state in J

m = mass in kg

L = specific latent heat in J/kg

Specific latent heat of fusion refers to a change of state from solid to liquid. **Specific latent heat of vaporisation** refers to a change of state from liquid to vapour.

The specific latent heat of vaporisation is much greater than the specific latent heat of fusion. Most of this energy is used to separate the particles so they can form a gas, but some is required to push back the atmosphere as the gas forms.

Change of state	Specific latent heat in J/kg
ice to water	340 000
water to steam	2 260 000

3. **Explain why there is no change in temperature when a block of ice melts.**

4. **Why is the specific latent heat of vaporisation much greater than the specific latent heat of fusion?**

Latent heat calculations

Many calculations on specific and latent heat require you to find the energy needed to change the state as well as the temperature of an object. This involves using both specific heat capacity and latent heat equations.

$\Delta E = m\,c\,\Delta\theta$ $\quad E = m\,L$

5. **Calculate the energy transferred from a glass of water to just melt 100 g of ice cubes at 0 °C.**

6. **a Calculate the total energy transferred when 200 g of ice cubes at 0 °C are changed to steam at 100 °C.**

   b Sketch a temperature–time graph for this transfer.

Figure 1.1.26 Machines in cafes use steam to heat milk quickly

KEY INFORMATION

In these calculations use the specific heat capacities given in the table in topic 1.1g.

KEY INFORMATION

Use the equation for specific heat capacity as well as the equation for latent heat.

DID YOU KNOW?

A jet of steam releases latent heat when it condenses (changes to a liquid). This can be used to heat drinks quickly (Figure 1.1.26).

KEY INFORMATION

Energy transfer does not always involve a change in temperature. When a change of state occurs, the energy supplied changes the energy stored (internal energy) but not the temperature.

MATHS SKILLS

1.1j Drawing and interpreting graphs

Learning objectives:

- draw a graph of temperature against time
- interpret a graph of temperature against time.

KEY WORDS

line of best fit
range
scale

A graph of temperature against time for a substance can show quite a lot about what is going on. If we know how to read a graph we can work out what that might be.

KEY INFORMATION

Suitable scales are 1, 2, 5 and 10 (or multiples of 10) units per square.

Drawing a graph

To set out the axes for a graph, the **range** of values has to be identified. The maximum and minimum values should be known.

The number of units per square on the graph paper should be chosen with care. It's essential to select a **scale** that is easy to interpret. One that uses five large squares for 100 units is much easier to interpret than a scale that has, say, three large squares for 100 units. Sometimes it is better to use a smaller scale (e.g. two large squares for 100 units) and have a scale that is easier to interpret than to try to fill the page.

A group of students conducted an experiment where they recorded the temperature of stearic acid every minute as it cooled down from 90 °C. The results are shown in the table below.

Time in minutes	Temperature in °C	Time in minutes	Temperature in °C
0:00	95.0	8:00	68.1
1:00	90.9	9:00	68.1
2:00	86.3	10:00	67.9
3:00	80.7	11:00	67.3
4:00	73.0	12:00	64.2
5:00	68.1	13:00	58.4
6:00	68.0	14:00	48.2
7:00	68.1	15:00	35.9
		16:00	25.0

1. **What are the maximum and minimum values that need to be plotted?**
2. **Draw and label axes for plotting this dataset.**
3. **Plot the points and draw a line of best fit.**
4. **Describe the features of the line of best fit.**

MATHS

Some graphs will have a line or curve of best fit. A line of best fit goes roughly through the centre of all the plotted points. It does not go through all the points. The line of best fit could be a curve. If all the points fall close to the line (or curve), it suggests that the variables are closely linked. Look at the points carefully and see what would fit them well.

Link: 1.1j ⟶ 1.1k

Interpreting a graph

The graph in Figure 1.1.27 shows temperature against time for heating a lump of paraffin wax. The temperature was recorded using a datalogger. The rate at which energy was supplied to the wax stayed constant. The temperature of the solid wax increases until about 7 minutes and then stops rising. It then starts rising again at about 15 minutes.

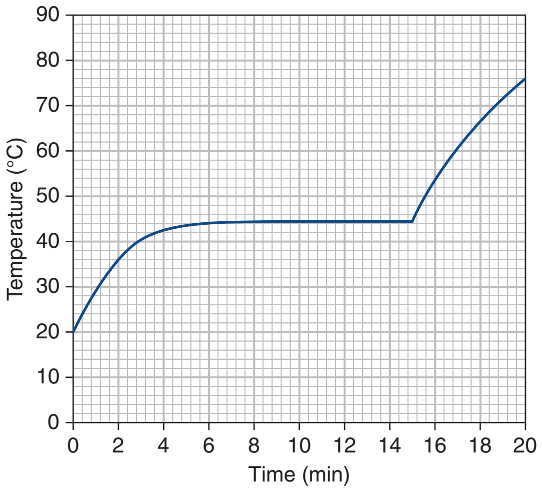


Figure 1.1.27 Graph of temperature against time for heating paraffin wax

5. **Why is there a curve and not a straight line when the energy is being supplied at a constant rate?**
6. **What is happening between 7 and 15 minutes?**
7. **What is the melting point of paraffin wax?**

Understanding the shape of the line

This graph shows a really important point. Whilst the wax is melting, energy is being supplied but the temperature isn't changing. The energy being supplied is being used to change the state of the wax and whilst this is happening, the temperature stays the same.

Now look at the graph you drew of temperature against time for stearic acid. This was cooling down but there are similarities.

8. **Suggest an explanation for the shape of the graph.**
9. **What is happening between about 5 and 9 minutes?**
10. **What is the melting point of stearic acid?**
11. **Describe the shape of the graph with reference to what is happening with regard to the internal energy of the stearic acid.**

DID YOU KNOW?

Steam at 100 °C can burn you more severely than the same mass of water at 100 °C. As well as the high temperature steam has latent heat – the energy it used to turn into a gas.

1.1k Meaning of purity

Learning objectives:

- explain what is meant by purity
- distinguish between the scientific and everyday use of the term 'pure'
- use melting and boiling point data to distinguish pure from impure substances.

KEY WORDS

pure
purity
unadulterated

Just because something is labelled as 'pure' does not mean that it really is. Chemists can investigate purity with some simple rules.

Meaning of purity

In everyday language, a 'pure' substance can mean a substance that has had nothing added to it, so it is in its natural state, or **unadulterated** – for example, pure milk. But this is not the chemical definition.

In chemistry, a **pure** substance is a single element or compound, not mixed with any other substance. A sample of gold with a **purity** of 100% only contains gold atoms – nothing else.

Figure 1.1.28 Separating 'pure' milk. This is not the chemistry definition of pure

A mixture consists of two or more elements or compounds not chemically combined. A mixture is not pure, even if the components are pure. The chemical properties of each substance in the mixture are unchanged.

DID YOU KNOW?

Pure and impure milk can both be separated into their components by centrifuging. This means spinning round at high speeds so that layers of substances can be separated. Blood can also be separated in this way.

1. **Identify which of these is a pure substance in the everyday sense of the word 'pure' and explain why: tea, salt, milk, cooking oil.**
2. **Draw out, using particle pictures, examples of:**
   - a **a pure single-atom element**
   - b **a mixture of two elements**
   - c **a pure compound, such as water (H_2O).**

The importance of purity

Pure substances are used in industry to make materials, food and medicines. Impurities in drugs might cause unwanted or dangerous side effects. Chemists who manufacture food, medicines or new materials such as plastics need to create products that are free from impurities that could be hazardous.

3 **Look at the label in Figure 1.1.29. What proportion of the mineral water is actually other substances, and would be left behind if the water was evaporated off? (Hint: this is the dry residue value.) Give your answer as a percentage.**

4 **Assess the benefits and potential risks of buying a nutritional supplement advertised as pure and natural, but with no other labelling information.**

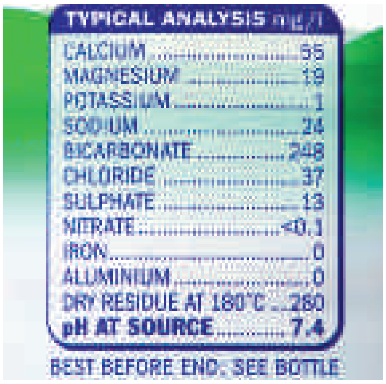


Figure 1.1.29 'Pure' mineral water contains many different substances

Establishing purity

Pure elements and compounds melt and boil at specific temperatures. The purity of a compound can be established using data from its melting point or boiling point.

When there is a mixture of the pure compound with other substances, the impurities affect the melting and boiling points in three ways:

- reduce the melting point
- increase the boiling point
- increase the range over which melting and boiling takes place.

This is because the impurities are themselves substances that each melt or boil at different temperatures from each other. The greater the amount of an impurity, the bigger the differences from the true melting point and boiling point.

Because pure elements and compounds have definite melting points and boiling points, we can use official data to decide if a substance is indeed pure.

Figure 1.1.30 Using a melting point to establish purity. A small sample in a thin tube is inserted into a metal block in the apparatus alongside the thermometer. The metal block is slowly warmed up and the observer records the temperature at which the sample melts

5 **Sam and Alex each made a sample of the same substance. They measured the melting point. They then crystallised their solid and measured the melting point again. They did this several times.**

	Melting point in °C				
Sam	46.5	46.6	46.7	46.7	46.7
Alex	42.8	43.7	44.5	44.9	45.1

Identify who made the purest sample and explain your reasoning.

6 **Akira and Ben tested their samples for their boiling points. The standard boiling point from data tables was 85.0 °C. Their results were: Akira 86.2 °C, Ben 87.1 °C. Identify who had the purer sample and explain your reasoning.**

DID YOU KNOW?

Mixing salt with ice lowers the melting point, so the mixture melts at a temperature below 0 °C. This is why salt is spread onto icy roads in winter.

Check your progress

You should be able to:

☐ describe and explain the properties of solids, liquids and gases using the particle model.	→ ☐ use the model to explain why physical changes are reversible.	→ ☐ identify the strengths and limitations of the particle model.
☐ use density = mass/volume to calculate density.	→ ☐ use particle diagrams to communicate ideas about relative densities of different states. ☐ use the density equation to calculate mass and volume. ☐ manipulate apparatus to collect data to discover the density of an unknown substance.	→ ☐ link the particle model for solids, liquids and gases with density values in terms of the arrangements of the atoms or molecules.
☐ describe how, in the particle model the higher the temperature the faster the molecules move.	→ ☐ explain how a gas has a pressure. ☐ use the particle model to explain the effect on temperature of increasing the pressure of a gas at constant volume.	→ ☐ describe how the temperature of a gas is related to the average kinetic energy of the molecules. ☐ use the particle model to explain that increasing the volume of a gas, at constant temperature, can lead to a decrease in pressure.
☐ describe changes of state as physical changes.	→ ☐ describe how mass is conserved when substances change state. ☐ explain that changes of state are physical, not chemical, changes because the material recovers its original properties if the change is reversed.	→ ☐ explain using the particle model how changes of state conserve mass.
☐ describe how heating raises the temperature of a system.	→ ☐ recognise that heating raises the temperature or changes the state of a system but not at the same time.	→ ☐ explain that the internal energy of a system is stored by the particles that make up the system.
☐ describe the effect of an increase in temperature on the motion of particles. ☐ define and explain specific heat capacity. ☐ use appropriate apparatus safely to make and record a range of measurements accurately.	→ ☐ use the specific heat capacity equation to calculate the energy required to change the temperature of a certain mass of a substance. ☐ state the factors that are involved in increasing the temperature of a substance. ☐ perform calculations to find the specific heat capacity of a material.	→ ☐ use the specific heat capacity equation to calculate mass, specific heat capacity or temperature change. ☐ calculate energy transferred when a material of a certain mass is heated. ☐ evaluate the safety and procedures you have used in practically investigating specific heat capacity.
☐ state that when an object changes state there is no change in temperature. ☐ describe changes of state from a graph.	→ ☐ describe the latent heats of fusion and vaporisation. ☐ use the equation $E = mL$.	→ ☐ use the particle model to explain why the latent heat of vaporisation is much larger than the latent heat of fusion.
☐ describe what is meant by a pure substance.	→ ☐ recognise that a pure substance has a definite melting and boiling point.	→ ☐ distinguish pure and impure substances using melting and boiling point data. ☐ discuss the risks of impurities in medicines and food.

Worked example

1 **Kiran uses an electric immersion heater to supply 20 kJ of thermal energy to a 1.5 kg aluminium block. He recorded a temperature rise of 14.6 °C. Calculate the specific heat capacity of aluminium.**

913

This is the correct numerical answer, but

a You have not given any units to the number. Always give the unit to the quantity.

b You have not shown any working. When working a calculation, write the equation, and show step by step how you do the calculation.

2 **Explain how raising the temperature of a gas, keeping the volume constant, increases the pressure exerted by the gas.**

The high temperature makes the molecules vibrate faster so there is a stronger force on the side of the container.

You are on the right lines. With a gas, the molecules are no longer vibrating but they are free to move around at speed. Heating gives them more kinetic energy. As the molecules move around they hit the side of the container, and it is the force of this that creates the pressure.

3 **What does it mean to say that the changes of state are reversible?**

It means that the changes go both ways.

Correct, but you should give an example as well. Give an example of a change that goes both ways, e.g. water turns to steam and steam turns back to water.

4 **Explain what heating does to the energy stores of a system.**

Heating raises the total energy inside the system.

Yes it does, but again you should give more specific information about the system and mention the energy transfers that have taken place. A good answer would mention that the energy supplied by heating increases the speed of movement of the particles (their kinetic energy).

End of chapter questions

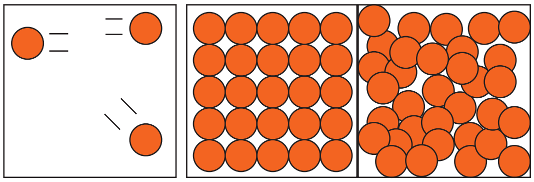
Specific heat capacity of water = 4200 J/kg °C

Specific latent heat of fusion of ice to water = 340 000 J/kg

Specific latent leat of vaporisation of water to steam = 2 260 000 J/kg

Getting started

1 Label these diagrams as solid, liquid and gas. 1 Mark



2 Describe how these models represent a solid, liquid and gas. 2 Marks

3 Substance G has a melting point of –33 °C and a boiling point of 52 °C. Explain which state it is in at 20 °C. 1 Mark

4 Two steel blocks, one with a mass of 100 g and the other with a mass of 200 g, are placed in boiling water for several minutes. Which of these statements is **not** true? 1 Mark

a They are both at the same temperature.

b They are made of the same material.

c They have the same amount of energy.

d They remain solid.

5 What is the term given to the energy needed to change the state of a substance? 1 Mark

6 Calculate the amount of energy needed to change the temperature of 2 kg of water by 10 °C. 2 Marks

7 State the equation for density. 1 Mark

Going further

8 Which of these does **not** affect the amount of energy needed to heat a material up? 1 Mark

a Its colour.

b Its mass.

c Its specific heat capacity.

d The temperature rise.

9 An object has a mass of 100 g and a volume of 25 cm^3. Will it float in water? 2 Marks

10. Calculate the energy needed to boil away 150 g water at 100 °C. **2 Marks**
11. Water in an ice cube tray is put into a freezer. Explain what happens to the energy stored inside the system. **3 Marks**
12. Using the particle model, explain how a gas exerts pressure on the container holding the gas. **2 Marks**

More challenging

13. Night storage heaters charge up during the night time and release energy during the day. Explain why they are made from a material with a high specific heat capacity. **2 Marks**
14. Calculate how much energy is needed to heat 100 g of water from 10 °C to 50 °C. **2 Marks**
15. 4.50 g of water was frozen to ice at 0 °C. How much energy had to be taken out of the water? **2 Marks**
16. Why is the specific latent heat of vaporisation of water to steam a much higher value than the specific latent heat of fusion of ice to water? [The values are given at the top of at the start of these questions.] **2 Marks**
17. Explain how raising the temperature of a gas, keeping the volume constant, increases the pressure exerted by the gas. **2 Marks**

Most demanding

18. Explain why changing the temperature of a material and changing its internal energy mean different things. **2 Marks**
19. A 2 kg block of copper is given 8.88 kJ of energy to raise its temperature by 10 °C. What is the specific heat capacity of copper? **2 Marks**
20. 50 g of steam condense to water at 100 °C. How much energy was given out? **2 Marks**
21. With reference to the particle model, explain how increasing the volume in which a gas is contained, at constant temperature, creates a decrease in pressure. **2 Marks**

Total: 37 Marks

ATOMIC STRUCTURE

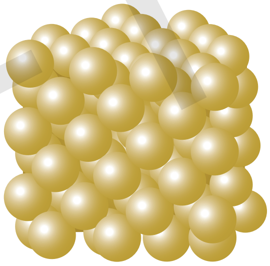
IDEAS YOU HAVE MET BEFORE:

ELEMENTS, MIXTURES AND COMPOUNDS

- Elements cannot be broken down by chemical means.
- Compounds are made from elements chemically combined.
- A pure substance is a single element or compound not mixed with any other substance.

THE PARTICLE MODEL OF MATTER

- A simple model of matter uses solid spheres to represent atoms, molecules and ions.
- The particles are arranged in different ways in solids, liquids and gases.
- Different elements are made from different atoms.



SIZE AND SCALE

- We use measurements expressed as numbers and units to compare properties of materials, such as length, mass, volume or density.
- SI units are an international system of units including the metre, kilogram and second.
- Atoms are so small that about 5 000 000 would fit side by side in a length of one millimetre.

1.2

IN THIS CHAPTER YOU WILL FIND OUT ABOUT:

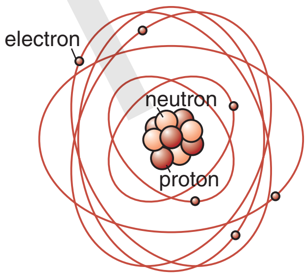
ARE ALL ATOMS OF AN ELEMENT THE SAME?

- All atoms of the same element have the same atomic number.
- Atoms of the same element can have different numbers of neutrons; these atoms are called isotopes of the element.
- Atoms can be represented by symbols showing the mass number and atomic number.

$^{12}_{6}C$

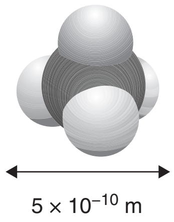
HOW DID THE MODEL OF THE ATOM DEVELOP?

- Atoms used to be thought of as small unbreakable spheres.
- Experiments led to ideas of atoms with a nucleus and electrons.
- Electrons in shells and the discovery of the neutron came later.



HOW DO WE WRITE VERY LARGE AND VERY SMALL NUMBERS?

- Sub-units use standard prefixes, such as 'milli' to mean one thousandth.
- Standard form uses powers of ten (such as 10^3 or 10^{-3}) to write very large or very small numbers.
- The radius of a typical atom is 0.1 nm (1×10^{-10} m).



1.2a Scientific models of the atom

Learning objectives:

- describe how and why the model of the atom has changed over time
- explain how data support theories, and how new data lead to changes in theories.

KEY WORDS

atom
electron
neutron
nuclear model
plum pudding model
proton
sub-atomic particle

The early model of the atom was of a solid sphere that could not be split. The discovery of the negatively charged electron upset this simple model. Because atoms are neutral, scientists had to incorporate a positive part to the atom as well.

Developing the atomic theory

In 465 BC the Greek philosopher Democritus hypothesised that matter was made from **atoms**. These were solid, but invisible, and had different shapes and sizes. They could not be divided into smaller particles.

In 1804 John Dalton proposed his atomic theory. Dalton's atoms were tiny spherical particles which could not be broken up. He suggested that the particles of each element were special to that element, and were solid like tiny 'billiard balls'. His model helped to explain the properties of gases for the first time, and the formulae of compounds.

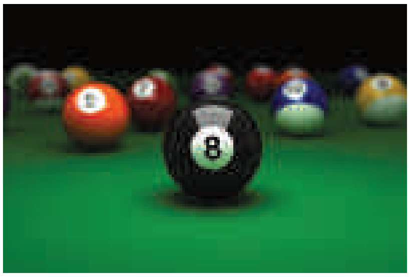


Figure 1.2.1 Dalton's idea of atoms: they were like tiny billiard balls

In 1897 J.J. Thomson discovered the negatively charged particle called the **electron**. The mass of the electron was about 1000 times smaller than the mass of the atom. This meant that there must be **sub-atomic particles** smaller than the atom.

Because atoms are neutral, Thomson proposed the **plum pudding** model, in which negative electrons are embedded in a ball of positive charge.

1. **Suggest why Dalton's atomic model did not include positive and negative charge.**
2. **Explain why the discovery of the electron changed the Dalton model of the atom.**

Changing theories

Dalton's theory lasted for nearly 100 years, but Thomson's model lasted for less than 20 years.

In 1909, a team of scientists working with Ernest Rutherford carried out an experiment where they aimed a beam of positive alpha particles (a form of radioactive decay) at a thin gold foil. Most alpha particles passed through but a few bounced back.

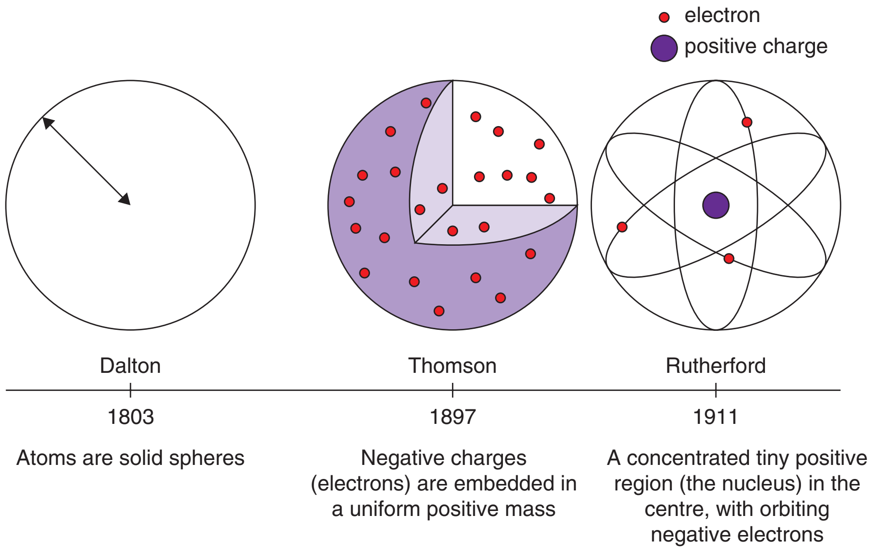


Figure 1.2.2 Timeline for the development of models of the atom

KEY INFORMATION

At each stage, the explanations of atomic theory were provisional until more convincing evidence was found to make the model better.

To explain this result, in 1911 Rutherford suggested the atom had a positively charged nucleus and much of the atom was empty space. This was the **nuclear model** of the atom.

Using the new model, scientists found that the tiny nucleus contained positively charged particles. These were first called **protons** in 1920. But further experiments showed the nucleus was too massive for the number of protons it contained.

In 1932 James Chadwick discovered the **neutron**, which had the same mass as the proton but no charge.

3. **Suggest how the discovery of the neutron changed ideas about the nucleus.**
4. **Explain why the model of the atom kept changing.**

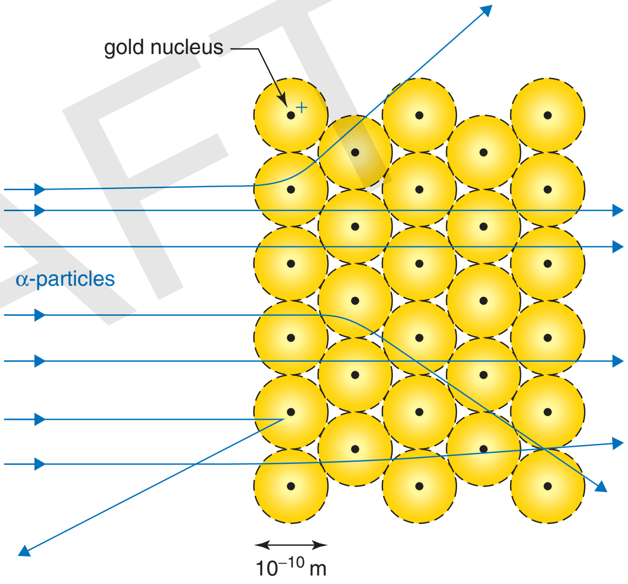


Figure 1.2.3 The positive nucleus repels the positive alpha particles

Challenging theories

The Rutherford alpha-particle experiment was very important – it changed the whole theory of the atom.

If Thomson's model was correct, the alpha particles should have passed through the foil, with nothing to attract or repel them. Yet some alpha particles bounced back. Rutherford's team had to think of a new theory to explain their unexpected observations.

5. **Explain why Rutherford's result did not support the Thomson model.**
6. **Suggest how a scientific theory becomes accepted.**

DID YOU KNOW?

The idea of atoms as small particles is not new. However, our ideas about the theory of atoms are still developing. Search on 'CERN LHC' to find out more.

1.2b The size of atoms

Learning objectives:

- recall the size and order of magnitude of atoms and small molecules
- recognise expressions in standard form
- estimate the size of atoms based on scale diagrams.

KEY WORDS

atomic radius
nanometre
order of magnitude

The size of the whole atom can be up to 100 000 times the size of the nucleus. So if you could imagine an atom to be the size of a football stadium, the nucleus would be a marble in the middle.

Sizes of atoms

Individual atoms are very small indeed. There are about five million of them in the full stop at the end of this sentence.

It depends on how it is measured, but the radius of an atom is about 0.000 000 000 1 m, which we can write as 1×10^{-10} m (this way of writing numbers is called 'standard form'). The **order of magnitude** is 10^{-10} m.

To describe such a small size, we use a unit called the **nanometre**, abbreviated to nm. 1 nm = 0.000 000 001 m, or 10^{-9} m. So the typical **atomic radius** is about 0.1 nm.

The nucleus is in the centre of the atom and the electrons surround it, but most of the atom is empty space.

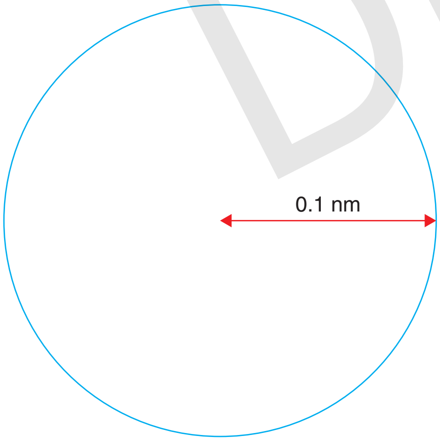


Figure 1.2.4 Typical atomic radius

1. **What is between the nucleus and the outer part of the atom?**
2. **What is the order of magnitude of the radius of the smallest atoms?**

DID YOU KNOW?

The radius of the atom, where the electrons are orbiting, is much larger than the radius of the nucleus in the centre of the atom. The nucleus has a radius of about 1×10^{-14} m. So there are about 4 orders of magnitude difference between the size of the atom and the size of the nucleus.

REMEMBER!

Always look carefully to see whether the question is talking about the radius or the diameter when it gives the measurements of an atom!

Link: 1.2b ⟶ 1.2c

Sizes of molecules

Although a typical atomic radius is about 0.1 nm (1×10^{-10} m), atoms are not all the same size. The outer boundary of the atom is not fixed, so its position can only be measured approximately.

The radius of a small molecule such as methane is about 0.5 nm, or 5×10^{-10} m. This is in the same order of magnitude as the radius of an atom.

You can see from Figure 1.2.5 that the methane molecule as a whole is not much more than the size of the five individual atoms.

3. **What is the size of the skin cell in nanometres?**
4. **What is the order of magnitude difference in size between the methane molecule and the skin cell?**

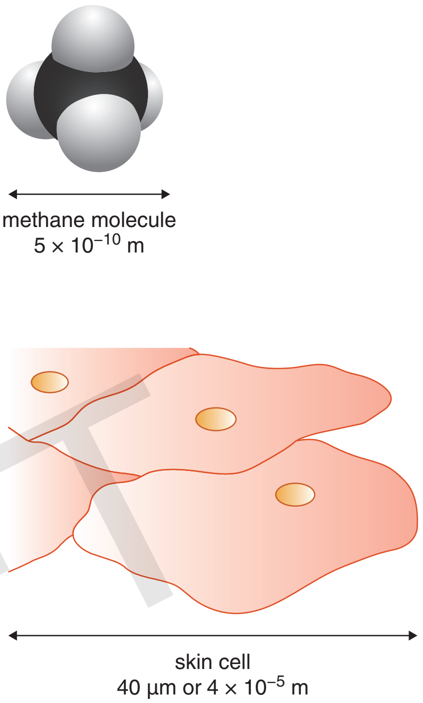


Figure 1.2.5 The size of a molecule of methane compared to a skin cell

Estimating atomic sizes

A useful skill is to estimate the sizes of objects using scale drawings.

A scale bar is usually provided for you to measure against.

5. **Look at Figure 1.2.6 below. If the radius of the sodium atoms is 0.18 nm, what is their *diameter*?**
6. **What is the *radius* of the chlorine atoms?**

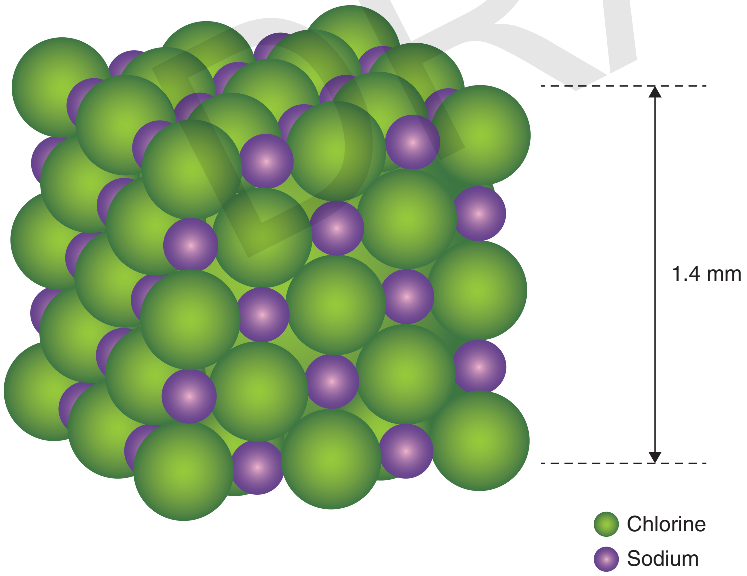


Figure 1.2.6 Sodium chloride

MAKING LINKS

See topic 5.1g to learn how sodium atoms and chlorine atoms react to form sodium chloride.

MATHS SKILLS

1.2c Standard form and making estimates

KEY WORDS

decimal point
standard form

Learning objectives:

- recognise the format of standard form
- convert decimals to standard form and vice versa
- make estimates without calculators so the answer in standard form seems reasonable.

When we talked earlier about an atom we used a model to describe it. We imagined it as a sphere with a radius of about 0.000 000 000 1 m. We also saw that the radius of the nucleus of the atom is about 0.000 000 000 000 01 m. It is very awkward to keep writing so many zeros – it is easy to lose count and it is not so easy to see the comparison between one number and the other. Another way of writing these numbers uses **standard form**.

KEY INFORMATION

Standard form is used to represent very large or very small numbers.
A number in standard form is written in the form $A \times 10^n$, where $1 \leq A < 10$ and n is an integer. For numbers less than 1, n is negative.

Positive powers of ten for very large numbers

We write 1, 10 and 100 knowing what we mean. We can also write them as 1, 1 × 10 and 1 × 10 × 10. We also know that 10 × 10 is 10^2. So 100 is 10^2. We can write the numbers 1, 1 × 10 and 1 × 10^2.

Standard form	M	HTh	TTh	Th	H	T	U	.	t
							1	.	0
1 × 10						1	0	.	0
1 × 10^2					1	0	0	.	0
1 × 10^3				1	0	0	0	.	0
1 × 10^4			1	0	0	0	0	.	0
1 × 10^5		1	0	0	0	0	0	.	0
1 × 10^6	1	0	0	0	0	0	0	.	0

1 Write 1 000 000 000 in standard form.

2 Write out the number 1 × 10^8.

10^6 is NOT 10 multiplied by itself 6 times. It is 10 multiplied by itself 5 times.

What about writing bigger numbers in standard form?

The **decimal point** is fixed and the position, or place value of the most significant digit, shows how big a number is.

To write 1 000 000 in standard form take the first number on the left, which is 1. Looking at the table, how many places do we have to move the 1 to the right to reach the decimal point?

REMEMBER!

1000 can be written as 1 × 10 × 100, which is the same as 1 × 10 × 10 × 10. How many tens? Three. So 1000 is written 1 × 10^3 (one times ten to the power of three). The number 3 tells you how many tens are in the multiplication.

We have to move the 1 six places to the right. So in standard form 1 000 000 is 1×10^6. The number 6 tells you how many tens there are when you write the number as a multiplication of 10 ($10 \times 10 \times 10 \times 10 \times 10 \times 10$).

Negative powers of ten for very small numbers

It is also possible to write numbers smaller than 1 in this form. If 1 is divided by 10 it is 0.1. The number 1 has moved one place to the right of the decimal point. This is written as 1×10^{-1} in standard form. What is 1 divided by 100? The number 1 moves two places to the right of the decimal point to be 0.01. In standard form this is 1×10^{-2}.

standard form	O	.	t	h	th	Tth	Hth	milliionth
1×10^{-1}	0	.	1					
1×10^{-2}	0	.	0	1				
1×10^{-3}	0	.	0	0	1			
1×10^{-4}	0	.	0	0	0	1		
1×10^{-5}	0	.	0	0	0	0	1	
1×10^{-6}	0	.	0	0	0	0	0	1

3 Write 0.000 000 000 000 000 001 in standard form.

4 Write out the number 1×10^{-9}.

Working with numbers to standard form

Standard form can also be used to represent numbers where the most significant digit is not one. For example, the ordinary number 6000 can be written as 6×1000, or 6×10^3, in standard form.

Remember that standard form always has exactly one digit bigger than or equal to one but less than 10. 0.3×10^4 is not in standard form. It is 3×10^3 in standard form.

The table gives some big and small numbers.

Distance from Earth to the Sun (m)	Speed of light (m/s)	Atomic radius (m)	Nuclear radius (m)	Mass of a gold atom (g)
1.5×10^{11}	3×10^8	1×10^{-10}	1×10^{-14}	3.3×10^{-22}

When you calculate with big and small numbers using a calculator it is essential that you first estimate what your answer should look like. Making an estimate of the result of the calculation can save you from making mistakes with your calculator. The best way to estimate the answer without a calculator is to round the numbers sensibly and then carry out the calculation in your head.

5 Calculate:

a) $6 \times 10^9 \times 3 \times 10^3$

b) $6 \times 10^9 \times 4 \times 10^{-2}$

c) $\dfrac{6 \times 10^8}{2 \times 10^2}$.

6 Convert the distance from Earth to the Sun from metres to kilometres.

7 Calculate the mass of 3.0×10^{26} gold atoms using the mass of a single gold atom given in the data table.

KEY INFORMATION

To multiply two numbers in standard form you simply add the indices or powers of the tens. For example, $2 \times 10^{15} \times 3 \times 10^9$ is 2×3 with 10^{15+9}, which is 6×10^{24}. With smaller numbers $2 \times 10^{-15} \times 3 \times 10^{-9}$ is 6×10^{-24}.

1.2d Sub-atomic particles

Learning objectives:

- interpret and draw diagrams of the structure of atoms
- recall that the radius of a nucleus is less than 1/10 000 that of the atom (about 1×10^{-14} m)
- recall the relative charges and masses of protons, neutrons and electrons
- calculate the number of protons, neutrons and electrons in atoms.

KEY WORDS

atomic number
electron
neutral
neutron
proton
relative mass
relative charge

Using expressions in standard form helps us to understand the very small size of atoms. When we compare atoms and sub-atomic particles, it can be easier to use relative masses and charges, rather than the actual values.

Structure of atoms

We saw how ideas about the structure of atoms developed in topic 1.2a. Currently, scientists believe that an atom is made up of a tiny nucleus that is surrounded by **electrons** occupying a larger space.

- The nucleus carries a positive charge.
- The electrons that surround the nucleus each carry a negative charge.

The nucleus of an atom is made up of protons and neutrons.

- **Protons** have a positive charge.
- **Neutrons** have no charge.

An atom always has the same number of protons (+) as electrons (–) so atoms are always **neutral**.

The **atomic number** is the number of protons in an atom. The atomic number for helium is 2 because it has two protons. Sometimes the atomic number is called the proton number.

All the atoms of a particular element have the same number of protons. Atoms of different elements have different numbers of protons.

1. **What type of charge does an electron carry?**
2. **Why is the charge on an atom neutral?**
3. **An atom of calcium has 20 protons. How many electrons are in a calcium atom?**

KEY INFORMATION

The word 'particle' is used in science to describe a tiny unit of matter. Sometimes this can mean atoms, as in the particle model (see topic 1.1a), and sometimes units that are even smaller, such as sub-atomic particles.

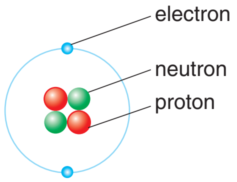


Figure 1.2.7 The structure of a helium atom. There are the same number of protons and electrons. Please note that this diagram is not drawn to scale

Link: 1.2d ⟶ 1.2e

Comparing sub-atomic particles

The nucleus of an atom is made up of particles (protons and neutrons) that are very much heavier than electrons. The nucleus contains almost all the mass of the atom and the electrons contribute very little.

The **relative masses** and **relative charges** of electrons, protons and neutrons are shown in the table. These are the masses and charges compared to the mass and charge of the proton.

Name of particle	Relative mass	Relative charge
proton	1	+1
neutron	1	0
electron	very small	–1

The radius of a nucleus is less than one ten-thousandth of the radius of the atom (about 1×10^{-14} m).

4 **A fluorine atom has 9 positive charges, 9 negative charges and a mass of 19. Describe the structure of its atom.**

5 **A chlorine atom has 17 electrons and a mass of 35. Describe the structure of its atom.**

6 **Explain why the radius of the nucleus is much smaller than the radius of the whole atom.**

DID YOU KNOW?

Electrons have such a small relative mass that it is usually treated as zero.

Atomic number and mass number

The nucleus of an atom is made up of protons and neutrons.

- The atomic number is the number of protons in an atom.
- The mass number of an atom is the total number of protons and neutrons in an atom.

If an atom has an atomic number of 11, a mass number of 23 and a neutral charge, it must have:

- 11 protons, because it has an atomic number of 11
- 11 electrons, because there are 11 protons and the atom is neutral
- 12 neutrons, because the mass number is 23 and there are already 11 protons (23 – 11 = 12).

Here are some more examples.

	Atomic number	Mass number	Number of protons	Number of electrons	Number of neutrons
carbon	6	12	6	6	6
fluorine	9	19	9	9	10
sodium	11	23	11	11	12
aluminium					

7 **Copy the table and complete the row for an atom of aluminium, Al.**

8 **How many protons, electrons and neutrons are there in an atom with an atomic number of 15 and a mass number of 31?**

MATHS SKILLS

1.2e Sizes of particles and orders of magnitude

Learning objectives:

- identify the scale of measurements of length
- explain the conversion of small lengths to metres
- explain the relative sizes of nuclei and atoms
- make order of magnitude calculations.

KEY WORDS

nanometre
order of magnitude
scale

All sub-atomic particles are so small that we use numbers in standard form to describe them. We can also compare them to other objects using orders of magnitude.

Scale of objects

Placing a tennis ball, golf ball, basketball and table tennis ball in order of size is easy.

unit	basketball	tennis ball	golf ball	table tennis ball
cm	25.0	6.8	4.1	4.0
m	0.25	0.068	0.041	0.04

Figure 1.2.8 It is easy to put these in order of diameter

We can measure objects smaller than these in millimetres.

1 m = 1000 mm   1 mm = 0.001 m   or   1 mm = 10^{-3} m

We can even see objects in the next set of smaller units, the *micrometre*. We measure the width of a human hair in this unit.

1 m = 1000000 μm   1 μm = 0.000001 m   or   1 μm = 10^{-6} m

After that we need instruments to help us see and measure lengths. Atoms and small molecules are on the 'nano-scale'. The unit is the **nanometre**.

1 m = 1 000 000 000 nm   1 nm = 0.000000001 m or
1 nm = 10^{-9} m

MATHS

1 cm = 0.01 m is the long way to write the conversion.
1 cm = 10^{-2} m is the conversion into *standard form*.

1. **Calculate the number of basketballs that would fit in a kilometre.**
2. **A carbon nanotube has a length of 2×10^{-9} m. Calculate the number of nanotubes that would fit in 1 mm.**

Atoms and sub-atomic particles

Going one step further down into the atomic scale:

- the radius of an atom is measured in *picometres* (pm), 10^{-12} m
- the radius of a nucleus is measured in *femtometres* (fm), 10^{-15} m

Link: 1.2e ⟶ 1.2f

Why is the radius of a nucleus so much smaller than the radius of an atom?

Between the nucleus and the electrons of the atom there is mostly empty space, so neutrons and protons have radii measured in femtometres (fm).

3 **The hydrogen atom has a radius of 2.5×10^{-11} m and its nucleus a radius of 1.75×10^{-15} m. Calculate how many times larger the atom is compared to the nucleus.**

4 **What is a radius of 0.000000000001 m in standard form?**

Order of magnitude

Two numbers that have the same **order of magnitude** are about the same size, and are on the same **scale**. If a number is one order of magnitude larger than another, it is 10 times bigger. If two numbers differ by two orders of magnitude, then one is 100 times larger than the other.

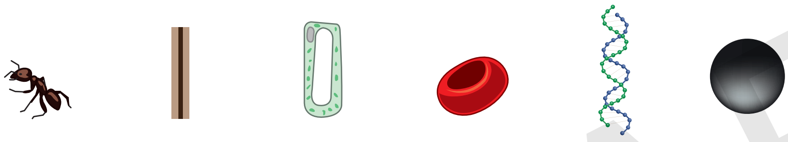


Figure 1.2.9 Size and scale

When comparing sizes, scientists often refer to differences in order of magnitude. That's the difference calculated in powers of 10.

So, to find the difference in order of magnitude between an ant and a carbon atom:

The ant is 3 mm in length = 3×10^{-3} m.

The carbon atom has a diameter of 0.3 nm = 3×10^{-10} m.

$$\frac{3 \times 10^{-3}\,\text{nm}}{3 \times 10^{-10}\,\text{nm}} = 1 \times 10^{7}$$

The difference in order of magnitude is 10^7, expressed as 7 orders of magnitude.

5 **What is the order of magnitude difference between 0.5 m and 500 000 m?**

6 **A white blood cell measures 1.2×10^{-5} m. An egg cell measures 1.2×10^{-4} m. Calculate the difference in order of magnitude.**

KEY INFORMATION

These measurements are within the 'human' scale from:

- **the diameter of a human hair to the diameter of a water droplet 10^{-6} m to 10^{-3} m**
- **the diameter of a pin-head to the diameter of a basketball 10^{-3} m to 10^{-1} m**
- **the length of a car to the height of the Shard building, London 1 m to 10^{3} m**
- **the height of Ben Nevis to the length of the Great Wall of China 10^{3} m to 10^{6} m.**

After that we measure on an 'astronomical' scale.

Ratio between values	Order of magnitude difference
0.0001	10^{-4}
0.001	10^{-3}
0.01	10^{-2}
0.1	10^{-1}
1	10^{0}
10	10^{1}
100	10^{2}
1000	10^{3}
10000	10^{4}

1.2f Isotopes

Learning objectives:

- recognise that atoms of the same element can have different masses because they have different numbers of neutrons
- calculate the number of protons, neutrons and electrons in isotopes
- interpret symbols representing the mass number and atomic number of an atom.

KEY WORDS

isotope
symbol

All atoms of an element have the same number of protons and the same number of electrons, but they do not all have the same number of neutrons. Chlorine has some atoms with mass number 35 and some with mass number 37, but they all have the same chemical properties.

Explaining isotopes

Most elements can exist in more than one form. These have the same atomic number, otherwise you'd have a different element, but they have different mass numbers. These different forms are called **isotopes**.

Carbon is a very common element that has different isotopes. *All* carbon atoms have 6 protons, so carbon's atomic number is 6. The left-hand carbon atom in Figure 1.2.10 has 6 neutrons, so it has a mass number of 6 + 6 = 12.

Another form of carbon (on the right in Figure 1.2.10) has an atomic number of 6 (6 protons) and a mass number of 14. It must therefore have 8 neutrons (14 – 6 = 8).

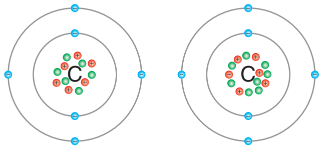


Figure 1.2.10 Two different isotopes of carbon. The letter in the centre of this kind of diagram represents the element

1. **What is an isotope?**
2. **Lithium has an atomic number of 3. There are two isotopes of lithium, one with a mass number of 6 and one with a mass number of 7.**

   Describe the difference in number of protons and number of neutrons between the two isotopes.

Using symbols to represent atoms

Atoms can be represented by the chemical **symbol** for the element together with the atomic number and mass number. The atomic number is the number of protons in the atom.

Using this notation, lithium-3 is:

mass number $^{7}_{3}Li$
atomic number

Link: 1.2f ⟶ 1.2g

For a general atom we can use the symbol $^{A}_{Z}X$, where:

- *A* is the mass number
- *Z* is the atomic number (or proton number)
- X is the chemical symbol for the element.

Z is the number of protons in the nucleus, so the number of neutrons is (*A* – *Z*).

$^{14}_{6}C$ has a mass number of 14. So the sum of the neutrons and protons in its nucleus is 14. The atomic number is 6, so it has 6 protons. The number of neutrons in the nucleus is 14 – 6 = 8 neutrons.

3 **How many protons and neutrons are in the nucleus of each of the isotopes of nitrogen, $^{14}_{7}N$ and $^{15}_{7}N$?**

4 **How many protons and neutrons are in the nucleus of each of the isotopes of uranium $^{235}_{92}U$ and $^{238}_{92}U$?**

Identifying patterns

Most elements have two or more isotopes. The oxygen you breathe is mostly $^{16}_{8}O$, but there is also $^{17}_{8}O$, and $^{18}_{8}O$. All do the same chemical job in your body!

The table below shows the three common isotopes of hydrogen.

Isotope	Electrons	Protons	Neutrons	Mass number
$^{1}_{1}H$	1	1	0	1
$^{2}_{1}H$	1	1	1	2
$^{3}_{1}H$	1	1	2	3

DID YOU KNOW?

A radioactive isotope of oxygen is used as a medical tracer in PET scans. The patient breathes in oxygen-15. Oxygen is used in respiration in the brain, so by recording where this isotope is present in the brain, the PET scan shows which areas are respiring the most.

5 **Explain the similarities and differences between the three isotopes of hydrogen.**

6 **What pattern, if any, is noted between:**

a **the atomic number, the number of protons and the number of electrons in any element?**

b **the atomic number, the number of protons and the number of neutrons in any element?**

1.2g Electrons in atoms

Learning objectives:

- recall that in atoms with more than one electron, the electrons are arranged at different distances from the nucleus
- recognise that the energy associated with an electron shell increases with distance from the nucleus
- explain how electrons occupy shells in an order.

KEY WORDS

electronic structure
electron shell

Isotopes of the same element are different because they have different numbers of neutrons. Neutrons have no charge – they are neutral. The number of protons is the same for all isotopes of an element, so the number of electrons is also constant. The number of electrons balances the number of protons.

Electron shells

The protons and neutrons are fixed in the nucleus, and do not move. Overall, the nucleus has a positive charge. Orbiting the nucleus are electrons, which have a negative charge. The number of electrons equals the number of protons in any stable atom.

Electrons move around the nucleus in 'shells' at different distances from the nucleus. The space between the nucleus and the **electron shells** is empty space.

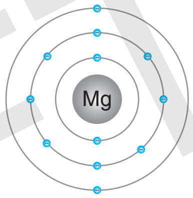


Figure 1.2.11 Electrons orbit in shells around the nucleus. In this type of diagram, the symbol for the element is given in the nucleus at the centre

1. **What is between the nucleus and the orbiting electrons?**
2. **Explain why the charge on the atom is neutral.**

Electronic structure

The shell closest to the nucleus has the lowest energy. This innermost shell can only hold two electrons. Electrons in an atom occupy the lowest available energy levels first.

Next, the second shell fills with electrons, which holds up to 8 electrons. When this is filled, electrons go into the third shell. The fourth shell starts to fill once there are 8 electrons in the third shell.

Fluorine has 9 electrons. The first two go into the first energy level. As the first shell is now full, the next 7 go into the second shell. This is written using numbers as the **electronic structure** 2,7. Information about the electrons can be written as numbers or drawn in a diagram showing the energy levels.

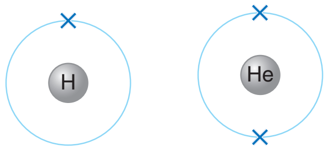


Figure 1.2.12 The structure of the first energy level. In this energy level diagram the electrons are shown by crosses

3. **Figure 1.2.13 shows the electronic structure of phosphorus (P). How many electrons does an atom of phosphorus have?**
4. **Use numbers to write the electronic structure of phosphorus.**

Developing patterns

The table shows the number of electrons in each shell for the first 20 elements in the Periodic Table. The number of electrons goes up by one each time and corresponds to a different element.

Element	Symbol	Number of electrons				
		Shell				Total
		1	2	3	4	
hydrogen	H	1	–	–	–	1
helium	He	2	–	–	–	2
lithium	Li	2	1	–	–	3
beryllium	Be	2	2	–	–	4
boron	B	2	3	–	–	5
carbon	C	2	4	–	–	6
nitrogen	N	2	5	–	–	7
oxygen	O	2	6	–	–	8
fluorine	F	2	7	–	–	9
neon	Ne	2	8	–	–	10
sodium	Na	2	8	1	–	11
magnesium	Mg	2	8	2	–	12
aluminium	Al	2	8	3	–	13
silicon	Si	2	8	4	–	14
phosphorus	P	2	8	5	–	15
sulfur	S	2	8	6	–	16
chlorine	Cl	2	8	7	–	17
argon	Ar	2	8	8	–	18
potassium	K	2	8	8	1	19
calcium	Ca	2	8	8	2	20

Reading across the table shows the electronic structure. For example, the electronic structure of magnesium is 2,8,2.

5. **Use numbers to write the electronic structure of argon.**
6. **Draw the electron shell diagrams for magnesium and argon, using crosses for electrons.**

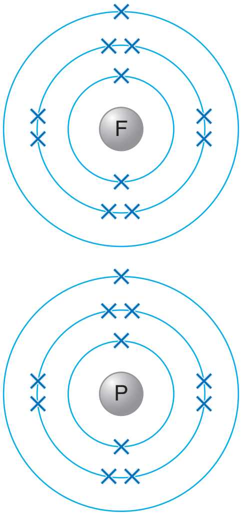


Figure 1.2.13 Electrons in the second and third energy levels. The energy increases as the distance from the nucleus increases

DID YOU KNOW?

It is the electrons of an atom that take part in chemical reactions. The different number of electrons in each shell makes a difference to the reactions that can take place.

Check your progress

You should be able to:

☐ Explain that early models of the atom did not have shells with electrons. ☐ Describe different models of the atom.	☐ Explain that early models of atoms developed as new evidence became available.	☐ Describe what the evidence was that led to the atomic model changing over time.
☐ Recall the size and order of magnitude of atoms and small molecules.	☐ Recognise and interpret expressions in standard form.	☐ Estimate the size of atoms based on diagrams.
☐ Use SI units and the prefix nano.	☐ Convert decimals to standard form and vice versa.	☐ Make estimates without calculators so that the answer in standard form seems reasonable.
☐ Describe the structure of atoms.	☐ Recall that the radius of a nucleus is less than 1/10000 that of the atom (about 1×10^{-14} m).	☐ Explain why atoms are neutral.
☐ Draw a diagram of a small nucleus containing protons and neutrons with orbiting electrons at a distance.	☐ Recall the relative charges and masses of protons, neutrons and electrons.	☐ Represent atoms symbolically showing their atomic information.
☐ Know that elements can differ in mass number due to having different numbers of neutrons.	☐ Calculate the mass number from the numbers of protons and neutrons in the nucleus.	☐ Complete data tables showing the atomic numbers, mass numbers and numbers of sub-atomic particles from symbols.
☐ Recall that in each atom the electrons are arranged at different distances from the nucleus.	☐ Understand that there is an amount of energy associated with each level or shell.	☐ Explain how electrons occupy shells in an order.

Worked example

1 **a What is the atomic number of an element?**

The number of protons.

This is correct, but a better answer would show that you know that the protons are in the nucleus.

b What is the mass number of an element?

Protons plus electrons.

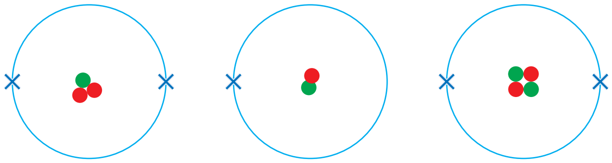
This is incorrect. Electrons have very little mass. The mass number is the number of protons plus the number of neutrons, all in the nucleus.

2 **a What is an isotope?**

Different numbers of neutrons.

This answer could be clearer. Isotopes are atoms of the same element with different numbers of neutrons, but the same number of protons

b Circle which of these are isotopes of the same element.

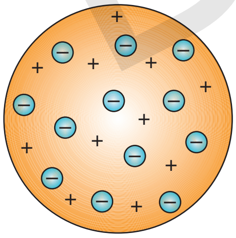


c Explain your reasoning.

Same number of protons, different neutrons.

The orange dots must be the protons, as they balance the number of electrons. The red dots are therefore neutrons, and the first and third diagrams have different numbers of neutrons in the nucleus, but the same number of protons.

3 **a After the discovery of the electron in the early 20th century, the 'plum pudding' model was used to explain the structure of the atom.**



What did scientists think that the 'pudding' part of the atom was?

The positive bit.

It would be more scientific to say that it was a uniform positively charged mass.

b What causes scientists to change a scientific model?

They find new data.

Through experimental enquiry and/or calculations, they find new data, which the previous model does not explain, so they have to adapt the model, or create a new one that does.

End of chapter questions

Getting started

1 Describe the structure of an atom using a diagram. 1 Mark

2 An atom has 3 protons, 4 neutrons and 3 electrons. What is its atomic mass? 1 Mark

a 3

b 6

c 7

d 10

3 What is the relative charge on: 3 Marks

a an electron

b a neutron

c a proton

4 Determine the electron arrangement in an atom with 10 electrons. 1 Mark

5 Write out 1 000 000 in standard form. 1 Mark

6 What is the typical size of the radius of the atom in metres? 1 Mark

7 Describe the Dalton model of the atom. 1 Mark

Going further

8 Define the atomic number of an element. 1 Mark

9 Sodium can be represented by the notation $^{23}_{11}Na$. 1 Mark

What are the numbers 23 and 11 and what do they stand for?

10 What is an isotope? 1 Mark

11 Write out 0.000 000 000 1 in standard form. 1 Mark

12 What discovery led to the Dalton model of the atom being changed? 1 Mark

More challenging

13 Identify the number of electrons in an atom of $^{31}_{15}P$. 1 Mark

14 There are two atoms $^{28}_{14}Si$ and $^{30}_{14}Si$.

Work out how many neutrons each atom contains. 1 Mark

15 Calculate: 2 Marks

a $4 \times 10^3 \times 8 \times 10^6$

b $5 \times 10^8 \times 3 \times 10^{-2}$

Most demanding

16. **Explain how the evidence from Geiger and Marsden's scattering experiment led to the development of the nuclear model of the atom.** 4 Marks

17. **Suggest how a scientific theory becomes accepted.** 3 Marks

18. **Deduce the number of sub-atomic particles that make up the atom $^{31}_{15}P$.** 2 Marks

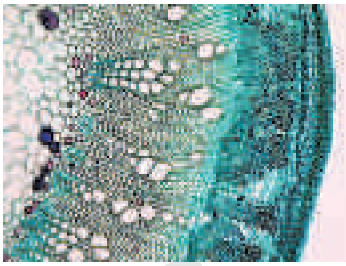
Total: 28 Marks

CELLS IN ANIMALS AND PLANTS

IDEAS YOU HAVE MET BEFORE:

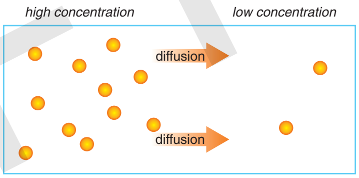
ALL LIVING ORGANISMS ARE MADE OF CELLS.

- Cells are the building blocks of life.
- Cells contain specialised structures.
- Organisms such as bacteria are unicellular.
- Most plants and animals are multicellular.



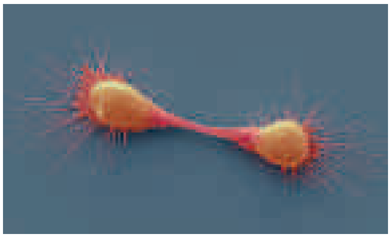
MOLECULES MOVE BY DIFFUSION.

- Diffusion is the net movement of molecules from a higher concentration to a lower concentration until they are equally distributed.
- Different factors can affect the rate of diffusion.
- The steepness of a concentration gradient affects the rate of diffusion.



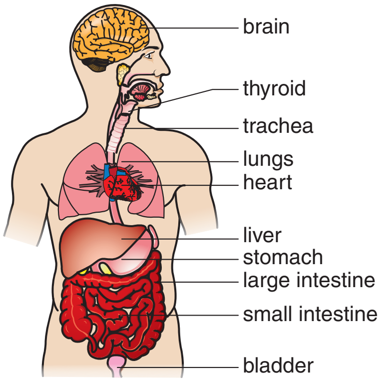
IN MULTICELLULAR ORGANISMS, CELLS HAVE TO DIVIDE.

- Cells divide as we're growing, and to replace cells that are injured, worn out or have died.
- This type of cell division is called mitosis.
- When a cell divides by mitosis, two daughter cells are produced, each with an identical number of chromosomes and identical DNA.



IN MULTICELLULAR ORGANISMS CELLS BECOME SPECIALISED.

- Specialised cells have a particular job to do.
- Specialised cells are organised into tissues, tissues into organs, and organs into body systems.

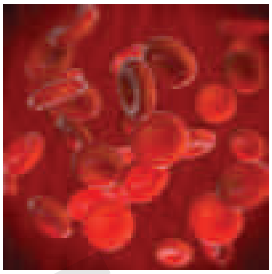


1.3

IN THIS CHAPTER YOU WILL FIND OUT ABOUT:

HOW HAVE SCIENTISTS DEVELOPED THEIR UNDERSTANDING OF CELL STRUCTURE AND FUNCTION?

- The structures inside cells and the jobs they do within the cell.
- The study of cells using different types of microscopes.
- The cells of bacteria, and how they are different to the cells of plants and animals.

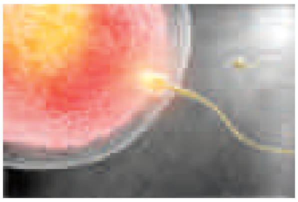


DO ALL MATERIALS MOVE BY DIFFUSION?

- In living tissues, water moves by osmosis from a high concentration of water to a lower concentration of water, across partially permeable membranes.
- The movement of water can affect the turgidity of living cells.
- Some substances that living cells need can be moved against a concentration gradient, by active transport.

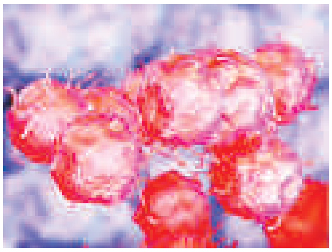
HOW DOES CELL DIVISION PRODUCE CELLS FOR REPRODUCTION?

- In asexual reproduction, only one parent is involved. No sex cells are produced and cells divide by mitosis.
- During sexual reproduction, a cell divides by meiosis to produce four gametes, each with half the number of chromosomes.
- Meiosis ensures that the chromosome number stays constant – 46, or 23 pairs in humans – in each generation.
- Meiosis also produces gametes that are genetically unique, leading to variation between individuals.



HOW DO WE DEVELOP INTO A COMPLEX ORGANISM FROM JUST A FERTILISED EGG CELL?

- How and when the body's cells divide, and that the newly formed cells are identical to the existing cells.
- How cells differentiate to become specialised, and how specialised cells are organised.
- Cells that are unspecialised in the embryo, and cells that remain unspecialised in adults, are called stem cells.



1.3a Electron microscopy

Learning objectives:

- identify the differences in the magnification and resolving power of light and electron microscopes
- explain how electron microscopy has increased our understanding of sub-cellular structures
- carry out calculations involving magnification, real size and image size
- use estimations and make order of magnitude calculations
- use prefixes centi, milli, micro and nano and interconvert units.

KEY WORDS

magnification
micrograph
resolving power
scanning electron microscope (SEM)
transmission electron microscope (TEM)

An electron microscope uses an electron beam to create a highly magnified image of a specimen. Because an electron beam has a much shorter wavelength than visible light, the electron microscope can produce images of much higher resolution than a light microscope.

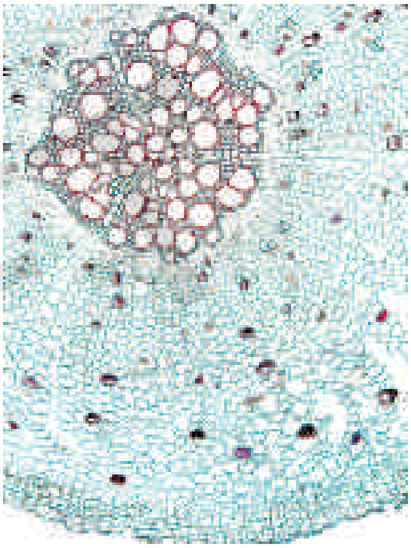


Figure 1.3.1 An image from a light microscope is called a light micrograph. In this light micrograph of a cross-section of a plant root, the magnification is ×100 and coloured dye has been added to show up the details

The light microscope

Microscopes magnify the specimen you are looking at, making it look bigger than it is.

In light microscopes the magnified image is produced by light passing through lenses. Very high magnifications are not possible because the power of the lenses and the amount of light that can enter the microscope are limited. The highest magnification is around ×1500.

Using higher **magnification** does not always mean that you can see greater detail. To see more detail in an image, you need higher **resolving power**, or resolution. At a higher resolution two dots close together can be seen as separate points, when with a lower resolution they would look like a single blob.

The maximum resolving power of a light microscope is around 0.2 mm, or 200 nm. This means that, in a light micrograph, you cannot separately pick out two points closer than 200 nm apart.

1. **What is the maximum resolving power of the light microscope?**
2. **What is the maximum magnification possible with a light microscope?**

Figure 1.3.2 A transmission electron microscope. The electrons are displayed as an image on a fluorescent screen

The electron microscope

An **electron microscope** has a much higher resolving power than a light microscope. This means that it can be used to study cells in much finer detail.

A **transmission electron microscope** (TEM) shoots a beam of electrons through an extremely thin section (slice) of cells. The image is formed by the electrons that pass through the specimen. The highest possible magnification from a TEM is around ×1 000 000. The maximum resolving power is less than 1 nm.

The **scanning electron microscope** (SEM) bounces electrons off the surface of a specimen coated in an ultra-thin layer of a heavy metal – usually gold. A narrow electron beam scans the specimen. Images are formed by the scattered electrons.

SEMs can reveal the surface shape of structures such as small organisms and cells. The resolving power is lower than for a TEM, and magnifications are also often lower.

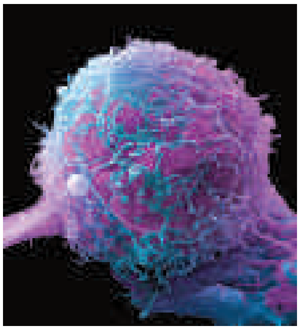


Figure 1.3.3 A scanning electron micrograph of a cancer cell (x4500). Electrons do not have a colour spectrum like the visible light used in a light microscope, so they can only be 'viewed' in black and white. Here, false colours have been added

3. **Estimate how many times greater a TEM's maximum resolving power is compared to that of a light microscope. What order of magnitude is this?**
4. **What types of samples would a TEM and an SEM be used to view?**

HIGHER TIER ONLY

Magnification of images

The magnification of an image is the number of times bigger it is than the object being viewed. Micrograph images must show the magnification to be meaningful.

$$\text{magnification of image} = \frac{\text{size of image}}{\text{size of real object}}$$

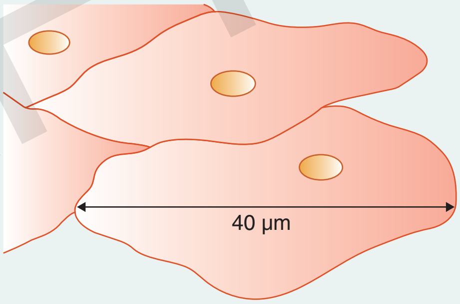


Figure 1.3.4 A drawing of a micrograph of a cell

The cell drawn in Figure 1.3.4 is 50 mm across on the page. In real life it measures 40 µm. To calculate the magnification, the values must all be in the same units. First convert 50 mm into µm (or convert 40 µm to mm).

50 mm = 50 000 µm

The cell measures 40 µm. Therefore:

$$\text{magnification of image} = \frac{50000\ \mu m}{40\ \mu m} = \times 1250$$

5. **In an SEM image of a leaf surface the length of a pore (stoma) was measured as 19.5 mm. If the image magnification was ×1500, calculate the actual length of the pore, in nanometres (nm). Write your answer in standard form (see topic 1.2c).**
6. **A TEM image of a plant cell in a book is 6.0 cm long. The plant cell measures 1.2×10^2 mm long. Calculate the magnification.**
7. **How do you think electron microscopy could improve our understanding of cells?**

COMMON MISCONCEPTIONS

Do not confuse magnification, which is how much bigger we can make something appear, with resolving power, which is the level of detail we can see.
Think about a digital photo. You can make it as big as you like, but at a certain point you will not be able to see any more detail.

1.3b Cell structures

Learning objectives:

- describe the structure of eukaryotic and prokaryotic cells and explain how the sub-cellular structures are related to their functions
- carry out calculations involving magnification, real size and image size including numbers written in standard form
- use estimations and make order of magnitude calculations
- use prefixes centi, milli, micro and nano and interconvert units.

KEY WORDS

cell membrane, cellulose, cell wall, chlorophyll, chloroplast, chromosome, cytoplasm, DNA, eukaryotic, mitochondrion, nucleus, plasmids, prokaryotic, ribosome, vacuole

Unlike light microscopy, electron microscopy reveals fine detail in tiny sub-cellular structures, because of its high resolving power. This has helped us understand how cell structures function and interact.

Eukaryotic cells

Almost all organisms are made up of cells. Plant and animal cells have a basic structure. This type of cell, containing a true nucleus in the cytoplasm, is called a **eukaryotic** cell.

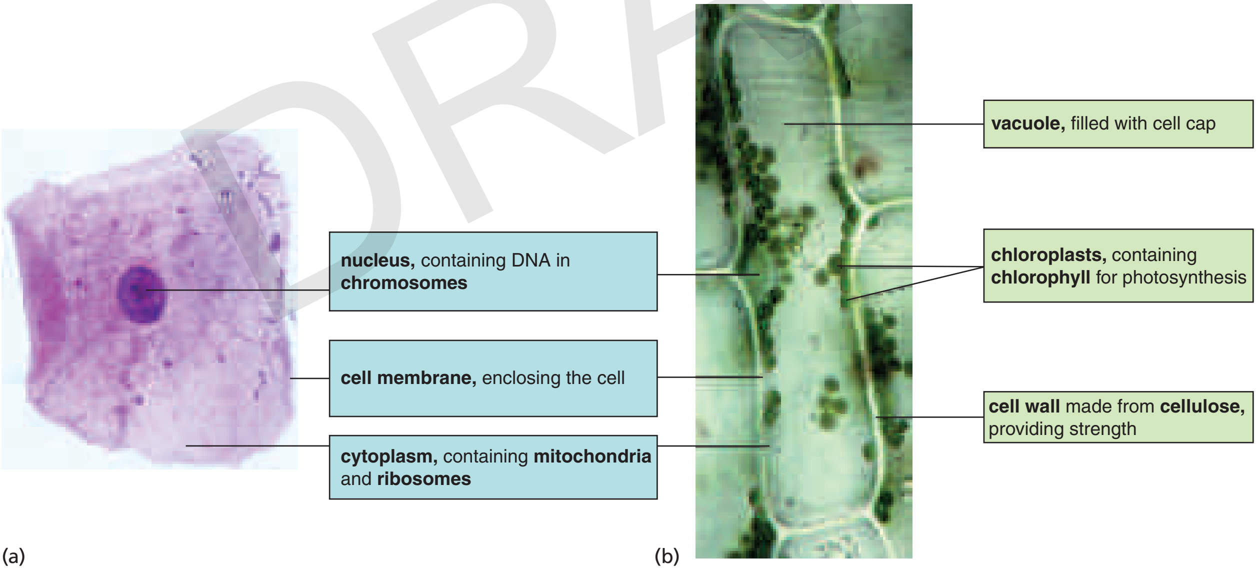


Figure 1.3.5 Light micrographs of (a) a simple animal cell and (b) a plant leaf cell, with colour added to the images

1. **List the sub-cellular structures found in both plant and animal cells.**
2. **Which sub-cellular structures are found only in plant cells?**
3. **What is the function of:**
   - **the nucleus?**
   - **the cell membrane?**
4. **What structure gives strength to a plant cell?**

Prokaryotic cells

Bacteria are among the simplest of living things. Along with bacteria-like organisms called Archaeans, they belong to a group called the Prokaryota. These are single-cell organisms with a **prokaryotic** cell structure.

Prokaryotic cells are much smaller than eukaryotic cells, around 0.1–5.0 μm in diameter. Their **DNA** is not enclosed in a nucleus. It is found as a single molecule in a loop. They may also have one or more small additional rings of DNA called **plasmids**.

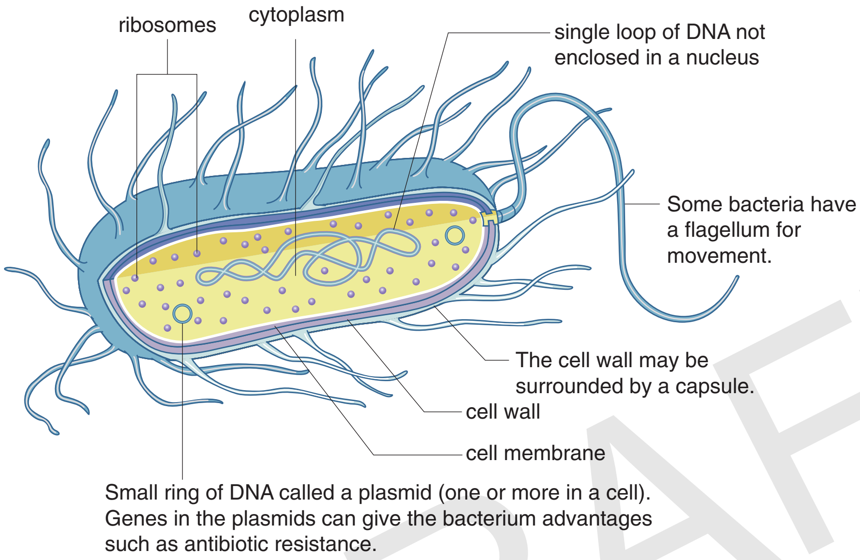


Figure 1.3.6 A diagram to show the structure of a prokaryotic cell

Cell ultrastructure

We can just about see some sub-cellular structures such as mitochondria and chloroplasts with the light microscope, but the electron microscope reveals their internal structure in more detail. Other structures, such as ribosomes, can only be seen using electron microscopes.

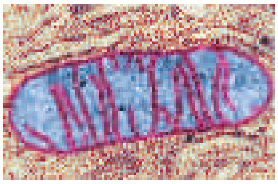
7 **The animal cell in Figure 1.3.5 is about 60 mm across, while the plant cell is about 30 mm wide.**

a **Calculate the magnification of each micrograph in Figure 1.3.5.**

b **How many times larger than a typical prokaryotic cell is the animal cell in Figure 1.3.5? What order of magnitude is this?**

HIGHER TIER ONLY

8 **Use the magnifications given in Figure 1.3.7 to estimate the actual lengths of the mitochondrion and the chloroplast shown. Give your answers in micrometres (mm), and also in nanometres (nm) using standard form (see topic 1.2c).**

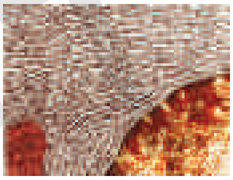


(a)

Mitochondria are where aerobic respiration takes place in the cell. A mitochondrion has a double membrane. The internal membrane is folded.

(b)

Chloroplasts are the structures in the plant cell where photosynthesis takes place. Like mitochondria, they also have a complex internal membrane structure.



(c)

Ribosomes are tiny structures where protein synthesis takes place. You can see them as dots in the micrograph. They can either lie free in the cytoplasm or may be attached to an internal network of channels within the cytoplasm.

Figure 1.3.7 Viewing (a) a mitochondrion, (b) a chloroplast and (c) ribosomes by transmission electron microscopy, with false colour added to show up the details

5 **List the differences between prokaryotic and eukaryotic cells.**

6 **Where is DNA found in prokaryotic cells?**

DID YOU KNOW?

Scientists sometimes investigate the ratio of the area of the cytoplasm to that of the nucleus in micrographs. A high ratio of cytoplasmic : nuclear volume can indicate that the cell is about to divide. A low ratio can be characteristic of a cancer cell.

REQUIRED PRACTICAL

1.3c Observing cells under a light microscope

Learning objectives:

- use appropriate apparatus to record length and area
- use a microscope to make observations of biological specimens and produce labelled scientific drawings
- use estimations to judge the relative size or area of sub-cellular structures
- carry out calculations involving magnification, real size and image size.

KEY WORDS

field of view
scale

These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

Many scientists use electron microscopes to observe fine detail in cells. But much of the microscope work carried out – including in hospital and forensic science labs – is done with the light microscope.

Preparing cells for microscopy

Live cells can be mounted in a drop of water or saline on a microscope slide.

Most cells are colourless. We must stain them to add colour and contrast. In the school laboratory, you may have used methylene blue to stain animal cells or iodine solution to stain plant cells.

Figure 1.3.8 A glass coverslip is carefully lowered onto the cells or tissue, taking care to avoid trapping air bubbles. The coverslip keeps the specimen flat, and retains the liquid under it

1 **Write an equipment list for looking at cheek cells with a microscope. State why each piece of equipment is used.**

2 **Suggest why it's better to mount the cells in saline than in water.**

3 **The micrograph of the frog's blood in Figure 1.3.9 shows red blood cells and two types of white blood cell.**

   a **Label the different types of cell and the cell structures that are visible. Hint: use a photocopy or printout of the page.**

   b **How is the structure of the frog's red blood cells different from that of human red blood cells?**

SAFETY

A risk assessment is required for this practical work.

Some local authorities do not allow students to make cheek cell slides. Where allowed, suitable disinfectant must be provided for the used cotton buds and slides/cover slips.

High and low power

The slide is first viewed with low power. This is because:

- the field of view with high power is small. It would be difficult to locate cells if starting with the high power objective.
- it enables you to see the layout of cells within the tissue.
- it's useful when estimating the numbers of different types of cell on the slide or in a tissue (though here, high power may be needed).

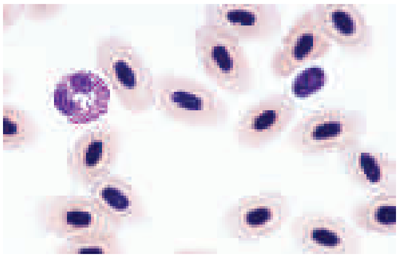


Figure 1.3.9 Blood cells in a frog, stained with false colour

A low power digital image (or drawing) can be used to show the arrangement of cells in a tissue. This includes regions of the tissue but not individual cells.

If required, the cells or tissue can then be viewed with high power to produce a detailed image of a part of the slide.

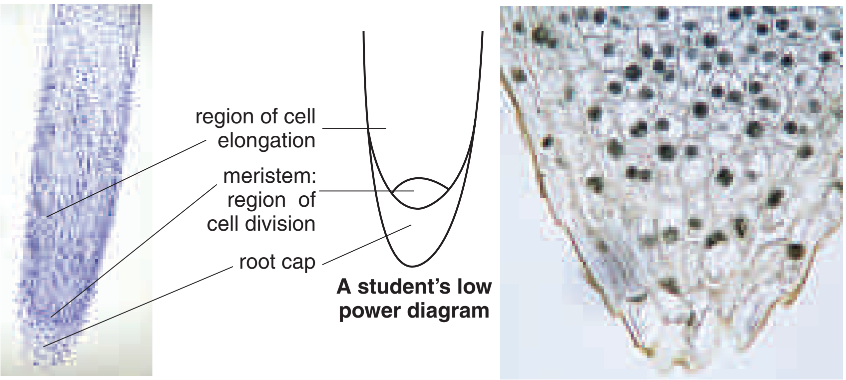


Figure 1.3.10 Low and high power micrographs, with false-colour staining, and a student diagram, of a plant root

DID YOU KNOW?

These slides are temporary. If a permanent slide of cells is required, the cells or tissue must be dehydrated, embedded in wax and cut into thin slices called sections before staining.

4. **Why is a slide viewed with low power first?**
5. **On a printout of the low power plan of the root, label the root cap, meristem (the region of cell division) and the region of cell elongation.**

Recording images

As you have seen in topic 1.3a, a microscope drawing or micrograph is of little value if it gives no indication of size.

It's usual to add a magnification to the image. We can then envisage, or work out, the true size of a specimen.

Alternatively, we can use a **scale bar**. Any scale bar must be:

- drawn for an appropriate dimension
- a sensible size in relation to the image.

Look at Figure 1.3.11. For the top micrograph, the magnification is *x1000*, which means that a 10 *millimetre* scale bar can be drawn to represent 10 *micrometres*.

You will find out how scientists measure, or sometimes estimate, the size of cells in section 1.3d.

6. **Complete the scale bar for the bottom micrograph in Figure 1.3.11.**
7. **Calculate the length of the *Paramecium* in the bottom micrograph.**

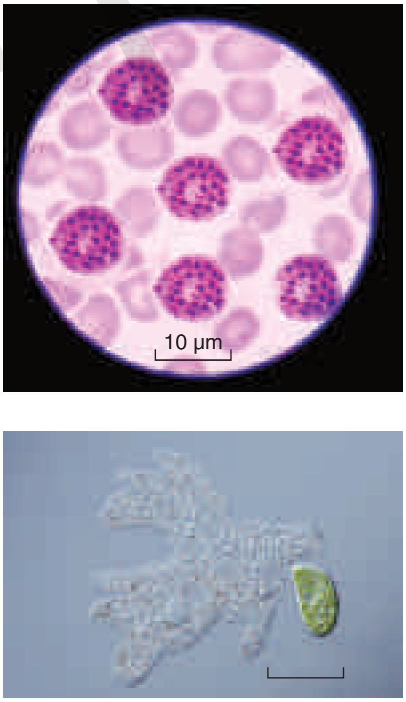


Figure 1.3.11 Light microscopy is also used to examine small organisms such as protists. The top image shows six blood cells infected with the malarial parasite. The bottom image shows two protists found in pond water – *Amoeba* on the left; *Paramecium* on the right (at x200 magnification).

MATHS SKILLS

1.3d Size and number

KEY WORDS

calibrate
graticule
standard form

Learning objectives:

- use appropriate apparatus to record length and area
- recognise and use expressions in decimal and standard form
- use ratios, fractions and percentages
- make estimates for simple calculations.

The sizes of structures are important in biology, from whole organisms to molecules, because their functions depend on their relative sizes. Using microscope images, scientists can estimate the sizes of tiny structures, or measure them accurately.

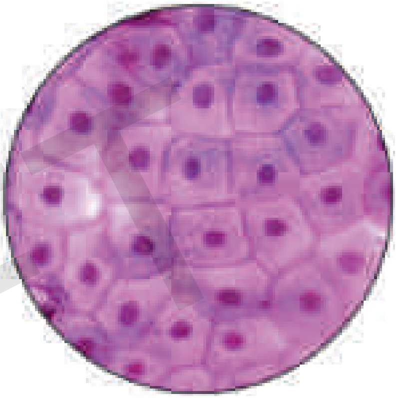


Figure 1.3.12 In this image, *approximately* five cells fit across the field of view. We round numbers up or down to make calculations straightforward

Estimating cell size

Accurate measurements are often essential. But estimating cell size or number is sometimes sufficient and may be quicker.

To estimate cell size, we can count the number of cells that fit across a microscope's field of view.

$$\text{Size of one cell} = \frac{\text{diameter of field of view}}{\text{number of cells that cross this diameter}}$$

If the field of view of this microscope, at this magnification, is 0.3 mm, or 300 μm, we can do a quick calculation without a calculator.

Each cell must be roughly (300 ÷ 5) μm, or 60 μm across. This is an approximation, but could be important.

1. **Suggest how to estimate the field of view of a microscope.**
2. **State one advantage of estimating cell size over exact measurement.**

DID YOU KNOW?

Scientists *estimate* cell or organism numbers when it is impossible or unnecessary to count them all.

Measuring cell size

To make accurate measurements of cell size a scientist **calibrates** their microscope. A **graticule** – piece of glass or plastic onto which a scale has been drawn – is placed into the eyepiece of the microscope.

A stage micrometer is placed on the microscope stage. This is simply a microscope slide onto which an accurate scale has been etched.

In Figure 1.3.13, 36 divisions on the eyepiece graticule are equivalent to 100 μm on the stage micrometer:
1 division is equivalent to $\frac{1}{36} \times 100\ \mu m = 2.8\ \mu m$

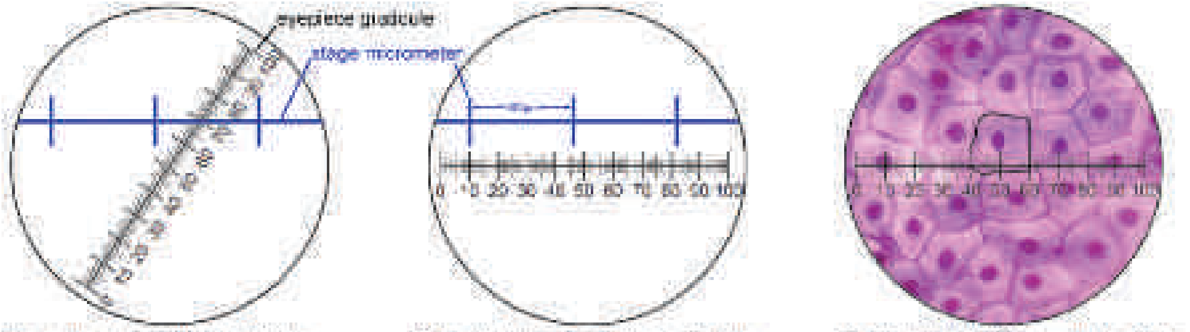
REMEMBER!

The decimal point remains fixed. It is the digits that move as a number is multiplied or divided by powers of 10. So, as a number gets larger, the digits move to the left (and vice versa).

The cell highlighted in the right-hand diagram is 20 eyepiece divisions across: the width of the cell = (20 × 2.8) μm = 56 μm

3 **What would be the diameter of a cell that was 65 divisions on this graticule?**

4 **How many graticule divisions would a cell that was 35 μm across take up?**



The graticule is enclosed within the eyepiece. A stage micrometer is placed on the stage of the microscope

The divisions on the eyepiece graticule and stage micrometer are lined up

The calibrated eyepiece graticule can be used to make measurements of any cells or other structures viewed with that microscope

Figure 1.3.13 Calibrating, then using an eyepiece graticule

Working with numbers in standard form

We can convert measurements in units of mm or μm to sizes in metres expressed in standard form. This makes it easier to compare sizes.

The table gives the sizes of some types of white blood cell in metres, written in standard form. A large capillary (a type of blood vessel) is about 40 μm across. Estimate how many small lymphocytes could fit side by side across a large capillary.

1 μm = 0.000 001 m = 1×10^{-6} m

40 μm = $40 \times (1 \times 10^{-6})$ m = 4.0×10^{-5} m

So the capillary is 4.0×10^{-5} m wide.

Dividing the capillary width by the width of the lymphocyte:

number of lymphocytes = 4.0×10^{-5} m / 7.5×10^{-6} m

= $(4.4 \div 7.5) \times 10^{-5} - (-6)$

= 0.53×101

= 5.3

So about 5 lymphocytes could fit across the capillary

Blood cell type	Width of an average cell (m)
Lymphocyte (small)	7.5×10^{-6}
Macrophage	5.0×10^{-5}
Megakaryocyte	1.5×10^{-4}
Neutrophil	1.2×10^{-5}

REMEMBER!

When you are working with numbers in standard form:
- **multiply – multiply numbers and add powers**
- **divide – divide numbers and subtract powers.**

5 **Look at the table of cell sizes. Arrange the cell types in descending order of size. (You do not need to memorise the names of the cells shown here.)**

6 **How many times larger is a megakaryocyte than a lymphocyte?**

1.3e Diffusion into and out of cells

Learning objectives:

- explain how substances are transported into and out of cells by diffusion
- identify the factors that affect rate of diffusion
- explain what the term 'partially permeable membrane' means.

KEY WORDS

concentration gradient
diffusion
partially permeable membrane

Living cells constantly need to take in important substances and get rid of other substances that may be harmful. Some of these substances move across the cell membrane by diffusion.

Diffusion in living systems

Diffusion is a spreading out and mixing process. It is sometimes called **passive transport**. This is because it happens due to the **random** motion of particles. No extra energy is required.

All that is needed for diffusion to happen is a **concentration gradient**. In diffusion, there is a net movement of particles from a region where they are in higher concentration to a region where their concentration is lower, due to the random movement of particles. Diffusion continues until the concentration is the same in both regions.

Cells are made largely of water containing many dissolved substances. These substances and water enter and leave the cells through cell membranes. Cell membranes allow some particles through, but block others. They are called **partially permeable membranes** (or selectively permeable membranes). Diffusion can occur across a partially permeable membrane, but it can also happen without any membrane separating the regions.

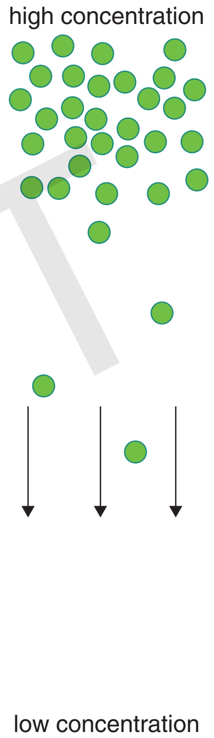


Figure 1.3.14 This diagram illustrates a concentration gradient, showing the net movement of particles from a higher concentration to a lower concentration

1. **Why is diffusion into and out of cells also called passive transport?**
2. **Why does diffusion stop when the concentration in both regions is the same?**

Factors affecting diffusion

Factors that affect the rate of diffusion across a membrane are:

- the **concentration gradient** – the difference in the concentrations of a substance on each side of the membrane
- the **temperature** – the higher the temperature, the higher the rate of diffusion, because the particles have more energy and their random movements are therefore greater

Link: 1.3e ⟶ 1.3f

- the **surface area of the membrane** – the greater the membrane's surface area, the higher the rate of diffusion.

3 **What effect do you think increasing the concentration gradient will have on the speed of diffusion?**

4 **Why do you think a larger surface area of membrane means a higher rate of diffusion?**

Diffusion and cells

Cells need continual supplies of dissolved substances such as oxygen and glucose for cellular activities. Waste products such as carbon dioxide need to be removed. To enter or leave a cell by diffusion, dissolved substances have to be small enough to pass through the partially permeable cell membrane.

Cell membranes are a bit like football nets. Large footballs cannot pass through the netting, but small golf balls easily pass through. In the same way, large molecules, for example starch, cannot pass through the cell membrane. However, small glucose molecules can easily pass through cell membranes. Because cell membranes are very thin, some substances can easily diffuse through them.

5 **Explain how glucose molecules pass in and out of cells. Use a diagram to help you.**

6 **Will diffusion ever stop completely? Explain your answer.**

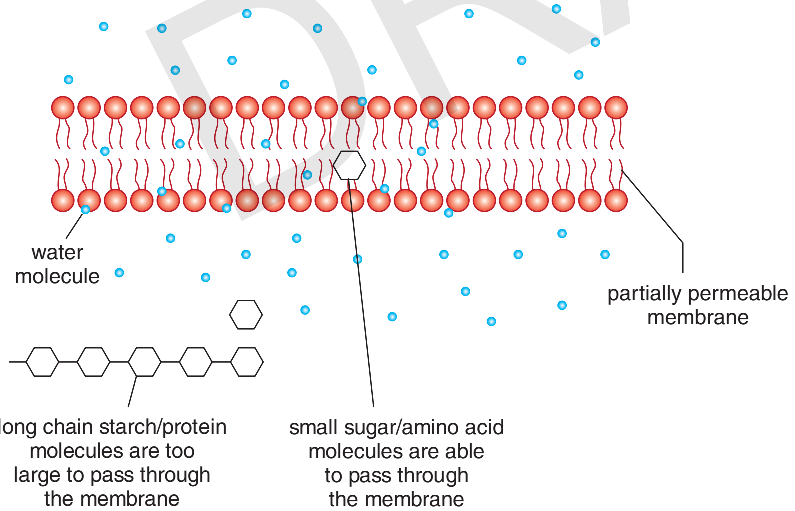


Figure 1.3.15 A cell membrane model. What is happening to the particles?

1.3f Osmosis

Learning objectives:

- describe how water moves by osmosis in living tissues
- identify factors that affect the rate of osmosis.

KEY WORDS

flaccid
osmosis
plasmolysis
solute
solvent
turgid

Water moves across cell membranes by a special kind of diffusion called osmosis. Cell membranes are partially permeable – they allow small molecules such as water through but not larger molecules.

The diffusion of water

A solution consists of a **solvent,** such as water, and a dissolved substance called a **solute,** such as sugar. A dilute solution has a high water concentration, and a low solute concentration. A more concentrated solution has a lower water concentration, and a higher solute concentration.

Osmosis is the diffusion of water molecules from a dilute solution to a more concentrated solution across a partially permeable membrane. Most solute particles are too large to pass through the tiny holes in a partially permeable membrane, but water molecules can pass through.

1 Cell membranes are partially permeable. How does water move in and out of living cells?

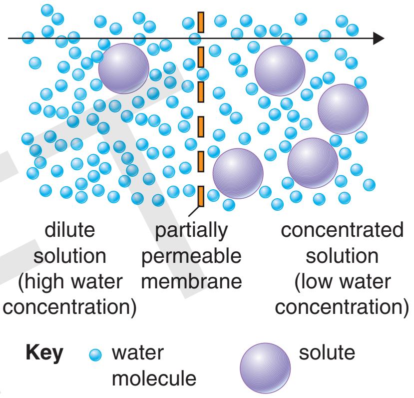


Figure 1.3.16 Osmosis is the net movement of water molecules from a dilute solution to a more concentrated one, across a partially permeable membrane

Osmosis and cells

Look at Figure 1.3.17, which shows model 'cells'. The partially permeable membrane bags represent cell membranes.

In (a) the cell has a concentrated solution. Water molecules enter by osmosis from the surrounding dilute solution.

In (b) the cell has a dilute solution. Water molecules move out to the surrounding concentrated solution.

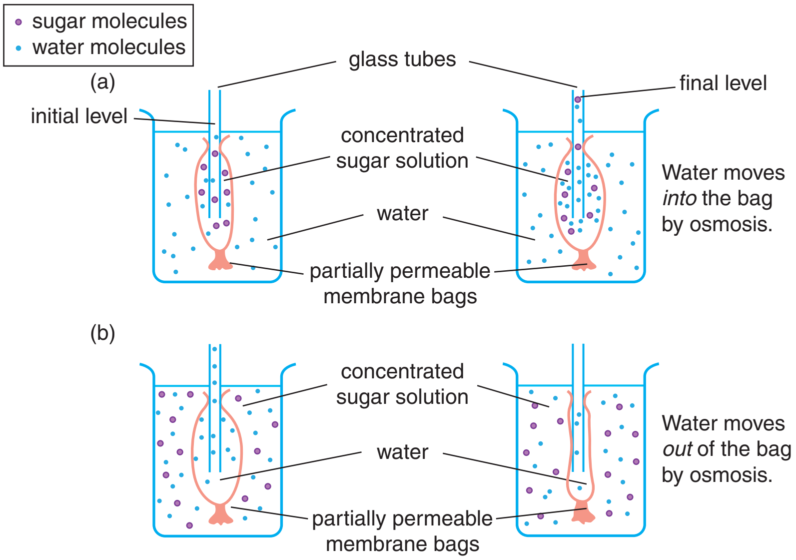


Figure 1.3.17 Model cells can be used to investigate osmosis

Living cells must balance their water content to work efficiently. Chemical reactions in cells use water. If the cytoplasm becomes concentrated, water enters by osmosis. If the cytoplasm becomes too dilute, water leaves the cell by osmosis.

Problems occur in animal cells when the external solution is more dilute than that inside the cell. Water enters; the cells swell and may burst.

When the external solution is more concentrated than that inside the cell, water moves out by osmosis. The cell shrinks and shrivels.

Plant cells have inelastic cell walls. Water enters the cell by osmosis and fills the vacuole. This pushes against the cell wall, making the cell swollen, or **turgid.**

If water moves out the cell by osmosis, the vacuole shrinks and the cell becomes floppy, or **flaccid.**

If too much water leaves the cell, the cytoplasm shrinks and moves away from the cell wall.

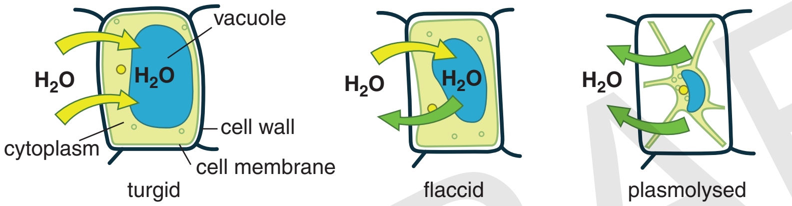


Figure 1.3.19 Movement of water in plant cells placed in a dilute solution, a more concentrated solution and a very concentrated solution

2 **How are osmosis and diffusion similar and different?**

3 **Describe how osmosis can affect plant cells.**

4 **Describe how osmosis affects animal cells.**

Explaining osmosis

Water molecules and sugar molecules in a solution move around randomly. When a sugar molecule hits the membrane, it bounces away. When a water molecule hits the membrane, it can pass through a hole to the other side.

In Figure 1.3.20, there are more water molecules on the left, so more water molecules can pass through the membrane to the right-hand side than can pass in the opposite direction. The water molecules move both ways, but the *net movement* is from left to right.

5 **Explain why there are differences in the effects of water on plant and animal cells.**

6 **Explain osmosis.**

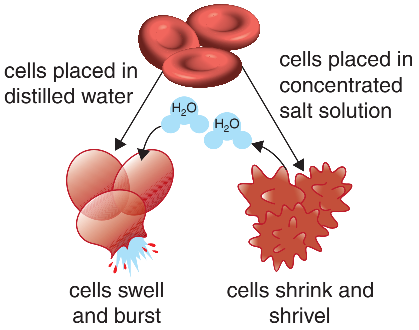


Figure 1.3.18 What happens when red blood cells are placed in a very dilute or a very concentrated solution.

REMEMBER!

Osmosis is only the movement of water across a partially permeable membrane. No other molecules move by osmosis.

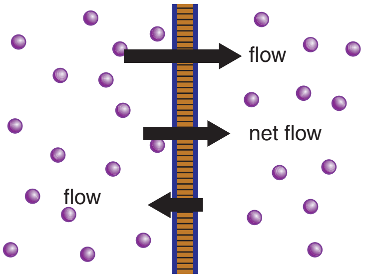


Figure 1.3.20 Water particles move both ways across the membrane. Note that for simplicity the sugar molecules are not shown in this diagram. The concentration of sugar is higher on the right of the membrane than on the left

REQUIRED PRACTICAL

1.3g Investigating osmosis

Learning objectives:

- use scientific ideas to develop a hypothesis
- plan experiments to test a hypothesis
- draw conclusions from data and compare these with hypotheses made.

KEY WORDS

osmosis
partially permeable membrane
plasmolysis

A concentration gradient between the solutions inside and outside a cell means that water moves by osmosis from the more dilute solution to the more concentrated solution. As a result, the cell either gains or loses mass. In plant tissue, where cell walls prevent the cells bursting or collapsing, we can measure the mass changes quite easily and investigate how they depend on the concentration of the outside solution.

These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

Developing a hypothesis

Gill and Aidan are going to investigate the effect of putting some onion cells into water and some into salt solution. They will examine the cells through a microscope. If the cell is short of water the cytoplasm comes away from the cell wall. It is said to be **plasmolysed**.

Before they do the investigation they are going to produce a hypothesis. Hypotheses need to be developed using previous knowledge or observations. They know that:

- the concentration gradient between the solutions inside and outside a cell causes water to move by **osmosis**
- water moves towards a higher solute concentration through a **partially permeable membrane**
- the salt solution is more concentrated than the cytoplasm in the onion cells.

1. **When the onion cells are put in water, how will the concentration inside the cell compare with that outside?**
2. **When the cells are put into salt solution, how will the concentration inside the cell compare with that outside?**
3. **When the cells are put into salt solution, in which direction will the water move?**
4. **Suggest a hypothesis for the experiment that Gill and Aidan are about to do.**

SAFETY

A risk assessment is required for this practical work.

Link: 1.3g ⟶ 1.3h

Planning an investigation

Lily and Ahmed investigated the effect of a range of salt solutions on pieces of potato. They weighed the potato pieces, placed them in salt solutions of various concentrations for 15 minutes and then reweighed them. They used five pieces in each solution. Before they reweighed the potato pieces, they carefully dried them using a paper towel.

SAFETY

A risk assessment is required for this practical work.

5. **Make a list of apparatus required for this investigation.**
6. **What were the independent and dependent variables in the investigation?**
7. **Why did Lily and Ahmed dry the potato pieces?**
8. **Lily and Ahmed collected these results:**

Concentration of NaCl solution (g/dm^3)	Mean starting mass (g)	Mean final mass (g)	Mean change in mass (g)	Mean percentage change in mass (%)
0.00	15.9	17.0		
9	19.2	20.1		
18	24.1	23.3		
26	20.7	19.2		
35	24.1	22.0		
44	14.9	13.5		

Copy and complete the table by calculating the mean change in mass and mean percentage change in mass of the pieces.

9. **The table shows the mean results for five potato pieces in each solution.**
   - a **Explain how to calculate the mean of five values.**
   - b **Why is it better to use five pieces in each solution and find the mean, rather than just one piece?**
10. **Why do Lily and Ahmed use percentage change in mass?**
11. **Plot a graph of mean percentage change in mass of the potato pieces against concentration of salt solution.**
    - a **Are any of the results anomalous?**
    - b **How should anomalous results be dealt with?**
    - c **Suggest what conclusion Lily and Ahmed can make from this data.**

Evaluating the experiment

Lily and Ahmed had written a hypothesis before they did their experiment. They thought that 'the more concentrated the salt solution was that the potato was put in, the greater the loss of mass would be from the potato'.

12. **Was their hypothesis supported or disproved?**
13. **Explain why they got the result that they did.**
14. **What possible changes would you suggest that Lily and Ahmed make to their experiment, to improve repeatability and accuracy of results and to consider aspects of health and safety?**
15. **Describe in detail how similar apparatus could be used to investigate the rate of water uptake by osmosis in plant tissue. Develop a hypothesis to test, and decide on the dependent, independent and controlled variables. Show your plan to your teacher, and then carry out your investigation. Plot a graph of your results and evaluate your experiment.**

MATHS SKILLS

1.3h The spread of scientific data

Learning objectives:

- be able to calculate means and ranges of data
- be able to use range bars on graphs
- understand how to estimate uncertainty from a set of measurements.

KEY WORDS

estimate
mean
precision
range
range bar
uncertainty

When results are collected, how they are spread out is important. It helps us to make judgements about the quality of the data we have collected. This is important when attempting to identify trends in data.

The spread of data

A person's blood glucose level was measured. The measurement was repeated three times on the same blood sample. The following values were obtained:

6.2 mmol/dm^3 6.1 mmol/dm^3 6.0 mmol/dm^3

If you carry out *any* experiment and then do it again, you often get a slightly different result. This may not be because you've used the equipment wrongly. In any measurement there are always random errors that cause measurements to be vary in unpredictable ways. This is why it's best to repeat measurements and find the mean.

A **mean** reduces the effect of random errors and gives you the best **estimate** of the true value.

The **mean** value of a set of measurements is the sum of the values divided by the number of values:

mean =

$$\frac{6.2\text{ mmol glucose}/\text{dm}^3 + 6.1\text{ mmol glucose}/\text{dm}^3 + 6.0\text{ mmol glucose}/\text{dm}^3}{3}$$

= 6.1 mmol glucose/dm^3

The **range** is a measure of spread. It is calculated as the difference between the largest and smallest values

6.0 – 6.2 mmol/dm^3, or 0.2 mmol/dm^3.

1 **Another set of readings, using a blood sample from a different person, were:**

9.6 mmol/dm^3
9.5 mmol/dm^3
9.8 mmol/dm^3

What is the mean of these values?

2 **What is the range of this set of values?**

The spread of data on graphs

Data that are consistent are said to be **precise**; the narrower the range of a set of data, the higher the degree of **precision**. We can be more confident of conclusions we draw from data with a high degree of precision.

Link: 1.3h ⟶ 1.3i

Estimating uncertainty in data

The **best estimate** of the true value of a quantity is the mean of repeated measurements. When calculating a mean, include all the values for data you have collected, unless you have any anomalous results. Anomalous results are measurements that do not fit into the pattern of the other results. You could check if a result was an anomaly by repeating it. The more repeated readings you take, the better estimate you'll get of the true value. Three to five repeats are often suggested.

The table shows the data collected on the effect of the hormone thyroxine on heart muscle tissue:

Time in minutes	Oxygen uptake, in cm^3 oxygen/g of heart muscle tissue					
	Experiment 1	Experiment 2	Experiment 3	Experiment 4	Experiment 5	Mean
10	3.3	3.9	3.6	3.8	3.9	3.7
20	7.8	8.3	8.0	7.8	8.1	8.0
30	11.7	11.2	11.5	11.6	11.5	11.5
40	14.6	14.8	15.1	14.9	14.6	14.8
50	17.7	17.2	17.5	17.6	17.5	17.5
60	26.7	26.0	26.5	27.4	26.9	

The effect of thyroxine on heart muscle was measured by the oxygen uptake by the cell.

For the data collected after ten minutes:

The mean is 3.7 cm^3 oxygen/g of heart muscle.

The range *about* the *mean* gives an estimate of the level of **uncertainty** in the data collected.

For this set of data, the upper limit is 3.9 cm^3/g; the lower limit 3.3 cm^3/g.

The range is 0.6 cm^3/g. So, according to our data, the true value could be up to 0.3 cm^3/g above the mean, or 0.3 cm^3/g below the mean.

Uncertainty is therefore calculated by:

$$\text{uncertainty} = \frac{\text{upper limit of range} - \text{lower limit of range}}{2}$$

So, as we have seen above, uncertainty $= \frac{3.9 - 3.3}{2} = \frac{0.6}{2} = 0.3$

Uncertainty is written next to the mean. In this instance, it is:

3.7 cm^3/g ± 0.3 cm^3/g

Note that the units are written *both* after the mean and value of uncertainty. The value of uncertainty has the same units and number of decimal places as the measurements.

3. **Calculate the mean for the set of data collected at 60 minutes.**
4. **Calculate the uncertainty in these measurements.**

1.3i Active transport

KEY WORDS

active transport

Learning objectives:

- describe active transport
- explain how active transport is different from diffusion and osmosis
- explain why active transport is important.

Diffusion and osmosis explain how gases and water move down a concentration gradient to enter (and sometimes exit) living things. Minerals are taken up into the root hair cells of a plant by another method.

Active transport

Cells can absorb substances that are at low concentration in their surroundings by **active transport**. These substances move *against* the concentration gradient, for example when plants absorb nitrate ions through their root hairs from the soil water. The concentration of nitrate ions in soil water is usually less than the concentration of nitrate ions inside the root hair cells.

Nitrate ions naturally diffuse down their concentration gradient, out of the cell and into the soil, but plants transport the nitrates *into* their cells using active transport.

Active transport moves substances from a more dilute solution to a more concentrated solution (against a concentration gradient). This requires energy from respiration.

KEY INFORMATION

Ions are charged atoms or molecules; see topic 5.1.

1. **Describe how minerals are absorbed by plants.**
2. **How is active transport different to diffusion and osmosis?**

Active transport and respiration

Investigations have shown that a plant can absorb different minerals in different amounts. The plant can select which minerals it needs. Look at the graph. Algae absorb a lot of chloride, but only a little calcium in comparison.

In 1938, scientists discovered that an increase in mineral uptake by a plant happened at the same time as an increase in its respiration rate. This gives evidence that the process needs energy – because the minerals are absorbed against the concentration gradient.

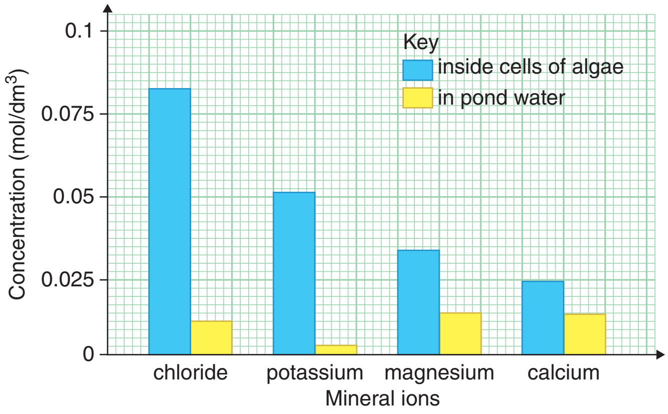


Figure 1.3.21 What does the graph show?

The greater the rate of cellular respiration, the more energy is available for active transport to happen.

Different cells use active transport for different purposes:

- The villi in the small intestine absorb glucose and amino acids into the blood, where they may already be in high concentration – after a meal, for example.
- Marine fish have cells in their gills that can pump salt back into the salty sea water.
- Cells in the thyroid gland take in iodine to use in the production of hormones.
- Cells in the kidney reabsorb sodium ions from urine.
- Crocodiles have salt glands in their tongues that remove excess salt from their bodies.

3 Suggest why cells that use active transport need to carry out this process.

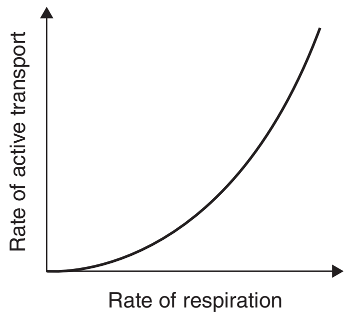


Figure 1.3.22 Explain the relationship between active transport and respiration

KEY INFORMATION

Active transport needs energy from respiration to move substances from a low concentration to a high concentration.

How does active transport work?

Look at the diagram. Special carrier molecules take mineral ions and other substances across the cell membrane. Different carriers take different substances. A carrier that moves glucose will not move calcium ions.

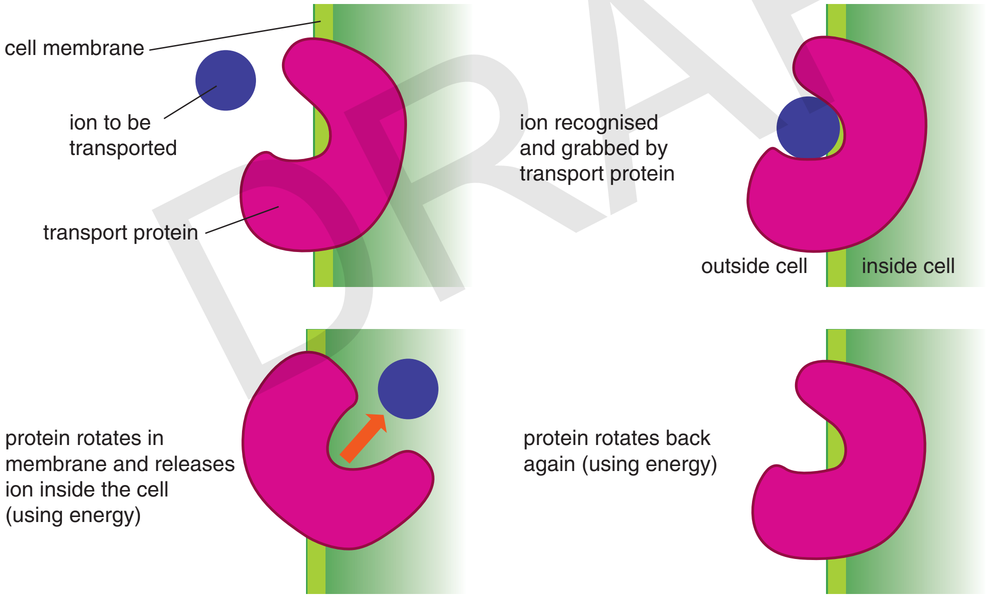


Figure 1.3.23 Each carrier molecule is specific to a certain mineral ion

4 Describe how ions are transported across a membrane in active transport.

5 Explain the similarities and differences between diffusion, osmosis and active transport.

DID YOU KNOW?

Many animals that live in the sea have salt glands near their eyes. These excrete a salt solution that is six times stronger than urine.

1.3j Mitosis and the cell cycle

Learning objectives:

- describe mitosis as part of the cell cycle
- describe the role of mitosis in growth and tissue repair
- describe how the process of mitosis produces cells that are genetically identical to the parent cell.

KEY WORDS

cell cycle
daughter cell
mitosis

Cells grow to a certain size, and then divide to form two new daughter cells. This process of cell division allows single fertilised egg cells to grow into multicellular organisms, and also produces new cells to repair damaged tissue.

Chromosomes

As we grow, the cells produced by cell division must all contain the same genetic information.

The genetic information of all organisms is contained in chromosomes, made of a molecule called DNA. The DNA in resting cells is found in the nucleus as long, thin strands, which can't be seen with a light microscope. For cell division, these strands form condensed chromosomes. Condensed chromosomes look thicker and can be seen with a light microscope.

Human body cells have 46 chromosomes, in 23 pairs. A chromosome carries a large number of genes. Each chromosome in a pair has the same pattern of genes along its length.

1. **How many chromosomes are found in human body cells?**
2. **How are the chromosomes arranged in a karyotype?**

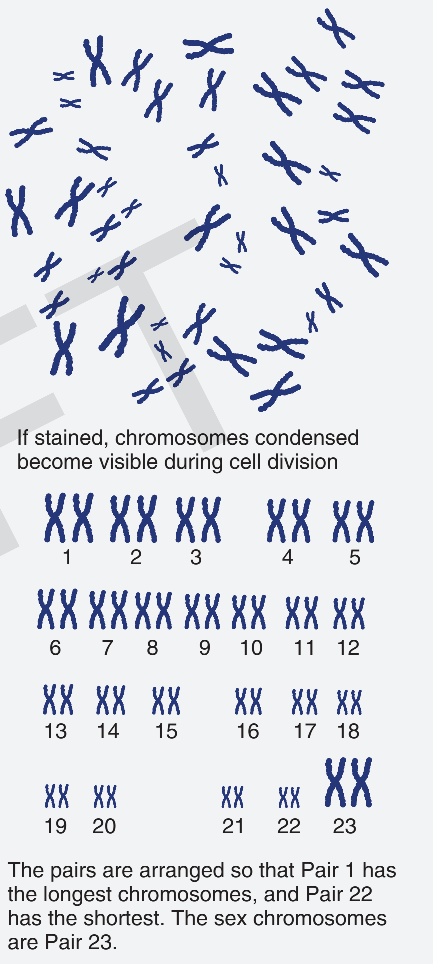


Figure 1.3.24 A profile of a set of chromosomes, called a karyotype

Mitosis

New cells have to be produced for growth and development, and to replace worn out and damaged body cells in injured tissues, for example.

When these new cells are produced, they must be the same as the parent cell. A parent cell divides to produce two new **daughter cells**, identical to each other and to the parent. This type of cell division is called **mitosis**.

3. **Why are new cells produced?**
4. **In this type of cell division:**
   - **how many chromosomes do daughter cells have?**
   - **how many daughter cells are produced?**

MAKING CONNECTIONS

To come up with a figure for how many cells there are in the human body, scientists must *estimate* by adding up cell counts from different organs.

Before a cell can divide it must grow, and make copies of all its organelles such as mitochondria and ribosomes. The 46 chromosomes in the nucleus are also replicated, so each chromosome consists of two identical molecules of DNA.

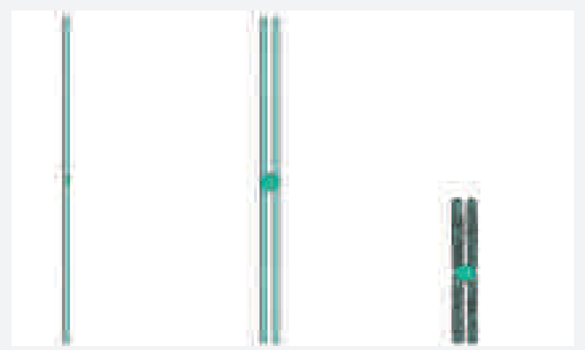


Figure 1.3.25 'Double chromosomes', consisting of two copies of DNA joined near the middle, often look 'X-shaped' in micrographs of cells

During mitosis, the double chromosomes are pulled apart as each new set of 46 chromosomes moves to opposite ends of the cell (Figure 1.3.26). Two nuclei then form. The cytoplasm and cell membrane then divides and two cells are produced.

5 **Why do chromosomes appear double, or X-shaped, in micrographs?**

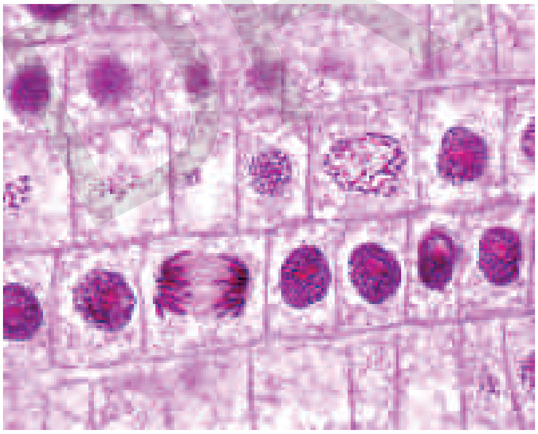


Figure 1.3.26 This light micrograph shows stained cells at different stages of the cell cycle in an onion root (x510). In one cell you can see the condensed chromosome copies being pulled to each end of the cell during mitosis

The cell cycle

A cell that is actively dividing goes through a series of stages called the **cell cycle**. Mitosis is the part of the cell cycle in which the cell divides into two. Before that can happen, the cell grows, the DNA replicates and new organelles are produced. All these processes together form the cell cycle.

DID YOU KNOW?

Using radioactive carbon (^{14}C) dating of a cell's DNA, researchers in Sweden have been able to estimate the lifespan of different types of cells.

6 **In the micrograph in Figure 1.3.26, you can't see chromosomes in all the cells. Explain why this is.**

7 **Why is it essential that each new cell produced in mitosis contains the same DNA as the parent cell?**

8 **Mitosis occurs rapidly in a newly formed fertilised egg. Suggest another situation in the body where you might expect cells to be actively dividing by mitosis.**

1.3k Meiosis

Learning objectives:

- explain how meiosis halves the number of chromosomes for gamete production
- explain how a new cell with the normal number of chromosomes is made at fertilisation
- understand that the four gametes produced by meiosis are genetically different.

KEY WORDS

gamete
genetic variation
meiosis

In sexual reproduction, two sex cells (one from each parent) join to make a new cell, which grows into a new organism. The new cell must have the normal number of chromosomes – so the sex cells must each have half the normal number. A special kind of cell division called meiosis creates sex cells with half the chromosomes of the parent cell.

Meiosis is a reduction division

Mitosis is the type of cell division used during growth, or when old or damaged cells need replacing.

Meiosis is another form of cell division, which take place when sex cells, or **gametes**, are produced in the ovaries and testes in animals, and in the carpels and stamens of plants.

During **meiosis**:

- four **gametes** are produced from one parent cell
- each gamete has half the number of chromosomes of the parent cell (in humans, that's 23 chromosomes instead of 23 pairs).

1. **How many gametes are produced from one cell during meiosis?**
2. **How many chromosomes does a gamete have?**

What happens during meiosis?

In meiosis, the DNA of each chromosome is copied, just as in mitosis. But it then divides *twice*, so the chromosome number is *halved*.

So, in mitosis, there is one replication of DNA and one division, but in meiosis, there is one replication of DNA and two divisions.

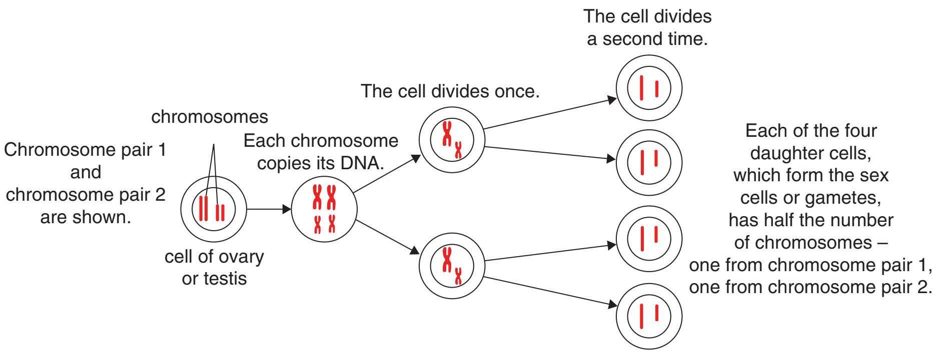


Figure 1.3.27 An overview of meiosis. Only two chromosomes are shown for clarity, but this process occurs for all chromosomes

When the gametes join at fertilisation, the new cell that is formed has the normal number of chromosomes. The diagram shows what happens at fertilisation in humans, showing only two pairs of chromosomes for simplicity. The new cell then divides by mitosis to grow into a new organism.

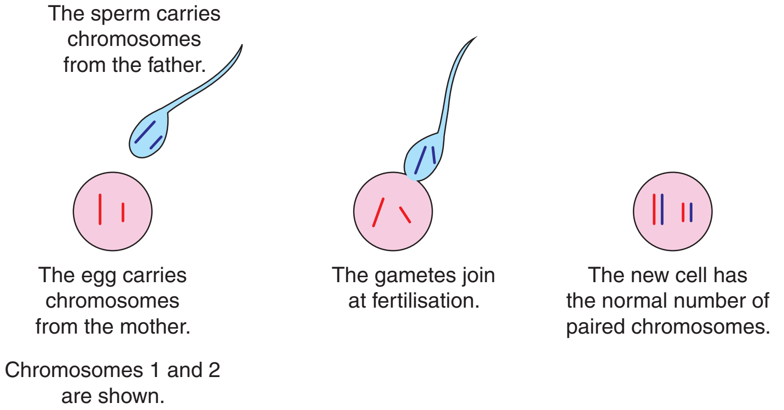


Figure 1.3.28 At fertilisation, the chromosomes from the gametes add together to make the normal number of chromosomes in the new cell

REMEMBER!

It is important to be able to recognise or describe differences and similarities between meiosis and mitosis.

3. **How many replications of DNA occur in meiosis?**
4. **How many divisions occur in meiosis?**

All gametes are genetically different

Of each pair of chromosomes in your cells, one chromosome was inherited from your mother and the other from your father. But when meiosis happens, which chromosome from each pair goes into each gamete is completely random. This means that the four gametes are genetically different.

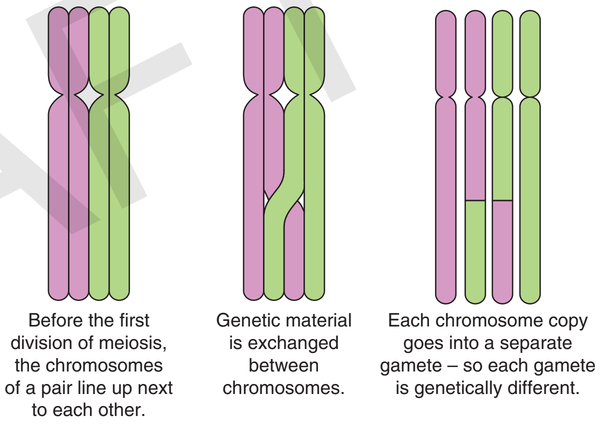


Figure 1.3.29 The set of chromosomes in a gamete is unique

Another thing that makes each gamete different is that there's some exchange of genetic material between the chromosomes in a pair when they line up together during meiosis. So when a gamete is produced, the chromosomes it receives may be different from those of the parent cell – they may be altered because parts of the DNA molecules have been swapped between two chromosomes in a pair. This also contributes to genetic variation because it means that every single gamete is unique.

5. **Explain how meiosis leads to genetic variation.**
6. **In mitosis, the pairs of chromosomes don't line up next to each other as they do in meiosis. Suggest why this means the two daughter cells are genetically identical in mitosis.**

1.3l Cell differentiation

Learning objectives:

- explain the importance of cell differentiation
- describe the function of stem cells in embryonic and adult animals.

KEY WORDS

differentiation
specialised
stem cells

For the first four or five days of our lives, the cells produced as the fertilised egg divides by mitosis are identical. Then, some of our cells start to become specialised to do a particular job.

Cell adaptations

As an embryo develops from a single fertilised egg into a multicellular organism, the cells need to take on different roles. Different types of cell are needed to ensure that the organism functions properly and as a whole.

As cells divide, new cells acquire certain features that make them **specialised** for a specific function. This is **differentiation**. A cell's size, shape and internal structure are adapted for its role. Most animal cells differentiate at an early stage of embryonic development.

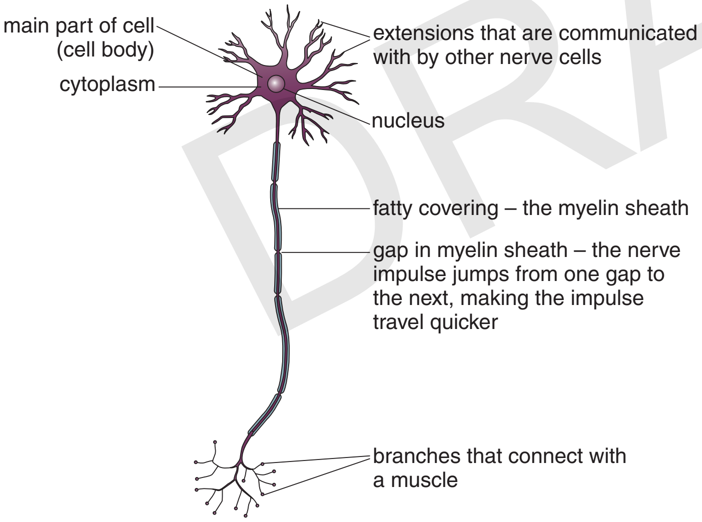


Figure 1.3.31 Nerve cells carry messages, or electrical impulses, from one part of the body to another. This diagram shows a motor nerve cell, which brings about movement of the skeleton by stimulating muscle cells to contract. Motor nerve cells can be 1 m or more in length, and 1–20 μm in diameter)

Figure 1.3.30 By around 13 weeks of embryonic development, a fetus has developed many of the 200 different cell types in the human body. It is around 7.5 cm long

1. **How is a motor nerve cell adapted to its function?**
2. **Red blood cells are specialised to carry oxygen around the body. They are small and flexible, and so packed with haemoglobin that they don't have room for a nucleus. Suggest how these features adapt red blood cells to their function.**

Link: 1.3l ⟶ 1.4a

Stem cells

At first, the cells in an embryo can grow and divide to form any type of cell. They are called **stem cells**.

Stem cells are unspecialised cells that can produce many different types of cell. Stem cells are found in the developing embryo, and some remain, at certain locations in our bodies, as adults.

3 **Describe the function of embryonic stem cells.**

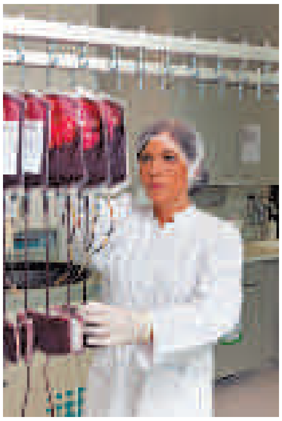


Figure 1.3.32 The UK has a shortage of blood donors. In the summer of 2015 the NHS announced that it planned to start giving people blood transfusions using artificial blood by 2017. The red blood cells in the artificial blood will be produced using stem cells

Adult stem cells

Cells that have become specialised cannot later differentiate into different kinds of cells. However, there are some stem cells in most adult tissues that are able to start dividing to replace old cells or to repair damage in the tissues where they are found.

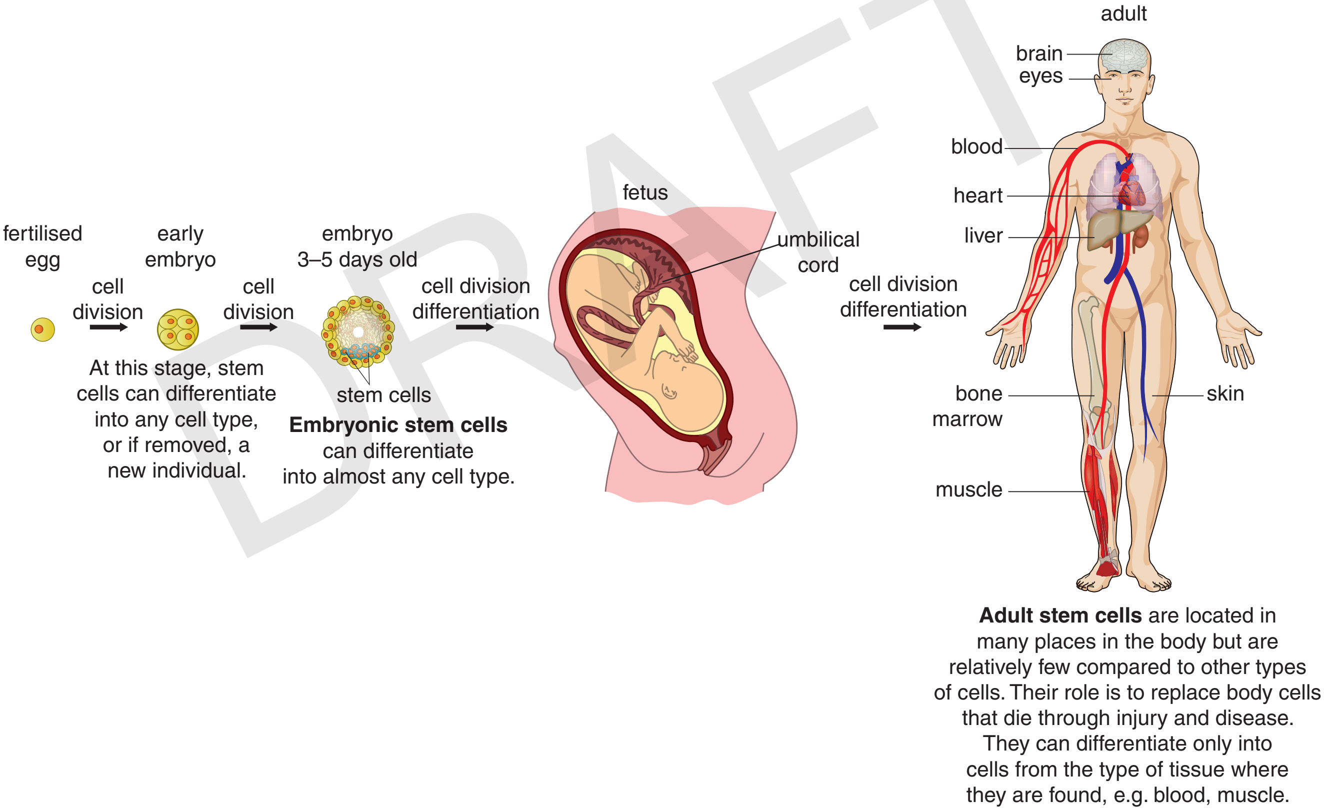


Figure 1.3.33 Stem cells in the human body

4 **What is the function of adult stem cells?**

5 **Which can differentiate into more cell types – embryonic stem cells or adult stem cells?**

6 **Suggest why artificial blood transfusions produced using stem cells might not be acceptable to some people.**

Check your progress

You should be able to:

calculate the magnification of a light or electron micrograph.	describe the differences in the magnification and resolving power of light and electron microscopes.	explain limitations of light microscopy and advantages of electron microscopy.
describe the functions of sub-cellular structures found in eukaryotic cells. describe the structure of a prokaryotic cell.	understand the size and scale of cells and be able to use and convert units. describe the differences between eukaryotic and prokaryotic cells.	carry out order of magnitude calculations when comparing cell size. calculate with numbers in standard form.
know the definition of diffusion.	explain diffusion using the idea of particles.	explain how substances pass in and out of cells.
recall that osmosis describes water movement in and out of cells.	explain osmosis as the movement of water through a partially permeable membrane, from a high water concentration to a lower water concentration.	predict water movement during osmosis. explain the words flaccid and turgid.
recall the theory of osmosis to create hypotheses on plant tissue.	plan and use appropriate apparatus and techniques to carry out an experiment to measure osmosis and test a hypothesis on plant tissue.	plot, draw and interpret appropriate graphs of results from an experiment to measure osmosis, evaluate the method and suggest possible improvements and further investigations.
recall that cells must divide for growth and replacement of cells.	describe how chromosomes double their DNA and are pulled to opposite ends of the cell, before the cytoplasm divides, during mitosis.	describe broadly the events of the cell cycle and explain the synthesis of new sub-cellular components and DNA.
identify meiosis as the cell division used to produce gametes.	explain the need for meiosis in producing gametes.	explain that the gametes produced by meiosis are genetically unique.
recall where stem cells are found. recall that organism development is based on cell division and cell specialisation.	describe how cells are specialised for their functions.	explain the importance of differentiation.

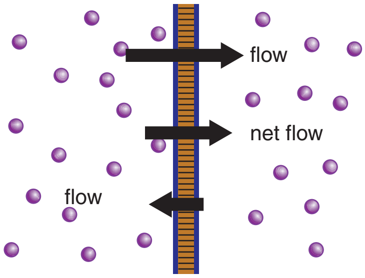
Worked example

1 **a What is a stem cell?**

A cell in a developing embryo that can divide to form any type of cell. After cells have become specialised they can't turn into other sorts of cell.

> This describes embryonic stem cells well, but remember that there are also stem cells in adult tissues that can divide to replace old cells or repair damage in the tissue.

2 **The diagram represents the movement of water molecules across a cell membrane. The solution to the right of the membrane has a higher solute concentration than the solution to the left.**



a Explain what 'net flow' means here.

Water is moving in the direction of the net flow.

> Not a full answer. Water molecules are moving in both directions, but the rate of movement is higher in one direction than in the other. The net flow is the overall, combined result of the movements.

b Why is there a net flow from left to right in this diagram?

The concentration is higher on the left so more water flows to the right.

> Be careful here. The *solute concentration* on the left is *lower* (more dilute), which means there is a higher water concentration. The net movement of water molecules is from a higher water concentration to a lower water concentration – from left to right in this case. Be sure to be clear in your answer.

c Write a definition for osmosis.

The diffusion of water.

> Not a full answer. Osmosis is the diffusion of water across a partially permeable membrane.

d Explain why there are differences in the effects of water on plant and animal cells.

When water enters animal cells by osmosis the cells swell and may burst. When water moves out the cells shrivel up.

When water enters a plant cell it cannot burst because of the cell wall. It becomes turgid. If water moves out the cell becomes flaccid but doesn't shrivel up completely.

> A clear, full answer.

3 **a Explain how dissolved minerals such as nitrate ions are absorbed by plants.**

By active transport through root hair cells.

> Good, but you should explain that active transport is necessary to move mineral ions into the cell against their concentration gradient.

b Explain the similarities and differences between diffusion, osmosis and active transport.

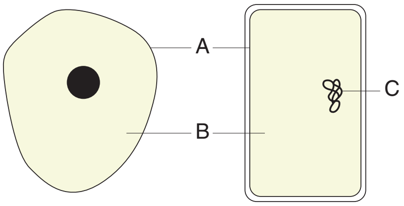
Diffusion	Osmosis	Active transport
passive	passive	needs energy
down concentration gradient	down concentration gradient	up concentration gradient
no membrane needed	membrane	membrane

> Table is a good idea. Don't forget also that osmosis is the movement of water molecules only – no other substance.

End of chapter questions

Getting started

1 **The diagrams below show an animal cell and a bacterial cell.**



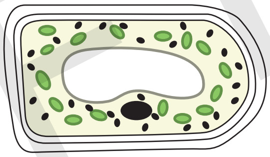
a **The parts of the cell labelled A and B are found in both animal cells and bacterial cells.**
Name cell parts A and B. 2 Marks

(i) **cell membrane**
(ii) **cell wall**
(iii) **cytoplasm**
(iv) **nucleus**
(v) **vacuole**

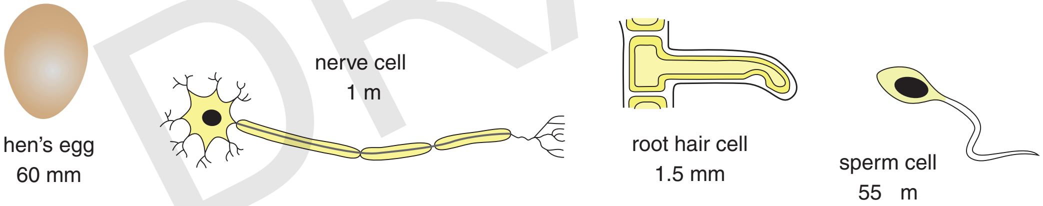
b **What is the name of chemical C?** 1 Mark

(i) **cellulose**
(ii) **chlorophyll**
(iii) **DNA**
(iv) **protein**

2 **Explain how you know that the cell shown is a plant cell.** 2 Marks



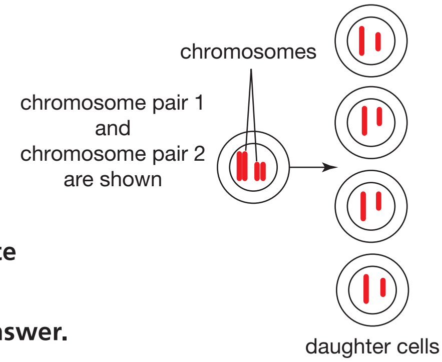
3 **The diagrams below show some different cells. The length of each is included on the diagram. Arrange them in order of length.** 2 Marks



4 **A bacterium divides into two every 30 minutes.**

Starting with one bacterium, how many cells will there be after $1\frac{1}{2}$ hours? 1 Mark

5 **Gemma is using a light microscope to observe some dividing cells. A drawing of one of the cells is shown below. Describe what is happening in the cell.** 2 Marks



6 **The diagram shows a process that is taking place when pollen grains are being produced.** 2 Marks

What conclusion can you draw? Explain your answer.

Going further

7 **Draw lines to match the two cell structures with their function.** 2 Marks

Cell structure	Function
	Controls what enters and leaves cells
Mitochondrion	Respiration
Ribosome	Protein synthesis

8 **Draw two lines to match the types of cell division with where they occur.** 2 Marks

Cell division	Where it occurs
	Asexual reproduction in bacteria
Meiosis	**Growth of a human embryo**
Mitosis	**Sperm production**

9 **Amoeba is a single-celled organism that lives in fresh water. It has a vacuole that fills with water, moves to the outside of the cell and bursts. A new vacuole starts to form. Use osmosis to explain why amoeba needs a vacuole.** 4 Marks

More challenging

10 **Explain why mitosis is important in plants and animals.** 2 Marks

11 **Explain how plant cells become turgid.** 3 Marks

12 **A teenage girl had her heartbeat measured at 74 beats per minute. Each beat pumped 70 cm^3 of blood. Calculate how much blood will be pumped in 10 minutes. Give your answer in litres.** 3 Marks

Most demanding

13 **Explain how meiosis leads to the production of gametes that are different genetically.** 6 Marks

14 **Name the processes by which a plant absorbs carbon dioxide for photosynthesis, essential minerals, and water, and explain the differences between them.** 6 Marks

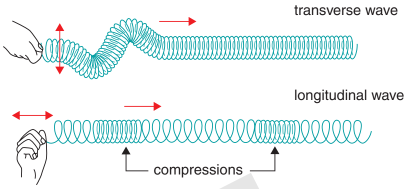
Total: 40 Marks

WAVES

IDEAS YOU HAVE MET BEFORE:

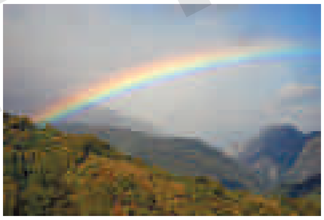
DESCRIBING WAVES

- Frequencies of waves are measured in hertz (Hz).
- Waves travel at different speeds in different materials.
- Sound waves are longitudinal.
- Sound waves are produced by vibrations.
- Sound needs a medium to travel.
- Water waves and light waves are transverse.
- Light waves can travel through a vacuum.



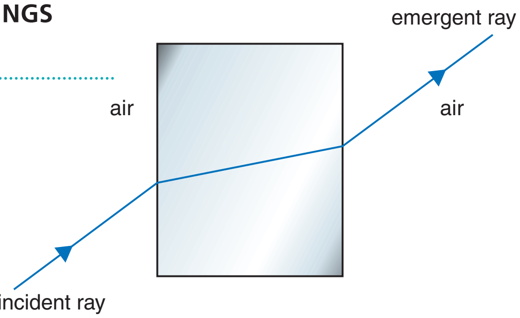
VISIBLE LIGHT

- White light is made up of a mixture of many different colours.
- Each colour of light has a different frequency.
- Different colours are absorbed or reflected by different surfaces.



LIGHT WAVES AND WATER WAVES HAVE SOME THINGS IN COMMON

- All waves carry energy from one place to another.
- When waves hit an object they may be absorbed by it, transmitted or reflected back.
- Waves may change direction (refract) at the point where two different materials meet.

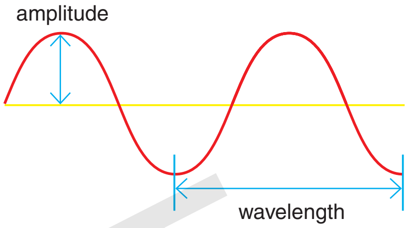


1.4

IN THIS CHAPTER YOU WILL FIND OUT ABOUT:

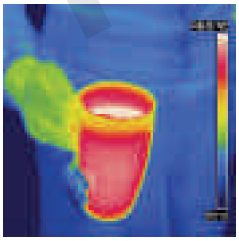
WHAT CHARACTERISTICS OF WAVES CAN BE MEASURED?

- We can measure the speed, wavelength and frequency of waves.
- We can calculate any of these three properties using the other two.
- The amplitude of a wave is its maximum displacement from its rest position.
- Echo sounding uses reflections of sound waves to detect objects hidden from view.



ARE THERE ANY WAVES BEYOND THE VISIBLE SPECTRUM?

- The visible spectrum is only a small part of a much wider spectrum called the electromagnetic spectrum.
- The invisible waves beyond red are called infrared and those beyond violet are called ultraviolet.
- Gamma rays, X-rays and ultraviolet rays have higher frequencies (smaller wavelengths) and transfer more energy.



IN WHAT WAYS DO OTHER ELECTROMAGNETIC WAVES BEHAVE LIKE LIGHT?

- All electromagnetic waves are transverse waves that transfer energy.
- All electromagnetic waves can be absorbed, reflected and refracted at a boundary between two different media.
- All electromagnetic waves can be refracted when they go from one medium into another medium of a different density.

KEY CONCEPT

1.4a Transferring energy and information by waves

Learning objectives:

- To understand that all waves have common properties
- To understand how waves can be used to carry information
- To understand various applications of energy transfer by different types of electromagnetic waves

KEY WORD

energy
transfer
vibration
amplitude
absorb

A wave is a regular vibration that carries energy. Some waves carry energy in a form that can be decoded to extract information – an example of this is the picture and sound information carried by radio waves from a transmitter to your television set at home. Ripples on the surface of a pond, sound in air, ultrasound, visible light, X-rays and infrared rays are all types of wave. In water, the surface just moves up and down, but the energy is carried outwards from the source. A Mexican wave in a stadium is caused by spectators just standing up and sitting down but the wave travels all round the stadium (Figure 1.4.1).

Why not look on YouTube at the world record of a Mexican wave?

Figure 1.4.1 A Mexican wave

Common properties of waves

Waves all transfer energy. When we watch a firework display, sound waves travel slowly compared with light waves. We see the flash of the explosion first, when light waves transfer energy to sensors in our eyes. Then we hear the bang, when sound waves transfer energy from the explosion to our eardrums.

Amplitude measures the height of the wave above or below its rest point. The larger the amplitude of a water wave, the more energy it can transfer. An underwater earthquake can create a tsunami with waves 30 m high. This huge amplitude can transfer enough energy to power the whole of the UK for a year.

1. **Why do you hear the sound of thunder after you see the flash of lightning?**
2. **Draw a diagram to show two transverse waves with different amplitudes.**
3. **What would you notice if the amplitude of a sound wave increased?**

Using waves to transmit information

Because waves can carry energy, we use them to transmit information by varying the amount of energy carried by the wave. This can be done by simply switching the wave source on and off to create a pulsed code, as in Morse code using flashes of light, or by varying the frequency or amplitude of the wave.

In the past humans could only communicate using sound and light, but now we can also use transmitters and receivers to send information using a whole range of wavelengths that we cannot see or hear.

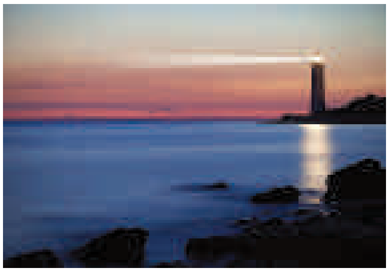


Figure 1.4.2 The beam of a lighthouse transmits information out to sea, warning sailors of dangerous rocks. Each lighthouse has its own distinct series of flashes

4. **Different colours of light have different frequencies. Give an example of where we use different frequencies of light to transmit information.**
5. **Give an example where information is transmitted by changing the amplitude of a wave, for example making a sound louder or a light brighter.**

Electromagnetic waves

Visible light is only a small part of a set of waves known as electromagnetic waves. The full range of electromagnetic waves is called the electromagnetic spectrum. These waves all travel at the same speed and can travel through empty space.

Each different part of the electromagnetic spectrum is used to transfer energy.

- Microwaves can transfer energy to cook food.
- An electric fire transfers energy to our bodies by infrared waves warming us up.
- Some energy from the Sun is transferred by ultraviolet rays.
- Not all energy from an X-ray machine is transferred.
- Some is absorbed by the body when an X-ray image is produced.
- Energy from radioactive sources can be transferred by gamma rays, and can be used to sterilise medical equipment or kill cancer cells.

Figure 1.4.3 Ultraviolet light can damage your eyes, and in extreme cases can even cause snow blind-ness. Skiers need to wear sunglasses that block out the ultraviolet, which can burn the surface of the eye

6. **For each of the examples of electromagnetic waves in the list above, suggest one piece of evidence that shows the energy transferred by the wave can be either absorbed or reflected.**

1.4b Transverse and longitudinal waves

Learning objectives:

- compare transverse and longitudinal waves
- describe water waves as transverse waves and sound waves as longitudinal waves
- describe evidence that the wave travels along, but not the medium itself
- describe how to measure the speed of water waves.

KEY WORDS

compression
longitudinal wave
rarefaction
transverse wave

All waves transfer energy, but not all in the same way. Ripples on water transfer energy as water particles move up and down. In sound waves, the particles move closer together and further apart, rather than up and down.

Transverse waves

Transverse and **longitudinal** waves can be produced on a Slinky spring.

In a transverse wave on a spring the vibrations of the particles are at right angles to the direction of the energy transfer (Figure 1.4.4). If the particles move up and down vertically, the energy carried in the wave is transferred horizontally, away from the energy source creating the wave. The wave moves but the spring oscillates about a fixed position.

Ripples on water are also transverse waves (Figure 1.4.5). The wave is moving outwards but the water particles move up and down.

A cork floating in water bobs up and down on a water wave. It only has vertical motion and it is not carried along by the wave.

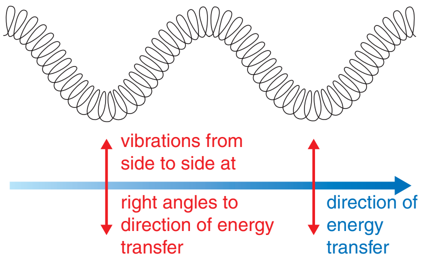


Figure 1.4.4 Transverse waves on a Slinky spring shaken from side to side on the floor

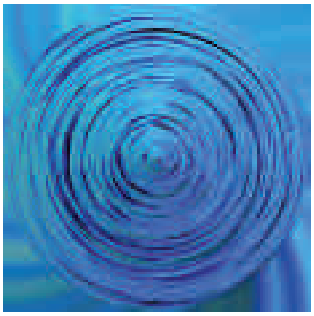


Figure 1.4.5 Ripples caused by a stone being dropped into water If the water moved outwards, it would leave a hole in the centre

1. **What evidence suggests water waves are transverse waves?**
2. **Alex sees a stick floating on a still pond. A boat creates waves that spread across the surface toward him. Alex expects the stick to move toward him too, but it does not. Suggest why this is.**

Longitudinal waves

In a longitudinal wave the vibrations of the particles are parallel to the direction of energy transfer (Figure 1.4.6). Longitudinal waves show areas of **compression** and rarefaction. A compression is when the waves bunch up. A **rarefaction** is

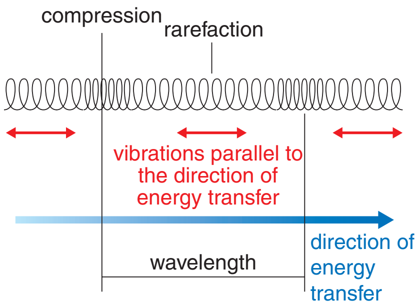


Figure 1.4.6 A longitudinal wave on a Slinky spring

when they spread out. If the particles move from side to side horizontally, the energy carried in the wave moves along the same horizontal direction, away from the energy source.

Sound waves in air are longitudinal waves.

Figure 1.4.7 Hitting the drum makes the drumskin vibrate, moving the air molecules next to it back and forth. The sound travels as the molecules pass on the vibration to their neighbours

3 **How is the longitudinal wave on a Slinky different when you push and pull gently from when you move your hand more vigorously?**

4 **Why wouldn't anyone hear you if you screamed in space?**

The speed of water waves

The speed of a water wave can be found by measuring the time it takes for a water wave to travel a measured distance. For example, make a splash at one end of a 25 m swimming pool and measure, with a stop clock, the time it takes the wave to travel to the other end.

5 **a** **Is this method an accurate way of measuring the wave speed? Explain your answer.**

b **Explain how you could improve the accuracy.**

6 **The crest of an ocean wave moves a distance of 20 m in 10 s. Calculate the speed of the ocean wave.**

KEY INFORMATION

A medium (plural media) is a material through which a wave travels.

1.4c Measuring wave speed

Learning objectives:

- describe how to measure the speed of sound waves in air using an echo method
- apply the echo method to waves in water
- apply the relationship between wavelength, frequency and wave velocity.

KEY WORDS

echo
echo sounding

Light and sound are both waves, but in a thunderstorm, you see lightning before you hear thunder. The lightning flash is almost instantaneous but sound travels much more slowly. We can use echoes to measure the speed of sound in air.

Measuring the speed of sound in air

Zoe and Darren measured the speed of sound in air. Sound reflects off a wall in a similar way to light reflecting off a mirror. The reflected sound is called an **echo**.

Zoe stood 50 m from a large wall. She clapped and listened to the echo (Figure 1.4.8).

Zoe tried to clap each time she heard an echo while Darren timed 100 of her claps with a stop clock. He timed 100 claps in 40 s.

The time between claps is $\frac{40\text{s}}{100} = 0.4$ s

During the time from one clap to the next the sound had time to go to the wall and back, a distance of 100 m.

Speed = distance / time

$$= \frac{100\text{m}}{0.4\text{s}} = 250 \text{ m/s}$$

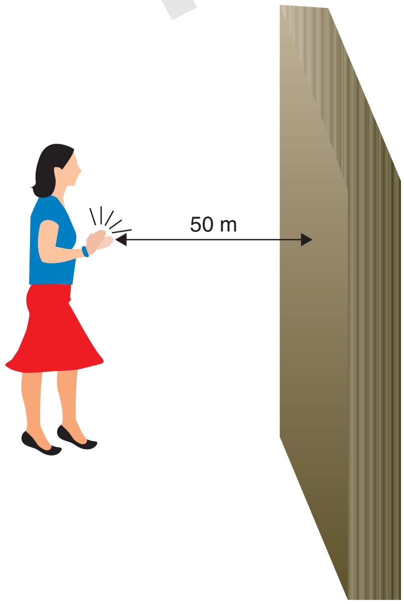


Figure 1.4.8 Zoe tried to clap each time she heard an echo

1. **Jo and Sam also measured the speed of sound in air using the same method. They counted 50 claps in 23 s. Jo also stood 50 m from the wall.**

   What value did they get for the speed of sound?

2. **Suggest why this method is not likely to produce an accurate value for the speed of sound in air.**

ADVICE

In echo sounding remember the wave goes 'there and back', so make sure you use the correct distance in calculations.

Echo sounding

Ships use high-frequency sound waves to find the depth of the seabed or to locate a shoal of fish (Figure 1.4.9). This is **echo sounding**.

Example: A ship sends out a sound wave and receives an echo after 1 second. The speed of sound in water is 1500 m/s. How deep is the water?

Time for sound to reach the seabed = 0.5 s.

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

distance = speed × time

= 1500 m/s × 0.5 s = 750 m

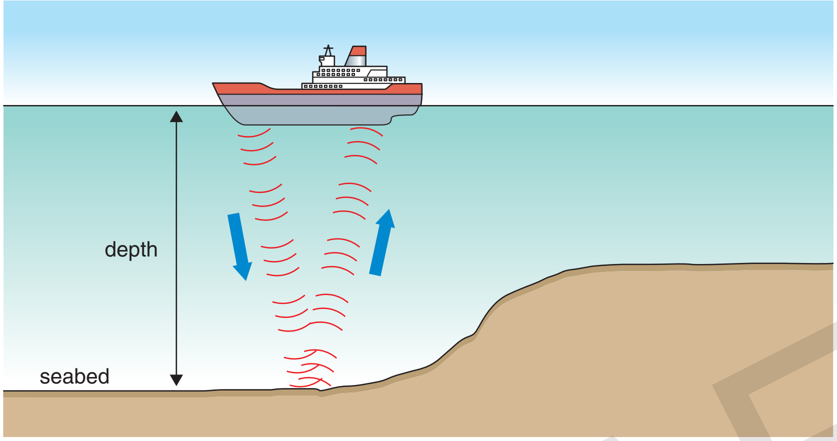


Figure 1.4.9 The sound waves are reflected off the seabed or from a shoal of fish, coming back as an echo

3 **On a fishing boat, the echo from the shoal of fish is received after 0.1 s. How far below the boat is the shoal?**

4 **A ship is 220 m from a large cliff when it sounds its foghorn.**

a **When the echo is heard on the ship, how far has the sound travelled? (The speed of sound in air is 330 m/s.)**

b **How long is it before the echo is heard?**

Change in speed of sound waves

When a sound wave is transmitted across a boundary from one medium to another, its speed may change. When the speed of a wave changes, there is a change in the wavelength, but there is no change in the frequency. This is because the number of waves leaving the medium each second is the same as the number of waves entering the medium each second.

Medium	Speed of sound (m/s)
air	330
water	1500
steel	5000

5 **Adjacent compressions in a sound wave are 15 cm apart. What is the wavelength of the sound?**

6 **Ann puts her ear to touch an iron railing. Jack hits the iron railing with a stick about 5 m away from Ann. Explain why she hears two sounds, one after the other.**

1.4d A wave equation

Learning objectives:

- describe wave motion in terms of amplitude, wavelength, frequency and period
- describe and apply the relationship between wavelength, frequency and speed
- apply the equation relating period and frequency

KEY WORDS

amplitude
frequency
hertz (Hz)
period
wavelength

We can describe waves in terms of their wavelength, frequency and speed – and if we know two of these variables, we can work out the other one using the 'wave equation'.

Wavelength, amplitude and frequency

Wavelength (λ) is the distance from a point on one wave to the equivalent point on the adjacent wave. Wavelength is measured in metres (m).

The **amplitude** of a wave is the maximum displacement of a point on a wave away from its undisturbed position.

Frequency (*f*) is the number of complete waves passing a point in one second. It is measured in **hertz (Hz).** A frequency of 5 Hz means there are five complete waves passing a point in 1 second. Frequencies are also given in kilohertz (kHz) and megahertz (MHz).

1000 Hz = 1 kHz

1000 kHz = 1 MHz

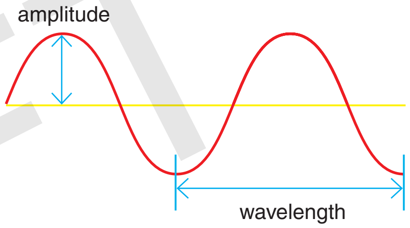


Figure 1.4.10 Amplitude and wavelength of a wave

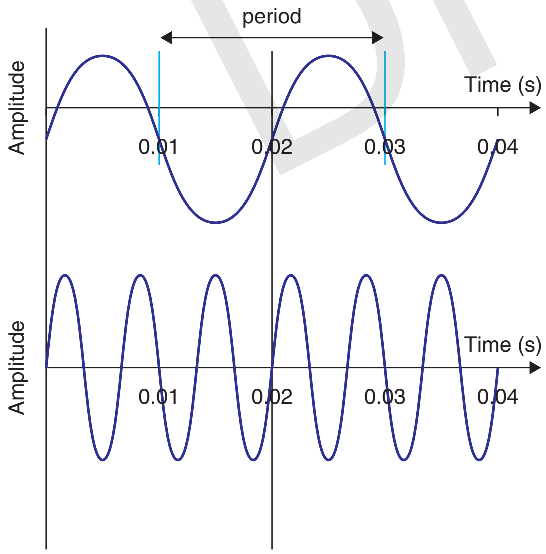


Figure 1.4.11: High-pitched sounds have a higher frequency than low-pitched sounds – the higher the pitch, the more vibrations per second

1. Define what we mean by

   a wavelength

   b frequency

   c amplitude.

2. Suggest how the amount of energy transferred by a wave changes as the amplitude increases.

Link: 1.4d ⟶ 1.4e

Period of a wave motion

The **period (T)** is the time to complete one wavelength.

Period is the reciprocal or inverse of frequency.

Frequency is the number of complete waves passing a point in one second. $T = \frac{1}{f}$,

For example: When the frequency of a wave is 5 Hz there are 5 waves passing a point each second. The time for one wave to pass is $\frac{1}{5}$ s or 0.2 s.

The period, T, $= \frac{1}{f}$

$= \frac{1}{5}$ s or 0.2 s

The wave equation

A wave transfers energy. The wave speed is the speed that the wave transfers energy, or the speed the wave moves at.

All waves obey the **wave equation**:

wave speed = frequency × wavelength

$v = f\lambda$

where the wave speed v is in metres per second (m/s), the frequency f is in hertz (Hz) and the wavelength λ is in metres (m).

If we know two of these three variables we can calculate the third using the wave equation.

Example: A radio station produces waves of frequency 200 kHz and wavelength 1500 m.

(a) Calculate the speed of radio waves.

(b) Another station produces radio waves with a frequency of 600 kHz. What is their wavelength? Assume that the speed of the wave does not change.

(a) $v = f\lambda$ **= 200 000 Hz × 1500 m = 300 000 000 m/s**

= 3×10^8 **m/s**

(b) wavelength, $\lambda = \frac{v}{f} = \frac{300\,000\,000 \text{ m/s}}{600\,000 \text{ Hz}}$

= 500 m

3 **A wave has a frequency of 2 Hz. How many waves pass a point in 1 second?**

4 **Work out the frequencies of waves with periods of**

a 0.1 s

b 0.25 s.

ADVICE

Always check that you put values into the wave equation using SI units (e.g. wavelengths in metres, frequency in hertz). If the values in the question are not in SI units, you first have to convert them.

DID YOU KNOW?

The light that we can see has a wavelength of about $\frac{1}{2000}$ of a millimetre!

5 **A wave has a frequency of 2 Hz and a wavelength of 10 cm. What is the speed of the wave?**

6 **When the frequency of a wave doubles, what happens to its wavelength?**

7 **A TV signal is broadcast at a frequency of 104 kHz. If the wave speed is 3×10^8 m/s, what is the wavelength?**

REQUIRED PRACTICAL

1.4e Measuring the wavelength, frequency and speed of waves in a ripple tank and waves in a solid

Learning objectives:

- develop techniques for making observations of waves
- select suitable apparatus to measure frequency and wavelength
- use data to answer questions.

These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

Frequency and wavelength of waves in a ripple tank

We can use a set of equipment called a ripple tank to explore waves. By careful observation and measurement we can measure and calculate the wavelength and frequency of the waves and then work out their speed. A strobe light can be used to 'freeze' the movement of the waves for making certain measurements.

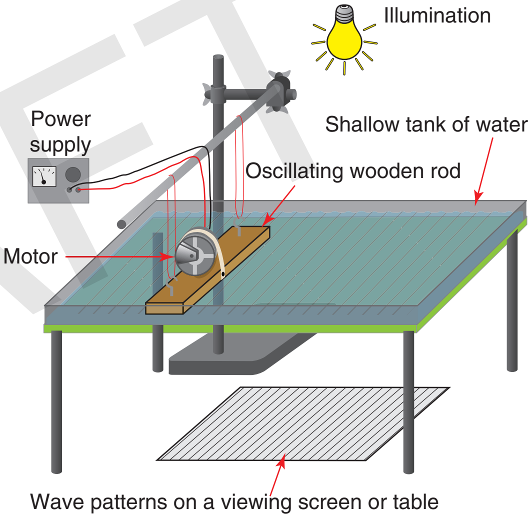


Figure 1.4.12 Ripple tank used for observing waves in water

1. **A motor is attached to the wooden rod. What does this do?**
2. **What are the units of**
   a wavelength?
   b frequency?
3. **Suggest what equipment you could use to measure the wavelength, and how you should set it up.**
4. **When measuring the wavelength, you might measure the length of ten waves on the screen or table and then divide by ten. Explain why this is done.**
5. **Louise is looking at a certain point on the screen and counting how many waves pass that point in ten seconds. How can she then calculate the frequency of the waves?**

SAFETY

A risk assessment is required for this practical work.

When using strobe lights it is necessary to be aware of students with epilepsy, as these lights can induce epileptic fits.

Speed of waves in a ripple tank

Sahil's group are comparing two ways of working out the speed of the waves as they travel through the water. One of these is by using speed equals distance/time and the other is by using speed equals frequency times wavelength.

Link: 1.4e ⟶ 1.4f

6 **Explain how the group could measure the speed of the waves using the equation speed = distance/time.**

7 **Now explain how the group could calculate the speed of the waves using the equation speed = frequency × wavelength.**

8 **Why do scientists sometimes try to use two different methods to measure a quantity**

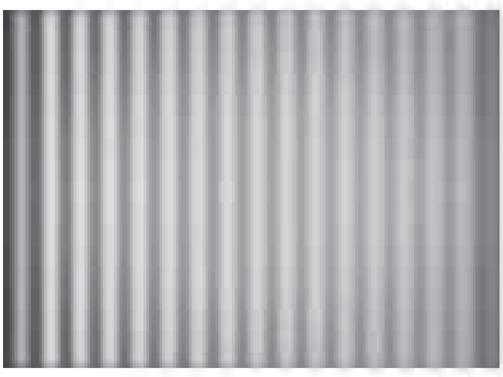


Figure 1.4.13 Shadows of waves travelling across a ripple tank. The wavelength is the distance between two dark patches, which are the peaks (crests) of the waves

Speed of sound in a metal rod

Sound also travels in waves. Unlike water waves we can't see them but we can still measure their speed. The apparatus needs to be different though.

The apparatus in Figure 1.4.14 can be used to measure the speed of sound in an iron bar, about 1 m long. One end of the bar is hit with the hammer. This electrical contact starts the timer running. The sound travels through the bar and is detected by the microphone. An electrical pulse generated by the microphone stops the timer.

This experiment was demonstrated several times and the following values obtained for the time interval: 0.18 milliseconds (ms), 0.21 ms, 0.32 ms, 0.17 ms and 0.22 ms.

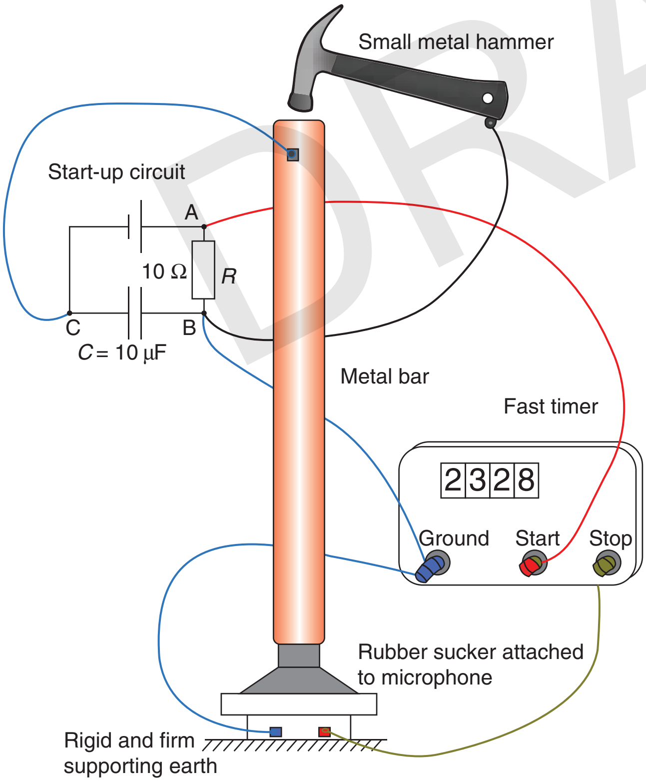


Figure 1.4.14 Measuring the speed of sound in an iron bar

REMEMBER

If you have a set of readings, don't simply average all the results but look at them first to see if there are any anomalies. These should be eliminated before finding the average or they will influence the outcome.

DID YOU KNOW?

Sound travels much faster through solids than through air. It travels through iron over 15 times faster than through air.

9 **Suggest how this data should be processed.**

10 **What calculation should then be done to get a value for the speed?**

11 **The accepted value for the speed of sound in iron is 5130 m/s. Comment on how well the experimental value compares.**

1.4f Electromagnetic waves

Learning objectives:

- recall that electromagnetic waves are transverse waves that can transfer energy through space
- describe the main groupings of the electromagnetic spectrum
- recall and apply the relationship between frequency and wavelength.

KEY WORDS

electromagnetic waves
longitudinal wave
spectrum
transverse wave
visible spectrum

Electromagnetic waves emitted by the Sun, including visible light, travel 149 million kilometres across space. They reach Earth in about 8 minutes.

Transverse and longitudinal waves

As you saw earlier, there are two types of waves: **transverse** and **longitudinal**. In a transverse wave the vibrations are at right angles to the direction of energy transfer and in a longitudinal wave they are parallel to the direction of energy transfer (Figure 1.4.15).

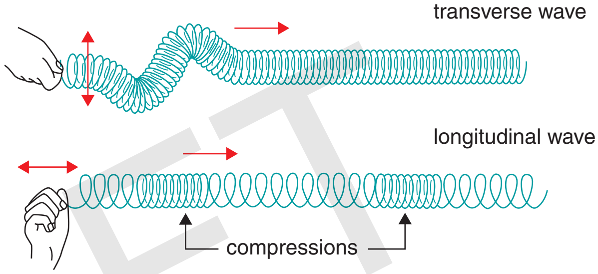


Figure 1.4.15 Comparing transverse and longitudinal waves

Waves in water (Figure 1.4.16) and a rope or slinky moved from side to side are transverse waves.

1. **Explain what is meant by a) the amplitude and b) the wavelength of a wave.**
2. **Give an example of a longitudinal wave.**

Electromagnetic waves

Light is a type of wave called an **electromagnetic wave**. White light is a mixture of electromagnetic waves with different wavelengths, which can be separated into what we call the **visible spectrum**. When scientists investigate the visible spectrum they can detect invisible waves on both sides, showing that the visible spectrum is really part of a much wider spectrum, which we call the electromagnetic spectrum.

Figure 1.4.16 When white light is passed through a prism, the different wavelengths of the visible spectrum appear to our eyes as different colours

All the waves in the electromagnetic spectrum are transverse waves with many properties in common with visible light.

Just like other waves, all electromagnetic waves transfer energy from one point to another – from a source to an absorber. In electromagnetic waves, electromagnetic fluctuations occur at right angles to the direction in which energy is being transferred by the wave.

Some waves have to travel through a material. Sound waves can travel through air, liquids and solids but not a vacuum. Water ripples travel along the surface of water.

Link: 1.4f ⟶ 1.4g

Electromagnetic waves are different from other waves because they do not need a material. They can travel through a vacuum. This is a special property of electromagnetic waves, which enables light and infrared waves to reach us from the Sun. All electromagnetic waves travel at the same speed in a vacuum, 3.0×10^8 m/s.

3 **What are the similarities and differences between transverse and longitudinal waves?**

4 **Explain how waves in the electromagnetic spectrum are different to other waves.**

5 **What properties do all electromagnetic waves have in common?**

ADVICE

Remember the order of electromagnetic wave groupings.

KEY INFORMATION

The shorter the wavelength (the higher the frequency) of an electromagnetic wave the more dangerous the radiation.

The electromagnetic spectrum

Figure 1.4.17 shows that electromagnetic waves span a wide, continuous range of wavelengths and frequencies.

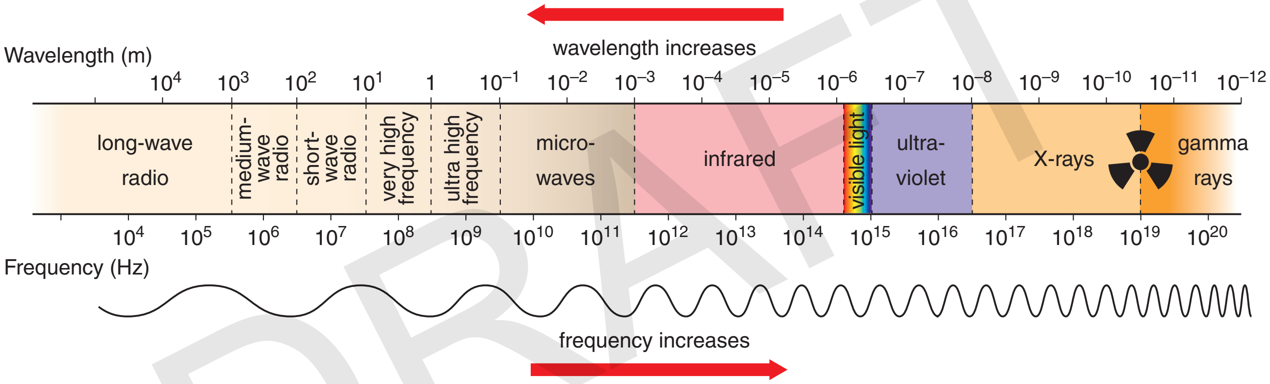


Figure 1.4.17 The wavelengths and frequencies of waves in the electromagnetic spectrum

The groups of waves in the electromagnetic spectrum are shown in the table.

Waves in electromagnetic spectrum	Wavelength (m)
radio, TV and microwaves	above 10^5 m to 10^{-3}
infrared	10^{-3} to 10^{-7}
visible (red to violet)	10^{-7}
ultraviolet	10^{-7} to 10^{-8}
X-rays	10^{-8} to 10^{-10}
gamma rays	10^{-10} to less than 10^{-12}

The shorter the wavelength of the electromagnetic wave, the further it can travel through other materials. The higher the intensity of a wave the more energy it can transfer to another object when the radiation is absorbed.

6 **Which grouping in the electromagnetic spectrum has the highest frequency?**

7 **Ultraviolet light used in a sunbed has a wavelength of 3.5×10^{-7} m. The speed of light is 3×10^8 m.**

Calculate the frequency of this light.

8 **Calculate the frequency of an electromagnetic wave with a wavelength of 20 cm. Use standard form for your answer.**

1.4g Uses of electromagnetic waves

Learning objectives:

- give examples of practical uses of electromagnetic waves
- show that the uses of electromagnetic waves illustrate the transfer of energy from source to absorber
- recall that radio waves can be produced by, or can induce, oscillations in electrical circuits.

KEY WORDS

gamma rays
infrared
microwaves
radio waves
ultraviolet
visible light
X-rays

Electromagnetic radiation has a huge number of uses in medicine, communications and everyday life. These uses illustrate the transfer of energy from a source (something that emits electromagnetic radiation) to an absorber (something that takes in electromagnetic radiation). An absorber is often a detector or a receiver.

Gamma rays and X-rays

Gamma rays have the shortest wavelengths in the electromagnetic spectrum and can be harmful to living cells. In controlled doses, gamma rays are used in radiotherapy to kill cancer cells, and to sterilise surgical instruments.

X-rays pass through soft tissues in the body but are absorbed by bone. This means X-rays can be used to check for broken bones, and also in computerised tomography (CT) scans – multiple images taken at different angles build up a detailed picture of inside a patient's body (Figure 1.4.18).

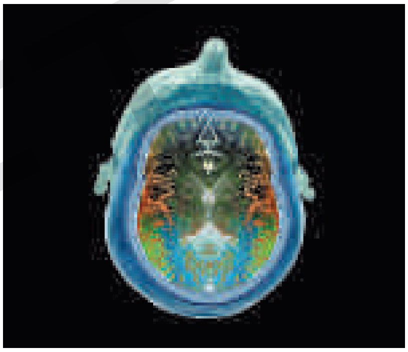


Figure 1.4.18 A CT scan can give good pictures of soft tissue regions but exposes a patient to a much higher radiation dose than a single X-ray

1. **What are the similarities and differences between gamma rays and X-rays?**
2. **Should X-rays used in radiotherapy have longer or shorter wavelengths than those used for medical diagnosis? Explain your answer.**

DID YOU KNOW?

X-ray machines called pedoscopes were used in shoe shops in the 1930s to measure people's feet. Although children loved to watch their toe bones wriggle, people did not realise how dangerous the energy transferred by X-rays can be. Some shop assistants developed cancer because of using them.

Ultraviolet, visible and infrared radiation

Ultraviolet rays have higher frequencies and shorter wavelengths than visible light. One use of ultraviolet is in fluorescent lighting, which is more energy efficient than traditional filament light bulbs.

In small doses, ultraviolet light from sunlight is good for us, as it produces vitamin D in our skin, but larger doses can be harmful to our eyes and may cause skin cancer.

Visible light from lasers is used to send digital data down fibre-optic cables at huge speeds with little loss of signal quality. This has transformed global communications over recent decades.

Infrared radiation has longer wavelengths than visible red light. Electrical heaters and traditional cookers (sources) transfer energy by infrared radiation. Thermal imaging cameras (absorbers) detect low levels of infrared radiation from warm objects.

3. **Suggest why you can't get sunburned through a window, even though you can still see the sunlight.**
4. **Suggest how a thermal image of your house might be useful.**

Microwaves and radio waves

Microwaves are radio waves with short wavelengths, between 1 mm and 30 cm. Microwaves are used for cooking in microwave ovens, and also to transmit mobile phone signals. Transmitters are placed on high buildings or masts to give better communication over large distances. Sometimes signals are sent from a transmitter (a source) to a receiver (an absorber) via a satellite.

Microwaves used for communication have a longer wavelength than those used for cooking.

Terrestrial radio and TV signals are sent by **radio waves,** travelling at the speed of light. A radio telescope forms images of objects in space by detecting the radio waves they emit. Radio waves have much longer wavelengths than visible light, and a radio telescope must be very large to have the resolution of an optical telescope.

5. **Suggest why satellite TV dishes are placed on the walls or roofs of houses.**
6. **Like many uses of electromagnetic radiation, a radio telescope illustrates the transfer of energy from a source to an absorber. In this example, identify the source, the form in which energy is transferred, and the absorber.**

HIGHER TIER ONLY

Radio waves are produced by oscillations in electrical circuits. When a current flows through a wire it creates electric and magnetic fields around the wire. When the current changes, fields change, which produces electromagnetic waves of radio frequencies. This is how radio transmitters work.

Radio waves can induce oscillations in an electrical circuit, giving rise to an alternating current with the same frequency as the radio wave itself.

7. **When radio waves are absorbed by an electrical conductor they create an alternating current with the same frequency as the radio wave itself. Suggest how this might be used in a radio receiver.**

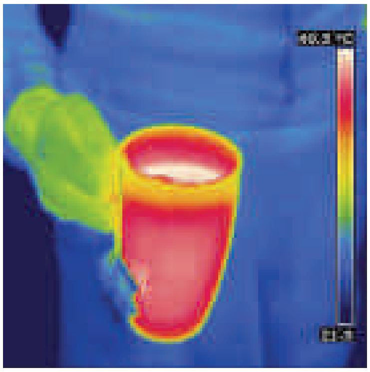


Figure 1.4.19 A thermal imaging camera detects infrared radiation given off by an object or person

DID YOU KNOW?

Halogen hobs use ring-shaped halogen lamps beneath a glass top. Although you see a bright red light, the glowing filament radiates mostly infrared radiation.

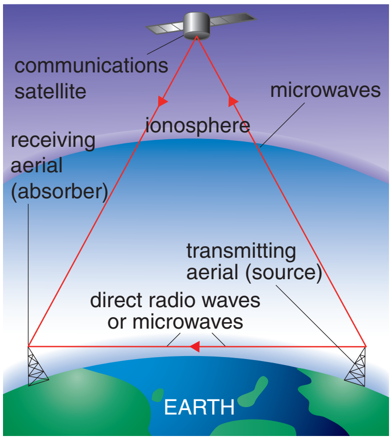


Figure 1.4.20 Direct and satellite wave communication. Microwave satellite communications are used for satellite phones and for satellite TV

DID YOU KNOW?

Bluetooth is a wireless technology for exchanging data over short distances using microwaves.

REQUIRED PRACTICAL

1.4h Investigating infrared absorption and radiation

Learning objectives:

- use appropriate apparatus to observe the interaction of electromagnetic waves with matter
- explain methods and interpret results
- recognise the importance of scientific quantities and understand how they are determined
- use SI units.

KEY WORDS

absorption
emission
infrared radiation
radiation

Anything that is warm gives off infrared radiation and the warmer it is the better a transmitter it is. However, the colour of an object also affects how much radiation it emits. If we want a radiator to work as well as possible, the colour matters.

Colour also makes a difference to absorbing infrared radiation. If you want to make sure you stay cool on a hot day, choose the right clothing. You'll cook in the wrong colour!

These pages are designed to help you think about aspects of the investigation rather than to guide you through it step by step.

SAFETY

A risk assessment is required for this practical work.

Ensure heater complies with local education authority and CLEAPSS regulations.

Investigating absorption

Alex's teacher is showing the class how to compare different surfaces to see which is better at absorbing infrared radiation. She has set up two metal plates, one on either side of a heater. One plate has a shiny surface and the other has been blackened. On the back of each plate a cork stopper has been stuck on with wax. The heater is turned on. After a few minutes one of the stoppers drops off and the other follows several minutes later.

1. **What does this experiment show?**
2. **Which stopper do you predict will drop off first? Explain your reasoning.**
3. **What needs to be done to make sure the experiment is a fair test?**

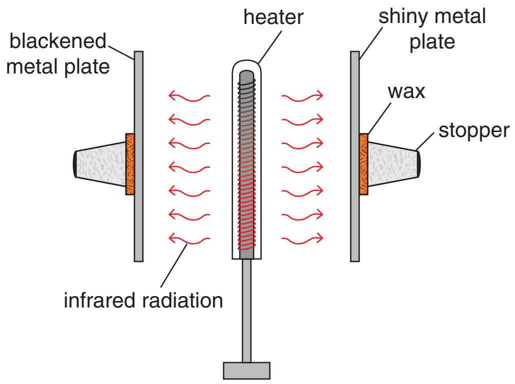


Figure 1.4.21 Experiment to compare absorption of infrared radiation by different surfaces

Link: 1.4h ⟶ 1.4i

Commenting on the design of an experiment

1.4h

Experiments have to be designed well if the results are to be meaningful. The experiment shown in Figure 1.4.22 has been designed to compare how good different surfaces are at emitting infrared radiation (radiating thermal energy). The cube is filled with very hot water and an infrared detector is held opposite each of the various faces in turn. The different faces have different finishes on them and it is possible to compare the readings from each.

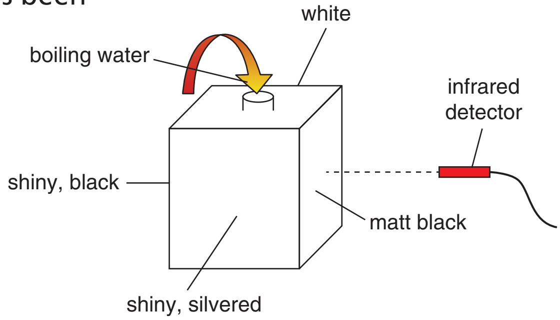


Figure 1.4.22 Experiment to compare infrared radiation emitted by different surfaces

4 **Why does the experiment use one can with four different surfaces rather than four cans, each a different type of surface?**

5 **Why is it designed so that each face has the same width?**

6 **What needs to be true about the positioning of the infrared detector?**

7 **If the detector is held at each face in turn for three 30-second periods, and the average reading for each face calculated, what type of graph could you use to display the data?**

An alternative way of investigating the amount of infrared radiation emitted by different surfaces is to replace the infrared detector with a thermometer with a blackened bulb.

8 **Using what you learned about absorbers of infrared radiation in the first investigation, explain why a thermometer with a blackened bulb is used.**

9 **How does the temperature shown give a measure of the amount of infrared emitted by each surface?**

DID YOU KNOW?

Firefighters use infrared cameras to locate unconscious bodies in smoke-filled buildings. Even though visible light can't penetrate the smoke to enable the body to be seen, the infrared radiation emitted by the body can.

KEY INFORMATION

Make sure you understand about the main features of the design of an experiment. The equipment has been developed in a particular way for good reasons and you need to know what they are.

Applying the ideas

Some ideas in science have an immediate application and ones about infrared affect our everyday lives. We can use the results of these experiments to inform us about the way that various objects should be designed.

Think about the results of the investigation into absorbing infrared radiation.

10 **What does this suggest about the best colour for:**
- **a** **a firefighter's suit?**
- **b** **solar panels on the roof of a house, absorbing thermal energy into water to use inside?**

Now think about the experiment on radiating infrared radiation.

11 **What does this suggest about the best colour for:**
- **a** **a teapot?**
- **b** **the pipes on the back of a refrigerator, which need to radiate thermal energy from the inside of the fridge to its surroundings?**

1.4i Reflection and refraction of electromagnetic waves

Learning objectives:

- recall that different substances may refract or reflect electromagnetic waves
- construct ray diagrams to illustrate refraction at a boundary
- use wavefront diagrams to explain refraction in terms of change of wave speed in different substances.

KEY WORDS

diffuse
ray diagram
reflection
refraction
specular
wavefront

When an electromagnetic wave meets the surface of another substance, it may be reflected or travel on into the substance. How the wave behaves depends on the nature of the surfaces and the speed of the wave in the different substances.

HIGHER TIER ONLY

Reflection of electromagnetic waves

Most objects you see are visible because they reflect light. If the surface is shiny, it acts like a mirror, and an image is formed. All the light rays from one direction are reflected at the same angle. But at a rough surface, like cloth or paper, the light rays from one direction are scattered in all directions.

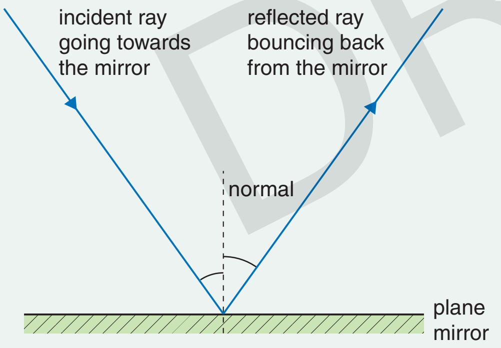


Figure 1.4.23 **Ray diagram** for reflection from a plane mirror. The incident and reflected rays make equal angles with the normal (a line at 90° to the surface of the mirror)

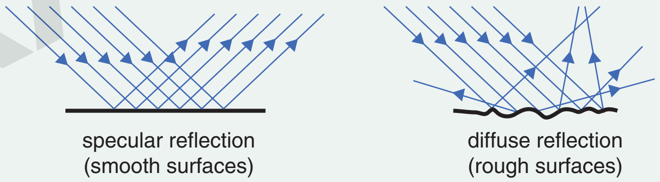


Figure 1.4.24 **Reflection** from a smooth, shiny surface is called a **specular** reflection. A rough surface scatters light in a **diffuse** reflection

1. **Explain why you can't see a reflection of yourself when you look at a sheet of paper.**
2. **Why do your clothes stay the same colour in a reflection from a mirror?**

KEY INFORMATION

Studying how visible light behaves is relatively easy because we can see what happens. We can then predict, check and understand how other electromagnetic waves behave.

Refraction of electromagnetic waves

If a light ray in air hits another transparent medium, such as glass or water, it may be transmitted. Using a ray of light directed at a glass block, we can see how the ray behaves.

The ray diagram in Figure 1.4.25 shows light bending towards the normal when it enters the glass block and away from the normal when it leaves.

This is called **refraction**. The change of direction happens at the boundary between the two media.

3 **Draw a ray diagram for a ray of light passing from water into air. (Hint: the ray behaves the same as when passing from glass to air.)**

4 **Explain what the 'normal' is in a ray diagram.**

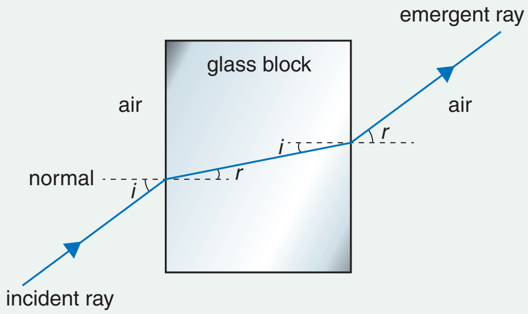


Figure 1.4.25 Light is refracted towards the normal when it travels from air to glass, and away from the normal when it travels from glass to air

Explaining refraction

A **wavefront** is a line that joins all the points on a wave that are moving up and down together at the same time. The wavefront is at right angles to the direction the wave is travelling.

We can see what happens when waves are refracted by looking at plane water waves in a ripple tank. In Figure 1.4.26 the water wave travels from deep water (Medium 1) into shallow water (Medium 2) at an angle to the boundary. The left-hand part of the wave reaches the boundary first. These wavefronts get closer together because waves travel more slowly in shallower water, and the wavefront changes direction. The wave is refracted towards the normal.

KEY INFORMATION

In a ray diagram, the arrow represents the direction in which the waves is travelling. For simplicity, the wavefronts are not shown, but they would be at right angles to the direction of the ray.

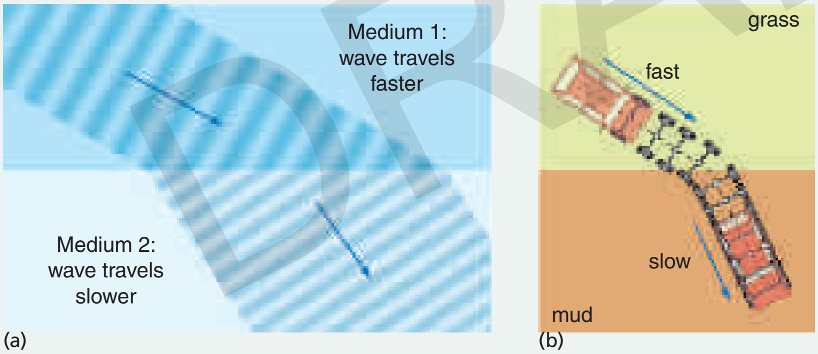


Figure 1.4.26 (a) The direction of travel of the wave, shown by the arrows, bends towards the normal when the wave slows down. (b) When a car drives at an angle into mud, the wheels that reach the mud first slow down first so the car changes direction. (The differential in the axle allows the wheels to turn at different speeds)

Wavefront diagrams like Figure 1.4.26 can be used to show how electromagnetic waves refract at boundaries. The diagram is the same for light travelling from air into water, as light travels more slowly in water than in air.

KEY INFORMATION

From the wave equation, speed = frequency × wavelength. The frequency (number of waves per second) does not change when a wave moves across a boundary, so for a smaller speed the wavelength must also be smaller.

5 **Draw a wavefront diagram for a wave travelling from water to air.**

6 **The wavefronts get farther apart after a wave leaves a boundary. What has happened to the speed of the wave?**

MATHS SKILLS

1.4j Using and rearranging equations

Learning objectives:

- select and apply appropriate equations
- substitute numerical values into equations using appropriate units
- change the subject of an equation.

KEY WORDS

proportional
rearrange an equation
subject of an equation
substitute

When we have values for all the variables in an equation except one, we can calculate the missing variable. It's easier to do this if we first rearrange the equation so the missing variable is the subject.

Period and frequency

Let's use the equation linking period and frequency as an example:

$T = \frac{1}{f}$

Remember, frequency, *f*, is the number of waves passing a point each second. The unit of frequency is the hertz (Hz), which means cycles *per second*. The period, *T*, is measured in seconds (s).

It's easy to use the equation in this form to calculate the period of a wave, *T*, if you know the frequency, *f*.

Example: A wave has a frequency of 5 Hz. What is its period?

Substituting 5 Hz into the equation $T = \frac{1}{f}$ gives $T = \frac{1}{5}$ s. The period is $\frac{1}{5}$ s or 0.2 s.

But what if you know the period, *T*, and you want to find out the frequency, *f*?

Example: Calculate the frequency when the period is 4 seconds.

Use the equation $T = \frac{1}{f}$

Rearrange it to make *f* the **subject of the equation.**

Multiply both sides by *f*: $Tf = 1$

Divide both sides by *T*: $f = \frac{1}{T}$

Substitute $T = 4$ s into the rearranged equation.

$f = \frac{1}{4\,s} = 0.25$ Hz

KEY INFORMATION

You do not need to remember the equations on this page as they will be on the equation sheet. But you need to know when and how to use each equation.
You also need to be able to rearrange an equation. Rearranging an equation means making another variable the subject of the equation. The subject of the equation is on its own, usually on the left-hand side.

1 **Work out the period of a wave when the frequency is:**

a **100 Hz** **b** **1000 Hz**
c **15 000 Hz.**

2 **Work out the frequency of a wave with period:**

a **5 s** **b** **10 s** **c** **150 s.**

Speed, frequency and wavelength

The wave equation links wave speed, frequency and wavelength:

wave speed = frequency × wavelength

$v = f\lambda$

Practise rearranging this equation as required to answer the following questions.

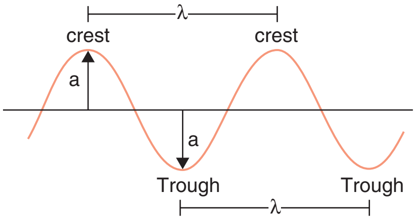


Figure 1.4.27 Wavelength of a transverse wave

3 **Use the equation $v = f\lambda$ to calculate the speed of a wave with:**
- **a frequency 100 Hz and wavelength 2 m**
- **b frequency 100 Hz and wavelength 2 cm**
- **c frequency 100 Hz and wavelength 2 mm.**

4 **Rearrange the wave equation to make frequency the subject.**

5 **Calculate the frequency of a wave with**
- **a wavelength 0.5 m and speed 25 m/s**
- **b wavelength 0.05 m and speed 250 m/s**
- **c wavelength 0.005 m and speed 2500 m/s.**

6 **a Rearrange the wave equation to calculate the wavelength given the speed and the frequency.**

b Calculate the wavelength of a sound wave in air with frequency 500 Hz and speed 330 m/s.

MATHS

When you rearrange an equation, always do the same operation (such as multiplication or division) to both sides. For example, if you divide one side of the equation by the variable λ, you must divide both sides of the equation by λ.

Changes in velocity, frequency and wavelength

Sound travels at different speeds through different media. One of the factors that contributes to this is density. The denser the material, the closer the atoms or molecules and the quicker the vibrations will travel through that substance.

If speed increases when a sound wave is transmitted from one medium to another, what effect does that have on the wave's frequency and wavelength?

If speed increases then either frequency or wavelength must also increase. This is because in the wave equation, wave speed is **proportional** to frequency and wavelength.

Material	Speed of sound (m/s)
Air	330
Water	1500
Wood	3300
Titanium	6100

7 **Red light has a wavelength of 6.5×10^{-7} m and moves a distance of 3.0 m in 1.0×10^{-8} s. Calculate the frequency of red light.**

8 **A sound wave has a wavelength of 25 cm in air.**

Use the data in the table to calculate its wavelength in titanium. Assume that the frequency of the wave does not change.

Check your progress

You should be able to:

☐ Understand that waves transfer energy and information. →	☐ Give examples of energy transfer by waves (including electromagnetic waves). →	☐ Describe evidence that, e.g. for ripples on a water surface, it is the wave and not the water itself that travels.
☐ Know that waves can be transverse or longitudinal. →	☐ Give examples of longitudinal and transverse waves. →	☐ Explain the difference between transverse and longitudinal waves.
☐ Describe how sound waves travel through air or solids. →	☐ Describe how to measure the speed of sound waves in air. →	☐ Explain how to calculate the depth of water using echo – sounding.
☐ Describe the amplitude, wavelength, frequency and period of a wave. →	☐ Use the wave equation $v = f\lambda$ to calculate wave speed. →	☐ Rearrange and apply the wave equation.
☐ Name the main groupings of the electromagnetic spectrum. →	☐ Compare the groupings of the electromagnetic spectrum in terms of wavelength and frequency. →	☐ Describe how radio waves are produced (HT only).
☐ Give examples of the uses of the main groupings of the electromagnetic spectrum. →	☐ Describe examples of energy transfer by electromagnetic waves. →	☐ Explain why each type of electromagnetic wave is suitable for its applications.
☐ Understand that waves can be absorbed, transmitted or reflected at a surface (HT only). →	☐ Describe examples of transmission and reflection of waves (including electromagnetic waves) at material interfaces (HT only). →	☐ Explain why different substances may refract or reflect electromagnetic waves (HT only).
☐ Draw a labelled ray diagram to illustrate reflection of a wave at a boundary (HT only). →	☐ Construct ray diagrams to illustrate refraction at a boundary (HT only). →	☐ Use wavefront diagrams to explain refraction in terms of a change in wave velocity (HT only).

Worked example

1 **The table below shows the electromagnetic spectrum.**

A	microwave	infrared	visible light	B	X-rays	gamma rays

Write down the names of the waves labelled A and B.

A = radio waves B = ultraviolet waves

Both answers are correct. Use a mnemonic to remember the correct order.

2 **X-rays and gamma rays are dangerous to humans. Explain how they can also be used in medical contexts without lasting harm.**

We can use them for X-rays to see our bones and for treating cancer by killing the cancer cells.

This answer is a good start but is incomplete. It doesn't give a full explanation. The answer should also say that we can use them in medical contexts by controlling the exposure dose.

3 **A ship is mapping the seabed using echo sounding. It sends out a sound wave and receives an echo 1.6 s later. If the depth of the water is 1200 m at that position, what is the speed of sound in water?**

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{1200\,\text{m}}{1.6\,\text{s}} = 750\,\text{m/s}$$

The correct equation has been chosen, but the calculation is incorrect. The student has forgotten that the sound wave travels down to the seabed and back in 1.6 s, so the total distance is 2400 m. The speed of sound in water should be 1500 m/s.

4 **A red laser pointer has a wavelength of 650 nm. If the speed of light is 3.0×10^8 m/s, what is the frequency of the laser light waves?**

speed = frequency × wavelength, or

$v = f\lambda$

Rearranging the equation to make frequency the subject:

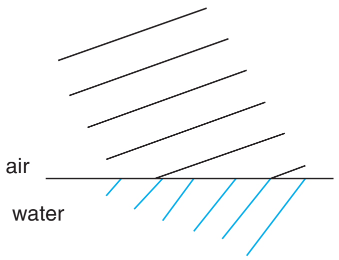
$f = \frac{v}{\lambda}$

$$f = \frac{3.0 \times 10^8\,\text{m/s}}{6.5 \times 10^{-7}\,\text{m}} = 0.46 \times 10^{15}\,\text{Hz}$$

frequency of red light waves = 4.6×10^{14} Hz

This is a good answer – the calculation is correct and it is clearly set out. The wavelength in nm has been correctly converted to a value in m. Always take extra care when working with standard form.

5 **Complete the wavefront diagram to show the refraction of light from air to water.**



The wavefronts are closer together in the denser medium, which is correct. But, crucially, when waves go from a less dense medium to a denser medium, they are refracted towards the normal. Here they are refracted *away* from the normal. Also, each wavefront must be continuous from one medium into the other.

End of chapter questions

Getting started

1 Which of the following is a longitudinal wave? **1 Mark**

A sound wave B water wave C light wave D radio wave

2 A wave is often drawn as a series of peaks and troughs. Use this idea to explain what is meant by the wavelength of the wave. **2 Marks**

3 Which is a correct unit of frequency? **1 Mark**

A metres B watts C hertz D metres per second

4 A water wave in a ripple tank has a frequency of 4 Hz. Calculate the period (T) of the wave using the formula $T = 1/f$. **1 Mark**

5 A microwave has a wavelength of 1 cm. What type of wave, other than a microwave, might have a wavelength of 1 m? **1 Mark**

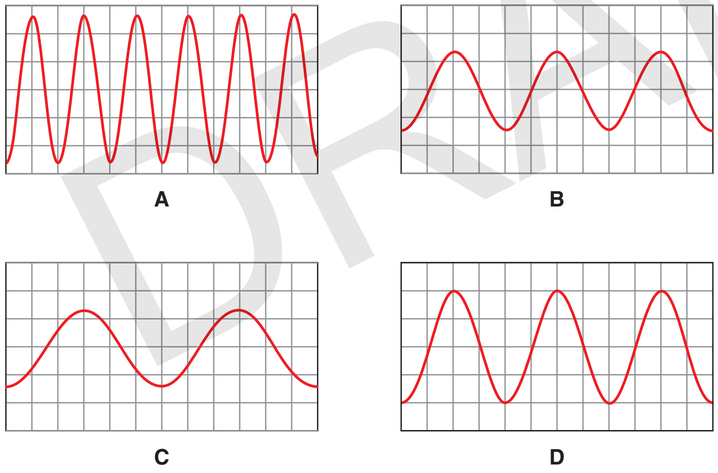
6 A ray of light is shone onto a dull, white object but no reflected ray is seen. Explain what type of reflection this is and what happens to the light. **2 Marks**

7 In the diagram, the red lines represent four different waves.

a Which two waves have the same frequency?

b Which two waves have the same amplitude?

c Which wave has the shortest wavelength? **6 Marks**



Going further

8 Name the parts of the electromagnetic spectrum labelled A and B in the diagram. **1 Mark**

radio waves	microwave	A	visible light	ultraviolet	B	gamma rays

9 Name the two types of electromagnetic radiation that are used to cook food. **1 Mark**

10 Describe one practical application each for

a microwaves

b gamma rays. **2 Marks**

11 a Which electromagnetic wave has the shortest wavelength?

b Which electromagnetic wave has the highest frequency? 2 Marks

12 What is the speed of a water wave if it has a wavelength of 8 cm and a frequency of 2 Hz? 2 Marks

More challenging

13 a What type of waves are electromagnetic waves?

b Describe the electromagnetic spectrum. 2 Marks

14 Explain what happens to a ray of light as it goes into a transparent plastic block. 2 Marks

15 Construct a wavefront diagram to show waves in a ripple tank passing into a shallower area created by a block on the bottom of the tank. 3 Marks

Most demanding

16 A survey ship sailing in a straight line at a speed of 4 m/s sends out a sound pulse from its echo-sounder every 10 s. The time between each pulse being sent and its reflection are as follows; 0.25 s, 0.30 s, 0.35 s, 0.40 s. 0.40 s, 0.40 s, 0.40 s, 0.05 s, 0,40 s, 0.35 s, 0.30 s, 0.25 s, 0.25 s and 0.25 s.

Use this data to describe the seabed the ship is sailing over and suggest a reason for the apparent anomalous result. 6 Marks

17 An ultrasound scanner was used to measure the size of a kidney stone. Use the following data to determine the thickness of the stone. 6 Marks

Speed of ultrasound in the stone = 4.00 km/s

Time between emitted ultrasound pulse and reflection from the front of the stone = 0.0500 ms

Time between emitted ultrasound pulse and reflection from the back of the stone = 0.0600 ms

Total: 40 Marks

11 Aluminium sulfate is a useful substance in many household and garden products. It can be made by reacting aluminium hydroxide with sulfuric acid.

$2Al(OH)_3 + 3H_2SO_4 \rightarrow Al_2(SO_4)_3 + 6H_2O$

a Calculate the ratio of reactant to product.

b Calculate how much aluminium sulfate can be produced by 250 g aluminium hydroxide.

c Calculate the mass of aluminium sulfate produced by 3000 kg of aluminium hydroxide.

(Relative atomic masses Ar: Al = 27; S = 32; O = 16; H=1)

6 Marks

Total: 23 Marks