4 Electricity and magnetism

Key terms

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Term	Definition
Alternating current (a.c.)	The direction of current flow reverses repeatedly
Direct current (d.c.)	Electrons flow in one direction only
Electric current	The charge passing a point per unit time (current $I = Q/t$ where Q is the charge flowing past a particular point in time t)
Electromagnet	Temporary magnet produced by passing an electric current through a coil of wire wound on a soft iron core
Electromagnetic induction	The production of a p.d. across a conductor when it moves through a magnetic field or is at rest in a changing magnetic field
Electromotive force (e.m.f.)	The electrical work done by a source in moving unit charge round a complete circuit
Kilowatt-hour (kWh)	The electrical energy transferred by a 1 kW appliance in 1 hour
Light-dependent resistor (LDR)	Semiconductor device in which the electrical resistance decreases when the intensity of light falling on it increases
Magnetic field	A region of space where a magnet experiences a force due to other magnets or an electric current
Magnetic materials	Materials that can be magnetised by a magnet; in their non-magnetised state, they are attracted by a magnet
Non-magnetic materials	Materials that cannot be magnetised and are not attracted to a magnet
Parallel circuit	Components connected side by side and the current splits into alternative paths and then recombines; current from the source is larger than the current in each branch
Permanent magnet	Made of steel and retains its magnetism
Potential difference (p.d.)	The work done by a unit charge passing through a component
Relay	Electromagnetic switch
Resistance	Opposition of a conductor to the flow of electric current; symbol R measured in ohms (Ω)
Series circuit	Components connected one after the other; the current is the same in each part of a series circuit
Solenoid	Long cylindrical coil of wire
Temporary magnet	Made of soft iron, and loses its magnetism easily
Thermistor	Semiconductor device in which the electrical resistance decreases when the temperature increases
Transformer	Two coils (primary and secondary) wound on a soft iron core which allow an alternating p.d. to be changed from one value to another
Conventional current	Flows from positive to negative; the flow of free electrons is from negative to positive
Electric field	A region in space where an electric charge experiences a force due to other charges
Light-emitting diode (LED)	Semiconductor device which emits light when it is forward biased but not when it is reverse biased
Potential divider	Provides a voltage that varies with the values of two resistors in series in a circuit

4.1 Simple phenomena of magnetism

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Key objectives

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

- describe the forces between magnets and magnetic materials
- describe induced magnetism
- understand that it is the interaction of magnetic fields which leads to magnetic forces
- state the differences between the properties of permanent and temporary magnets and between magnetic and non-magnetic materials
- describe a magnetic field and know how to draw the magnetic field around a bar magnet showing its direction which is the direction experienced by a north pole at that point
- know that the spacing of magnetic field lines represents the strength of the magnetic field
- describe how to plot magnetic field lines using either iron filings or a compass and how the compass is used to determine the direction of the magnetic field.
- describe the uses of permanent magnets and electromagnets

Properties of magnets

Materials can be divided into two types:

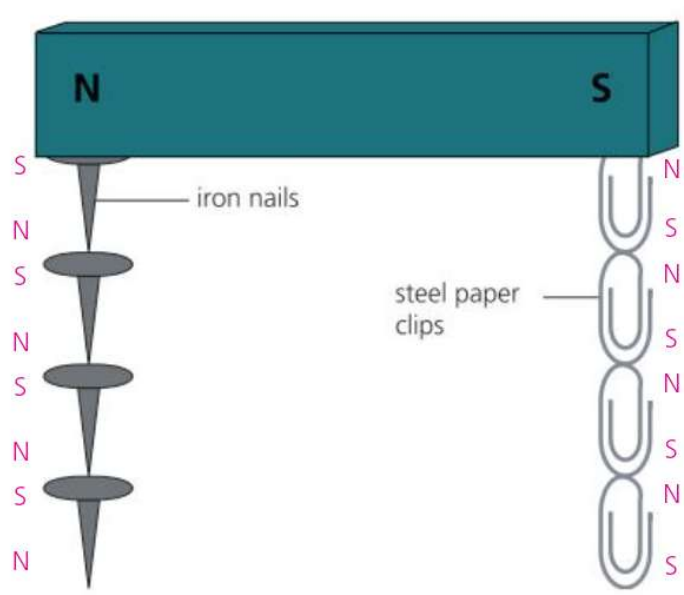
- **magnetic materials** – materials which are attracted to magnets. Mainly the ferrous metals iron and steel and their alloys. Cobalt, nickel and certain alloys are also magnetic materials. These materials can all be magnetised to form a magnet.
- **non-magnetic materials** – materials which are not attracted to magnets and cannot be magnetised to form a magnet.

Every magnet has two poles: a north pole (N pole) and a south pole (S pole). If a magnet is supported so that it can swing freely, the N pole will always point towards the Earth's magnetic north pole. The other end is the S pole. When you bring two magnets near each other they both experience a magnetic force. If two magnets are close together, poles N and N will repel, poles S and S will repel, but poles N and S will attract.

Remember *like poles repel* and *opposite poles attract*.

Induced magnetism

A unmagnetised magnetic material can be magnetised by bringing it close to or by touching a magnet. This is called induced magnetism.
Figure 4.1 shows iron nails and steel paper clips becoming magnetised.



▲ **Figure 4.1 Induced magnetism**

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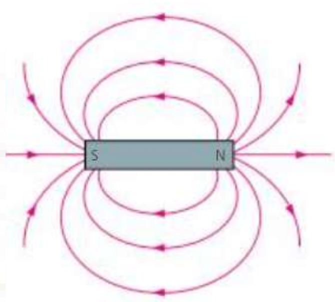
As you can see, each nail or paperclip has their own N and S pole as they have each become magnets. If you remove the iron nails from the magnet, the chain collapses. If you take the steel paperclips away, they are still attracted to each other. This is because:

- iron is an example of a soft magnetic material (one that loses its magnetism easily and is unmagnetised easily). The induced magnetism in the iron is **temporary**. Soft magnetic materials are used to make **temporary magnets**.
- steel is an example of a hard magnetic material (one that is harder to magnetise but also harder to unmagnetise). The induced magnetism is **permanent**. Hard magnetic materials are used to make **permanent magnets**.

Magnetic fields

A **magnetic field** is a region in space where a magnet experiences a force. Figure 4.2 shows the magnetic field around a bar magnet.



▲ **Figure 4.2 Magnetic field lines around a bar magnet**

The arrows show the direction of force. It has been agreed that the arrows show the direction of the force on the N pole of a magnet at that point.

In Figure 4.2 you can see the magnetic field lines are closer together at the poles. This shows that the strength of the magnetic field is greater here. You can use the spacing of the magnetic field lines to work out where the magnetic field is stronger and where it is weaker.

As you know, two magnets feel a force without touching. This is because their magnetic fields are interacting. It is the interaction of the magnetic fields which causes the force.

Skills

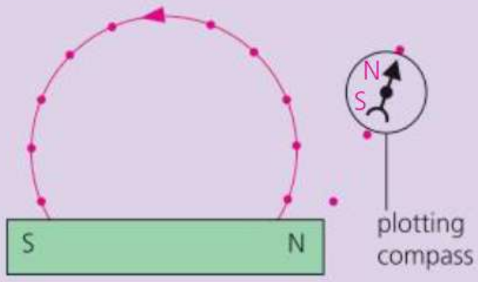
Plotting magnetic field lines

To plot magnetic field lines, you can use a compass or iron filings. To show the direction of the magnetic field you must use a compass.

Plotting compass method: The magnet is placed on a sheet of paper and a small plotting compass is placed near one pole. Mark dots on the paper at the positions of the ends of the compass needle. The compass is moved along so that the end that was over the first dot is now over the second dot. The other end is marked on the paper as the third dot. Continue this process until the other pole of the magnet is reached.

Joining the dots with a smooth line shows the field, with the direction being given by the compass arrow. Repeat for further lines starting at different points.

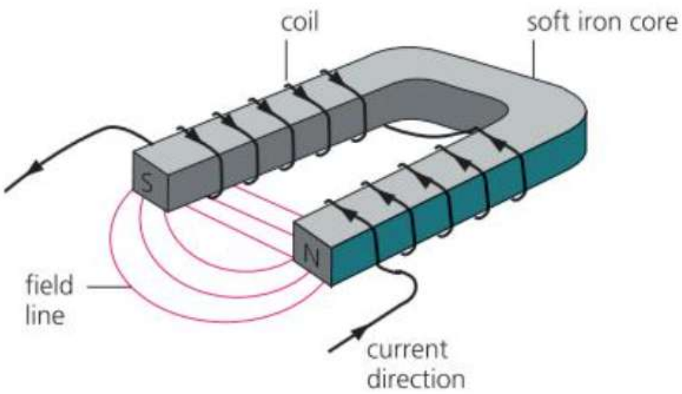
Iron filings method: Iron filings are sprinkled on a piece of paper placed over a magnet. When the paper is tapped gently, the filings will be seen to line up with the field lines. The field pattern can then be drawn along these lines on the paper.



▲ **Figure 4.3 Plotting field lines**

Electromagnets

An **electromagnet** is a temporary magnet produced by passing an electric current through a coil of wire wound on a soft iron core. The soft iron core is magnetised only when there is a current in the wire.



▲ **Figure 4.4 An electromagnet**

The strength of an electromagnet can be increased by:

- increasing the current
- increasing the number of coils
- moving the poles closer together

The different features of permanent magnets and electromagnets mean they have different uses. Table 4.1 summarises these.

▼ **Table 4.1 Uses of permanent magnets and electromagnets**

Type of magnet	Description	Examples of uses
Permanent	Magnetic field strength is constant and permanent	Compass, electric motor (topic 4.5.5), electric generator (topic 4.5.2), microphone, loudspeaker
Electromagnet	Temporary magnet so can be switched on and off and the magnetic field strength can be varied.	In cranes to lift scrap metal, in electric bells, magnetic locks, relays, in motors and generators.

Sample question

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1 Describe how to plot the magnetic field, including its direction, around a bar magnet using iron filings. [5]

Student's answer

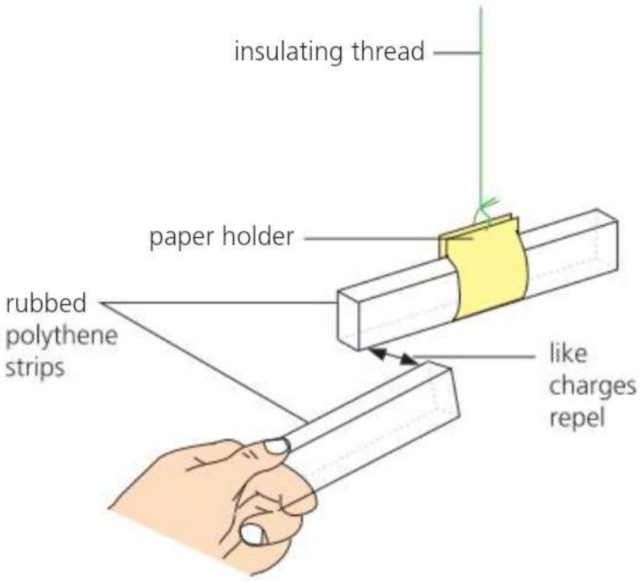
The iron filings should be spread around the magnet and the pattern drawn.

Use a plotting compass to find the direction. [1]

Teacher's comments

The student basically knows the right experiment, but the description is very vague and lacking in essential detail.

charged objects are close together (+ and +, or – and –) they will repel, but unlike charges (+ and –) will attract.



▲ **Figure 4.5 Investigating charges**

Charges, atoms electrons

Atoms are made of small positively charged nucleus containing positively charged protons surrounded by an equal number of negatively charged electrons (Topic 5.1.1). The charge on an electron and proton is equal and opposite, and as there is the same number of each in an atom, the atom is neutral.

Rubbing an object makes it charged because the friction causes electrons to be transferred from one material to the other.

- The material gaining electrons becomes negatively charged (it now has more electrons than protons).
- The material losing the electrons becomes positively charged (it now has fewer electrons than protons).

Remember the protons are in the nucleus; they cannot move. It is only the electrons that move.

The charge on an electron is the smallest possible quantity of charge. Charge is measured in coulombs (C). The charge on one electron is 1.6×10^{-19} coulombs, but you do not need to remember that number.

Electrons, insulators and conductors

Electrical insulators are materials in which electrons are firmly held in their atoms and cannot move, so electric charge cannot flow. Most plastics are good insulators.

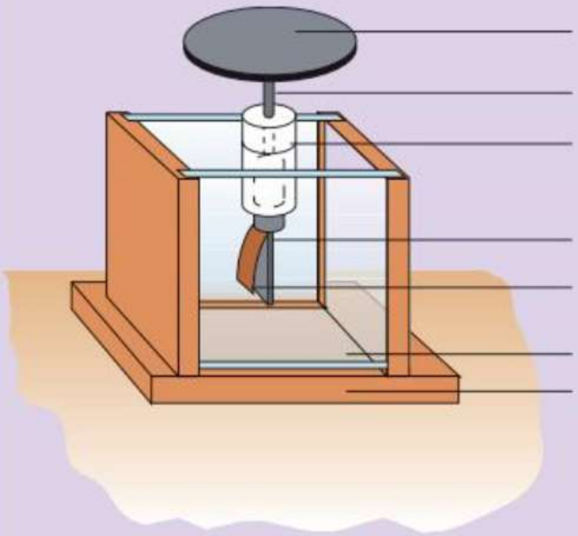
Electrical conductors are materials in which electrons can move freely from atom to atom, so electric charge can flow easily. All metals and some forms of carbon are conductors.

Insulators can become charged because the charge cannot move from where the transfer happened. To charge the polythene rod (insulator) you use a cloth (another insulator). A conductor will only become charged if it is held by an insulating handle. This is because electrons are transferred between the conductor and the ground through the body of the person holding the conductor.

Skills

Detecting charges and testing materials

You can detect a charge using a gold-leaf electroscope (Figure 4.6). The gold leaf is only attached to the metal rod by the top edge and is free to move. The rod is held in place by a plastic support and in a wooden box with glass sides to protect from any movement of air.



▲ **Figure 4.6 Gold-leaf electroscope**

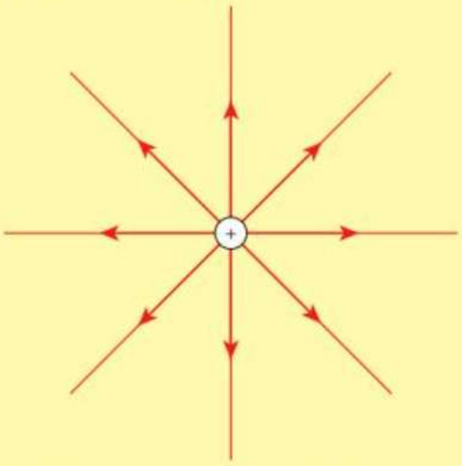
To detect a charge: Bring the charged rod near to the metal cap of the electroscope. The gold leaf rises away from the plate. When the charged rod is removed, the leaf falls. The gold leaf will behave the same whether the object is negatively or positively charged.

Charging the electroscope: Drag a charged polythene rod (negatively charged) across the surface of the metal cap. The leaf will rise and remain up even when the rod is removed. Electrons have been transferred from the polythene rod to the electroscope. The electroscope is now negatively charged.

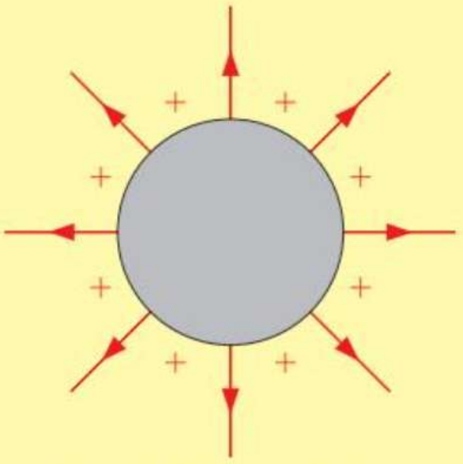
Testing materials to see if they are insulators or conductors: Touch the charged electroscope with different objects made of different materials, e.g. a wooden or glass rod, or a piece of metal or plastic. If the leaf falls, the object is a conductor. If the leaf remains in place, the object is an insulator.

Electric field

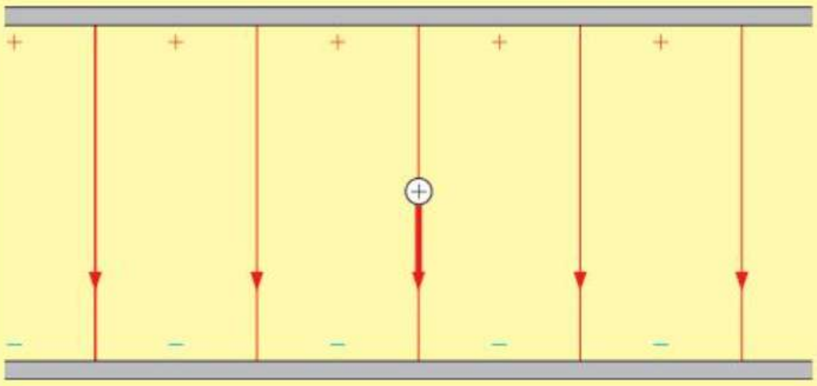
An **electric field** is a region in space where an electric charge experiences a force. The field can be represented by lines of force in the direction that a positive charge would move if placed at a point in the field. You should be able to describe the pattern and direction of the electric field around a point charge (Figure 4.7a), a charged conducting sphere (Figure 4.7b) and between two oppositely charged parallel plates (Figure 4.7c).



▲ **Figure 4.7a Electric field around a positive point charge**



▲ **Figure 4.7b Electric field around a positively charged sphere. Notice the field lines appear to start in the centre of the sphere. Do not draw them inside though.**



▲ **Figure 4.7c Electric field between two parallel plates. This is a uniform field. You can tell because the field lines are parallel and evenly spaced.**

Sample question

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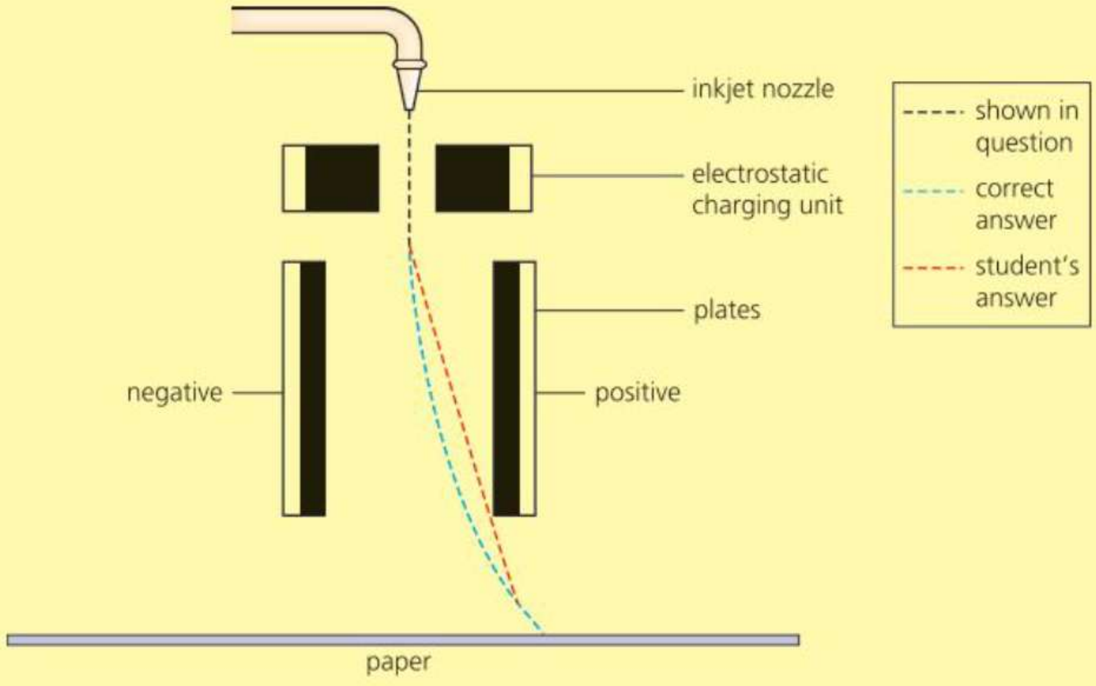
2 An inkjet printer produces a stream of very small droplets from a nozzle. The droplets are given a negative electric charge and then pass between two plates with positive and negative charge, as shown in Figure 4.8.



▲ **Figure 4.8**

- **a** State the type of field in the region between the charged plates. [1]
- **b** State and explain the force acting on the droplets in this region. [2]
- **c** Extend the dashed line to complete the path of the droplets. [3]

Student's answers

- *a* *There is an electric field in this region.* [1]
- *b* *There is a force to the right on the ink droplets.* [1]
- *c* *The student's answer is shown by the red dashed line in Figure 4.8.* [2]

Correct answers

- **a** There is an electric field in this region. [1]
- **b** There is a force to the right on the ink droplets, which are attracted to the positive plate. [2]
- **c** The correct answer is shown by the blue dashed line in Figure 4.8. [3]

Teacher's comments

- **a** Correct answer.
- **b** The student correctly stated that the force is to the right but failed to explain it.
- **c** The path between the plates must be curved, as the droplets are accelerated to the right by the electric force.

4.2.2 Electric current

Key objectives

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

- understand that an electric current is the flow of charge and in metals is the movement of free electrons
- describe the use of ammeters and know the difference between direct (d.c.) and alternating current (a.c.)
- define electric current as the charge passing per unit time and use the correct equation
- understand the difference between conventional current and the flow of electrons in a circuit

Electric current is a flow of charge. In metals there are free electrons. These are electrons that are only loosely attached to a particular atom. When you connect a battery across the ends of a metal wire, these free electrons start to move. They move slowly in the direction of the positive terminal of the battery (remember positive and negative charges attract).

Calculating current

An electric current is defined as the charge passing a point per unit time. This can be written as:

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

where I is the current and Q is the charge flowing past a particular point in time t.

Conventional current

The agreed direction of **conventional current** in a circuit is from the positive terminal to the negative terminal of a battery. The electrons flow in the opposite direction to conventional current.

Ammeters

Electric current is measured in amperes, usually abbreviated to amps (symbol A), by an ammeter, which must be connected in **series**. The positive terminal of the ammeter is connected to the positive terminal of the supply. Figure 4.9 shows an ammeter in series with component X.

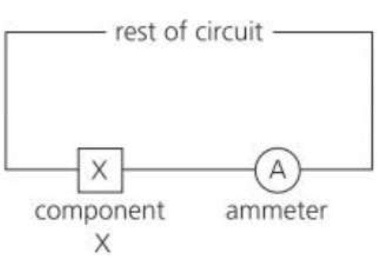


Figure 4.9 Measuring the current through component X

Ammeters can be analogue (have a scale and pointer like a moving-coil ammeter) or have a digital display. Whichever type you use you should use the correct range. If the current you are measuring is unknown, it is good practice to start on the largest scale, for example, 0 to 10 A. If the reading is very small or not detected, you can reduce the range perhaps to 0 to 1 A. Choose the smallest possible range to get the most accurate result, e.g if the current is 0.02 A, you would choose the 100 mA range.

Skills

Expressing quantities using multipliers

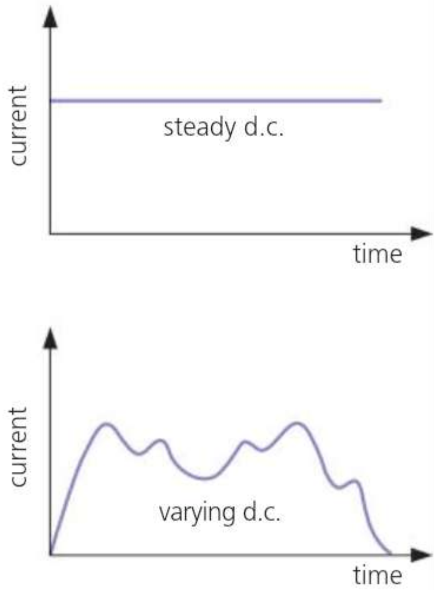
You should be able to use the common multipliers. These are used to express very large or very small numbers.

▼ **Table 4.2 Common prefixes**

Prefix	Symbol	Multiply by	Prefix	Symbol	Multiply by
centi	c	$\times 10^2$			
kilo	k	$\times 10^3$	milli	m	$\times 10^{-3}$
mega	M	$\times 10^6$	micro	μ	$\times 10^{-6}$
giga	G	$\times 10^6$	nano	n	$\times 10^{-9}$

For example,

1200000 N = 1.2 MN　　0.03 A = 30 mA　　5 km = 5000 m

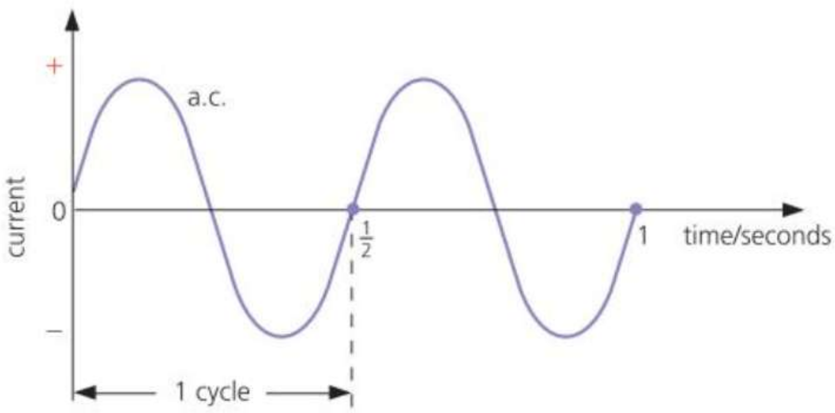


▲ **Figure 4.10a Direct current**

Direct and alternating current

In a **direct current (d.c.)**, the charge flows in one direction only (Figure 4.10a).

In an **alternating current (a.c.)**, the direction of the current changes repeatedly (Figure 4.10b).



▲ **Figure 4.10b Alternating current**

The number of complete cycles per second of a.c. is the frequency of the alternating current.

Sample question

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3 A charge of 35 C flows around a circuit in 14 s.

a Calculate the current flowing. [2]

b The charge on each electron is 1.6×10^{-19} C. Calculate the number of electrons flowing around the circuit in this time. [2]

Student's answers

a $I = \frac{Q}{t} = \frac{35}{14} = 2.5\text{ A}$ [2]

b number of electrons $= \frac{35}{1.6 \times 10^{-19}} = 2.19 \times 10^{19}$ [1]

Teacher's comments

a Correct answer.
b The student started the calculation correctly, but made a mistake in the calculation of the powers of 10.

Correct answers

a $I = \frac{Q}{t} = \frac{35}{14} = 2.5\,\text{A}$ [2]

b number of electrons $= \frac{35}{1.6 \times 10^{-19}} = 2.2 \times 10^{20}$ to 2 s.f. [2]

Revision activity

There are three important electrical quantities used to describe circuits that are sometimes confused: current (Topic 4.2.2), electromotive force (Topic 4.2.3) and resistance (Topic 4.2.4). To help you remember and understand them, take a piece of plain paper and divide it into three equal sections. In the first section, summarise the information about electric current.

4.2.3 Electromotive force and potential difference

Key objectives

By the end of this section, you should be able to:
- define electromotive force (e.m.f.) and potential difference (p.d.) and know that they are both measured in volts
- describe the use of voltmeters
- recall and use the correct equations for e.m.f. and p.d.

Electromotive force (e.m.f.) is the electrical *work done by a source* in moving unit charge around a circuit. It is measured in volts.

Potential difference (p.d.) across a component is the *work done by unit charge* passing through a component. It is also measured in volts.

Calculating e.m.f. and p.d.

The equations for e.m.f (E) and p.d. (V) appear the same:

$$E = \frac{W}{Q} \text{ and } V = \frac{W}{Q}$$

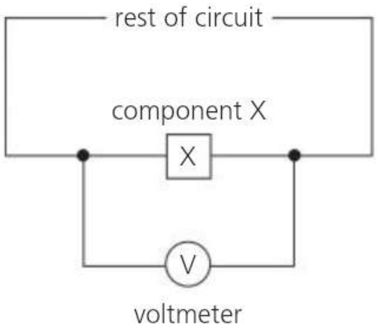
When calculating e.m.f. (E), W is the energy transferred to an amount of charge Q by the battery or power supply.

When calculating p.d. (V), W is the work done when the amount of charge Q passes between two points.

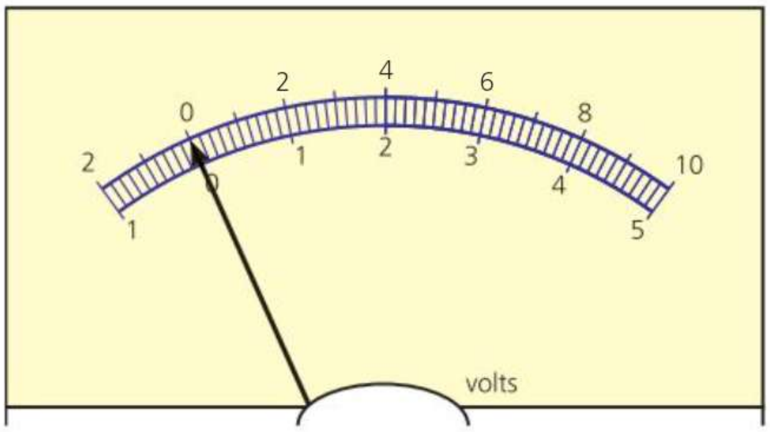
Voltmeters

The p.d. across a component is measured by a voltmeter, which must be connected in **parallel** with the component. It can be helpful to build the circuit and then place the voltmeter across the component. The positive terminal of the voltmeter should be connected to the side of the component nearest to the positive side of the battery. Figure 4.11 shows a voltmeter in parallel with component X.

Voltmeters can be analogue (have a scale and pointer as in Figure 4.12) or have a digital display.



▲ **Figure 4.11 Measuring the p.d. across component X**



▲ **Figure 4.12 An analogue voltmeter scale**

Revision activity

In the second section of your electrical quantities sheet, summarise the information about e.m.f and p.d.

Whichever type you use, you should use the correct range. Choose the smallest possible range to get the most accurate result. For example, if you expect the measurement to be 12 V, you must choose a suitable scale such as 0 to 20 V. If the reading is 0.006 V, you should use 0 to 10 mV.

4.2.4 Resistance

Key objectives

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

- recall and use the correct equation to calculate resistance
- describe an experiment using a voltmeter and ammeter to determine the resistance of a component using the correct equation
- describe how resistance of a wire is affected by its length and its cross-sectional area
- sketch and explain the voltage–current graphs for a resistor, a filament lamp and a diode
- recall and use the relationship between the resistance of a wire and its length and cross-sectional area

Resistance is the opposition of a conductor to the flow of electric current.

Resistance is calculated using the equation:

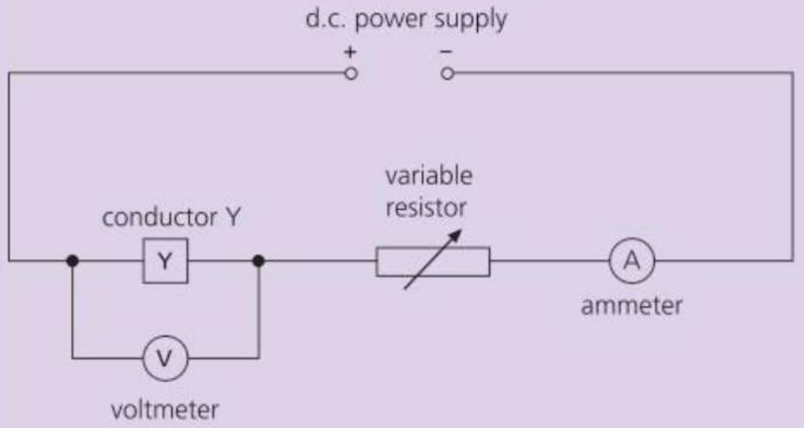
$$R = \frac{V}{I}$$

where R = resistance in ohms (Ω), V = p.d. and I = current.

Skills

Determining resistance

To determine the resistance of an unknown component, you must connect the circuit as shown in Figure 4.13.

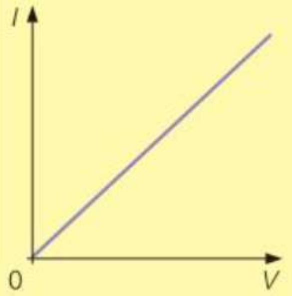


▲ **Figure 4.13 Circuit to determine the resistance of unknown conductor Y**

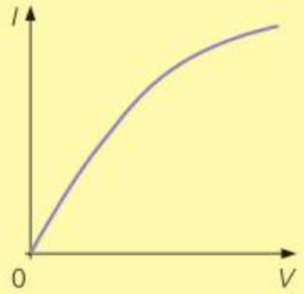
1 The ammeter is connected in **series** with the power supply and conductor Y (so that the current flows *through* the ammeter).
2 The voltmeter is in **parallel** with conductor Y (so that the voltmeter measures the p.d. *between* the ends of the conductor).
3 Record the values of the p.d. in volts and the current in amps.
4 Change the setting of the variable resistor and record at least five more pairs of values.
5 Work out the value of the resistance using the equation $R = \frac{V}{I}$ for each pair of readings.

Current–voltage graphs

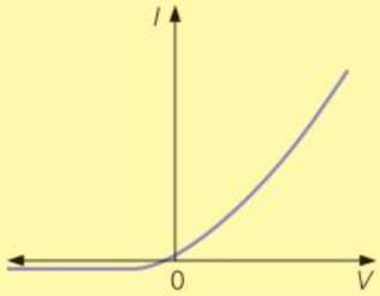
If you plot the values of current and voltage from your experiment on a graph, you get distinctive shape graphs for different components (Figure 4.14).



▲ **Figure 4.14a Resistor**



▲ **Figure 4.14b Filament lamp**



▲ **Figure 4.14c Diode**

The resistance is equal to the inverse of the gradient of the current–voltage graph of a component.

A resistor or metal wire at constant temperature shows a directly proportional relationship (a straight line through the origin). The gradient is constant because the resistance is constant (Figure 4.14a).

For a filament lamp, the gradient decreases. This shows the resistance is increasing. As the voltage and current increase, the temperature of the filament increases. Resistance increases with a large increase in temperature (Figure 4.14b).

Diodes (including LEDs) have an extremely high resistance in the reverse direction, so no reverse current can flow. Resistance is very low in the forward direction, so current can flow easily (Figure 4.14c). Diodes are used in circuits to make sure the current only flows in one direction. They can be used to change alternating current to direct current.

Resistance of a metal wire

The resistance of a metal wire depends on:

- length – the longer the wire, the greater the resistance
- cross-sectional area – the thicker the wire, the smaller the resistance
- the material the wire is made from

Resistance is directly proportional to the length. This means if you double the length, the resistance will double. Resistance is inversely proportional the cross-sectional area. This means if you double the cross-sectional area, the resistance halves.

Sample questions

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4 A student carries out an experiment to find the resistance of a wire. They vary the supply voltage and take measurements using an ammeter and a voltmeter. The table shows their first three readings.

Reading	1	2	3	4
voltage/V	1.10	2.10	2.95	1.75
current/A	0.20	0.35	0.50	?
resistance/Ω	5.50	6.00	?	?

Make sure you show your working for all parts of this question.

a Calculate the resistance for the third pair of readings. [1]

b Calculate the average value of resistance for the first three readings. [1]

c Using this average value of resistance, calculate the current the student can expect when they take the fourth reading. [2]

Student's answers

a Reading 3: $R = \frac{V}{I} = \frac{2.95}{0.50} = 5.9\,\Omega$ [1]

b Average $V = \frac{1.10 + 2.10 + 2.95}{3} = \frac{6.15}{3} = 2.05\,V$

Average $I = \frac{(0.20 + 0.35 + 0.50)}{3} = \frac{1.05}{3} = 0.35\,A$

Average $R = \frac{2.05}{0.35} = 5.86\,\Omega$ [0]

c Reading 4: $I = VR = 1.75 \times 5.86 = 10.26\,A$ [0]

Teacher's comments

a Correct answer.

b The student should have taken the average of the three values of resistance, using the answer for part **a**. It is simply good fortune that their answer is close to the correct answer.

c The student has rearranged the equation $V = IR$ incorrectly. Observation and comparison with the first three readings show that the calculated value is unlikely.

Correct answers

a Reading 3: $R = \frac{V}{I} = \frac{2.95}{0.50} = 5.9\ \Omega$ [1]

b Average $R = \frac{5.50 + 6.00 + 5.90}{3} = \frac{17.40}{3} = 5.8\ \Omega$ [1]

c Reading 4: $I = \frac{V}{R} = \frac{1.75}{5.80} = 0.30$ A to 2 s.f. $(0.3017\ \text{A})$ [2]

5 Sample A is a length of wire of given material.

a Copy and complete the table for the resistance of three more samples of wire of the same material. Choose from the following words: greater, less, same.

Sample	B	C	D
length compared with A	×2	same	×2
diameter compared with A	same	$\frac{1}{2}$	$\frac{1}{2}$
resistance compared with A			

[3]

b Add numerical values to your entries in the table to show the magnitude of resistance compared with sample A. [3]

Student's answers

Sample	B	C	D
length compared with A	×2	same	×2
diameter compared with A	same	$\frac{1}{2}$	$\frac{1}{2}$
resistance compared with A	*greater* ×2 [2]	*greater* ×2 [2]	*greater* ×4 [1]

Teacher's comments

a Correct answers – all three samples have greater resistance than sample A.

b The resistance of sample B will be ×2 greater – the student's answer to B is correct. Resistance varies with the inverse of area, not diameter, so the answer to C is incorrect. Although the answer to D is incorrect, the student has correctly carried over from the answer to C, so no further marks are lost. The answer for C should be ×4 and the answer for D should be ×8.

Correct answers

Sample	B	C	D
length compared with A	×2	same	×2
diameter compared with A	same	$\frac{1}{2}$	$\frac{1}{2}$
resistance compared with A	greater ×2	greater ×4	greater ×8

[5]

Revision activity

In the third section of your electrical quantities sheet, summarise the information about resistance.

4.2.5 Electrical working

Key objectives

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

- understand that a cell or mains supply is a source of electrical energy and that circuits transfer this energy to the circuit components and then to the surroundings
- recall and use the correct equations for electrical power and electrical energy
- define the kilowatt-hour and calculate the cost of using electrical appliances

Electrical energy and electrical power

The electrical cell, battery or mains supply are a source of electrical energy. Electric circuits transfer this energy to components in the circuit and then into the surroundings. For example, a torch battery transfers energy to the lamp; this energy is then transferred by light and by heating to the surroundings.

To calculate the electrical energy transferred, use the equation:

$$E = Ivt$$

where E is the energy transferred (J), I is the current (A), V is the p.d. (V) and t is the time (s).

It is also useful to consider the electrical power of an appliance. Remember power is the amount of energy transferred every second ($P = W/t$); the unit of power is the watt (W).

To calculate electrical power, use the equation:

$$P = IV$$

Paying for electricity

When buying electricity from a supply company, a much larger unit of electricity is used: the **kilowatt-hour (kW h)**. This is the electrical energy transferred by a 1 kW appliance in 1 hour. The company then charges a price per kilowatt–hour for the energy transferred. Remember 1 kW is 1000 W.

To calculate the energy transferred in kW h, use the equation:

$$\text{energy transferred (kW h)} = \text{power (kW)} \times \text{time (h)}$$

Sample question

REVISED

6 A travel kettle is designed for international use. With a 230 V supply, the power rating is 800 W.

a Calculate the current with a 230 V supply and the resistance of the element. [2]

b Find the current and power output of the kettle when used in another country with a 110 V supply. [3]

c Comment on the use of this kettle in the country with the 110 V supply. [1]

Student's answers

a $I = \frac{P}{V} = \frac{800}{230} = 3.48\,A$ $R = \frac{V}{I} = \frac{230}{3.48} = 66.1\,\Omega$ [2]

b I will stay the same.

$P = 110 \times 348 = 383\,W$ [1]

c The kettle will take longer to boil water. [1]

Teacher's comments

a Correct answers.

b The current cannot stay the same because R is the same but V is different. 1 mark was awarded as the student calculated the power from the wrong value of current without any further error.

c The student made a valid comment from the calculated value of P.

Correct answers

a $I = \frac{P}{V} = \frac{800}{230} = 3.48\,\text{A}$

$R = \frac{V}{I} = \frac{230}{3.48} = 66.1\,\Omega$ [2]

b The element is the same so R will stay the same.

$I = \frac{110}{66.1} = 1.66\,\text{A}$

$P = 110 \times 1.67 = 183\,\text{W}$ [3]

c The kettle will take much longer to boil water. [1]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

4 When rubbed with a dry cloth, Perspex becomes positively charged. Polythene becomes negatively charged when rubbed with a dry cloth

a Describe an experiment you could do to show the two rods have opposite charges. [3]

b Explain in terms of electron movement how a Perspex rod becomes positively charged when rubbed with a dry cloth. [3]

c Each time the cloth is used it also becomes charged. State and explain the charge on the cloth when it is used to charge the polythene rod. [2]

5 Describe the electric field around a negative point charge. [2]

6 A student is attempting to measure the current through a component. They are told it will be approximately 0.15 A. Choose the most appropriate range for the ammeter. [1]

0 to 10 A 0 to 1 A 0 to 100 mA

7 A charge of 75 C passes a point in the circuit in 5 minutes. Calculate the current in the circuit. [2]

8 Use the analogue voltmeter in Figure 4.12 to answer this question.

a Name the two ranges shown on the voltmeter. [2]

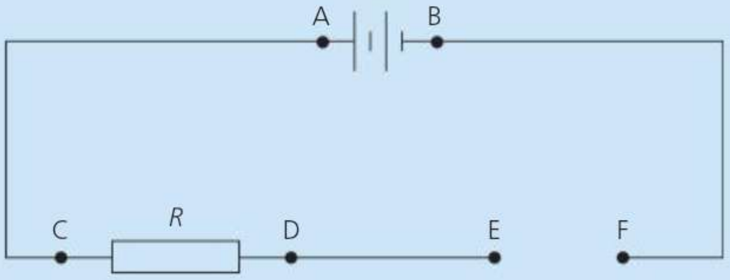
b State the value of the small divisions between 4 and 6 on the voltmeter. [1]

c A student connects the voltmeter into their circuit and the needle moves to the left. Describe what they should do to correct this. [1]

Revision activity

Create flash cards for all the equations and key words in Topic 4.2 and learn them.

9 You are asked to take measurements from the circuit shown in Figure 4.15 and are provided with an ammeter, a voltmeter and any necessary connecting wires.



▲ **Figure 4.15**

Complete the table to indicate which component, if any, you should connect across the points AB, CD and EF to take each measurement. [2]

Measurement to be taken	AB	CD	EF
current through *R* when connected to battery			
p.d. across *r* when connected to battery			

10 a Calculate the e.m.f. of a battery if it does 45 J of work moving 15 C of charge around a complete circuit. [1]

b The p.d. across a lamp is 12 V. Calculate the energy transferred to the lamp if 180 C passes through it. [2]

11 A lamp has a potential difference of 6.0 V across it and a current of 1.5 A through it. Calculate its resistance. [1]

12 The potential difference across a resistor is 2.5 V and it has a resistance of 20 Ω. Calculate the current in the resistor. [2]

13 A cylindrical block of conducting putty has a resistance of 100 Ω. Explain a change you could make to the block to reduce the resistance to 25 Ω. [4]

14 A microwave has a power rating of 800 W. It is used for 30 minutes during the day. Calculate the energy transferred by the microwave in the day in kW h. [3]

15 The potential difference across a lamp is 12 V and the current is 4.0 A. The lamp is on for 4 minutes.
Calculate:
a the energy transferred by the lamp in joules [2]
b the power of the lamp [1]

16 A 3 kW electric heater is used to heat up 2.5 kg of water of specific heat capacity 4200 J/(kg °C). The initial water temperature is 16 °C. Calculate the temperature of the water after the heater has been switched on for 2 minutes. [4]

4.3 Electric circuits

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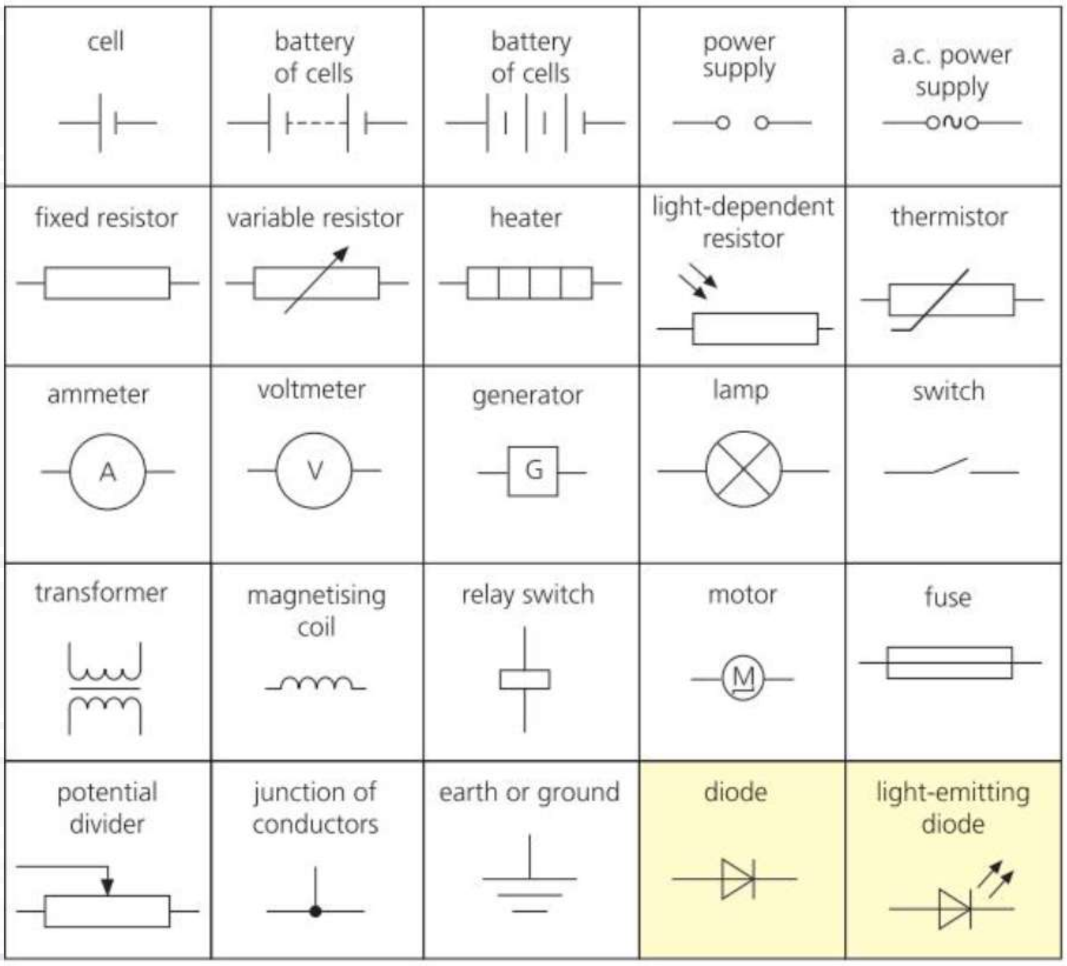
4.3.1 Circuit diagrams and components

Key objectives

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

- draw and understand circuit diagrams containing many different circuit components including diodes and light-emitting diodes (LEDs)

You must be able to draw and interpret all the symbols shown in Figure 4.16.



▲ **Figure 4.16 Circuit symbols**

Revision activity

Test yourself by creating flash cards of the circuit symbols. Make sure you recognise each of them and can draw each of them.

4.3.2 Series and parallel circuits

Key objectives

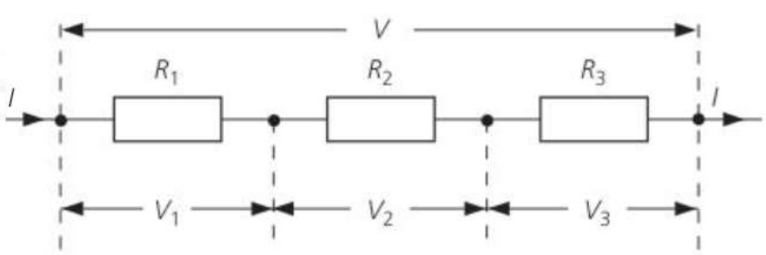
By the end of this section, you should be able to:

- understand current and potential difference in a series circuit
- understand how to build and use series and parallel circuits
- calculate the combined e.m.f. and combined resistance for components in series
- understand current and resistance in a parallel circuit
- state the advantages of using parallel circuits for lighting

- calculate current, potential difference and resistance for components in parallel
- explain why the sum of the currents entering a junction equals the sum of the currents leaving the junction

Series circuits

In a **series circuit**, there is just one path for the current to follow.



▲ **Figure 4.17 Resistors in series**

Rules for components in series:

- The current at every point in a series circuit is the same, I.

- The total resistance (R_T) in a series circuit is the sum of the individual resistances:

  $R_T = R_1 + R_2 + R_3$

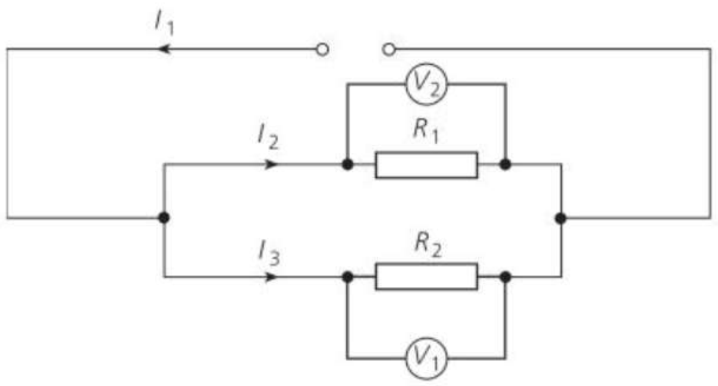
- The potential difference across components in series is equal to the sum of p.d.s across each component:

  $V = V_1 + V_2 + V_3$

- The combined e.m.f. of different sources in series is the sum of each individual e.m.f. For example, if you connect two cells which each have an e.m.f. of 1.5 V, the total e.m.f. is 3.0 V.

Parallel circuits

In a **parallel circuit**, there are alternative paths or branches for the current.



▲ **Figure 4.18 Resistors in parallel**

Rules for components in parallel:

- When components are in parallel, the current from the source is greater than the current in each branch.
- The combined resistance of components in parallel is less than the resistance of any one resistor.

- Sum of the currents entering a junction = sum of the currents leaving the junction:

  $I_1 = I_2 + I_3$
- The p.d. across components in parallel is the same:

  $V_1 = V_2$
- The total resistance R_T of R_1 and R_2 is given by:

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

Current is a flow of electrons. The electrons cannot be created or destroyed. The same number must flow per second through every point in a circuit. This is why the sum of the currents entering a junction is equal to the sum of the currents leaving the junction. It is also why the current in a series circuit is the same at every point.

In lighting circuits in homes and businesses, lamps are connected in parallel. This is because:

- Each lamp has the same p.d. across it, which is the p.d. of the supply. Each lamp is therefore the same brightness and you can have as many lamps as you want in the circuit.
- You can switch each lamp on and off individually. If one lamp should fail, the other lamps will continue to work.

Sample questions

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7 In Figure 4.17, $R_1 = 4\,\Omega$ and $R_2 = 3\,\Omega$.

a Calculate the total resistance of R_1 and R_2. [2]

b The current through R_1 is 1.5 A. State the current through R_2. [2]

c Calculate the potential differences V_1 and V_2. [2]

d The potential difference across all three resistors is 12 V. Calculate the value of V_3 and hence the resistance of R_3. [4]

Student's answers

a total resistance = 4 + 3 = 7 Ω [2]

b current through $R_2 = \frac{3}{4} \times$ current through $R_1 = 0.75 \times 1.5 = 1.125$ A [0]

c $V_1 = I_1 \times R_1 = 1.5 \times 4 = 6$ V

$V_2 = I_2 \times R_2 = 1.125 \times 3 = 3.375$ V [2]

d $V_3 = 12 - (4 + 3) = 12 - 7 = 5$ V

$R_3 = \frac{V_3}{I_3} = \frac{5}{1.125} = 4\,\Omega$ [2]

Teacher's comments

a Correct answer

b The student did not recognise that current stays the same through components in series.

c The student correctly applied their answers from part **b**.

d The student might have been on the right lines and then made errors in substituting resistances instead of voltages. With little working and no explanation, it is impossible for the examiner to know. The answer for R_3 followed on reasonably from earlier working, so credit was gained for this. [2 marks given]

Correct answers

a total resistance = 4 + 3 = 7 Ω [2]

b current through R_2 = current through R_1 = 1.5 A [2]

c $V_1 = I \times R_1 = 1.5 \times 4 = 6$ V

$V_2 = I \times R_2 = 1.5 \times 3 = 4.5$ V [2]

d supply potential difference = sum of p.d.s of rest of circuit = 12 V

$12 = V_1 + V_2 + V_3$

$12 = 6 + 4.5 + V_3$

$V_3 = 12 - (6 + 4.5) = 12 - 10.5 = 1.5$ V

$R_3 = \frac{V_3}{I} = \frac{1.5}{1.5} = 1\,\Omega$ [4]

8 In Figure 4.18, $R_1 = 4\,\Omega$, $R_2 = 3\,\Omega$, $I_1 = 4.2\,A$ and $I_2 = 1.8\,A$.

- **a** Calculate the current I_3. [2]
- **b** Calculate the total resistance of R_1 and R_2. [2]
- **c** Calculate the e.m.f. of the power supply. [2]

Student's answers

- **a** current $I_3 = I_1 + I_2 = 4.2 + 1.8 = 6.0\,A$ [0]
- **b** total resistance $= \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{3} = 0.25 + 0.333 = 0.583\ \Omega$ [0]
- **c** e.m.f. $= 6.0 \times 0.583 = 3.50\,V$ [2]

Teacher's comments

- **a** The student has wrongly thought that I_3 is the total current.
- **b** The student has applied the wrong equation.
- **c** Full marks are given despite the wrong answer. The student correctly followed on from parts **a** and **b**.

Correct answers

- **a** current $I_3 = I_1 - I_2 = 4.2 - 1.8 = 2.4\,A$ [2]
- **b** $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{3} = \frac{3+4}{12} = \frac{7}{12}$, $R_T = 1.7\,\Omega$ [2]
- **c** e.m.f. $= 2.4 \times 3 = 7.2\,V$ [2]

Revision activity

Create a table summarising the key features of series and parallel circuits. Include circuits diagrams.

4.3.3 Action and use of circuit components

Key objectives

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

- understand that for a constant current, the p.d. across a conductor increases as its resistance increases
- describe how a variable potential divider can change the voltage output, and recall and use the correct equation for two resistors used in a potential divider.

Increase in resistance of a conductor

Consider a conductor with a constant current through it. The product of the resistance and the current gives the potential difference ($V = IR$, remember the resistance $R = V/I$).

If the resistance of the conductor increases and the current remains constant, then the potential difference across the conductor increases.

Light-dependent resistors and thermistors

The resistance of a **light-dependent resistor (LDR)** falls with increasing light level. It can be connected in a circuit that is required to respond to changes in light level.

The resistance of a **thermistor** decreases considerably with increasing temperature.

8 In Figure 4.18, $R_1 = 4\,\Omega$, $R_2 = 3\,\Omega$, $I_1 = 4.2\,A$ and $I_2 = 1.8\,A$.

a Calculate the current I_3. [2]

b Calculate the total resistance of R_1 and R_2. [2]

c Calculate the e.m.f. of the power supply. [2]

Student's answers

a current $I_3 = I_1 + I_2 = 4.2 + 1.8 = 6.0\,A$ [0]

b total resistance $= \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{3} = 0.25 + 0.333 = 0.583\ \Omega$ [0]

c e.m.f. $= 6.0 \times 0.583 = 3.50\,V$ [2]

Teacher's comments

a The student has wrongly thought that I_3 is the total current.

b The student has applied the wrong equation.

c Full marks are given despite the wrong answer. The student correctly followed on from parts **a** and **b**.

Correct answers

a current $I_3 = I_1 - I_2 = 4.2 - 1.8 = 2.4\,A$ [2]

b $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{1}{4} + \frac{1}{3} = \frac{3+4}{12} = \frac{7}{12}$, $R_T = 1.7\,\Omega$ [2]

c e.m.f. $= 2.4 \times 3 = 7.2\,V$ [2]

Revision activity

Create a table summarising the key features of series and parallel circuits. Include circuits diagrams.

4.3.3 Action and use of circuit components

Key objectives

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

- understand that for a constant current, the p.d. across a conductor increases as its resistance increases
- describe how a variable potential divider can change the voltage output, and recall and use the correct equation for two resistors used in a potential divider.

Increase in resistance of a conductor

Consider a conductor with a constant current through it. The product of the resistance and the current gives the potential difference ($V = IR$, remember the resistance $R = V/I$).

If the resistance of the conductor increases and the current remains constant, then the potential difference across the conductor increases.

Light-dependent resistors and thermistors

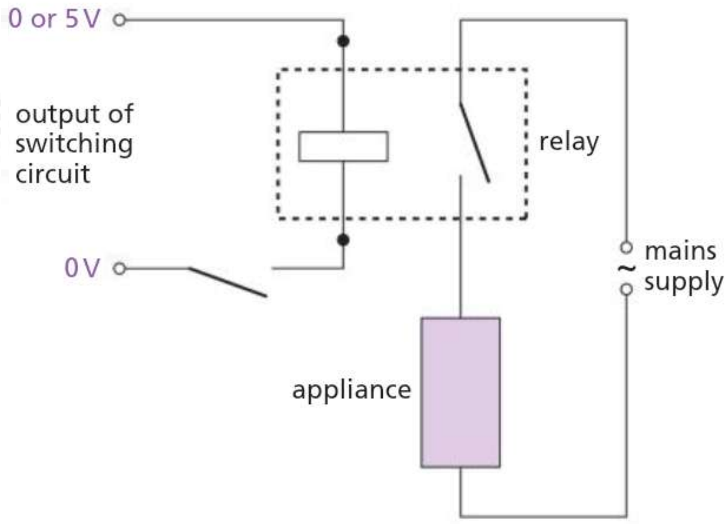
The resistance of a **light-dependent resistor (LDR)** falls with increasing light level. It can be connected in a circuit that is required to respond to changes in light level.

The resistance of a **thermistor** decreases considerably with increasing temperature.

These components can be used as an input to a switching circuit such as in a security light that only works at night or in a fire alarm that switches on when it detects heat.

Relays

Switching circuits cannot power the appliance they are switching on, for example, starting the motor of a washing machine when the water is at the correct temperature. A **relay** is a switch turned on or off by an electromagnet.



▲ **Figure 4.19 A relay is used to switch on a mains appliance**

The small current from the switching circuit, switches on the electromagnet which attracts the switch, closing it. The appliance is then switched on.

Variable potential divider

A **potential divider** provides a voltage that varies with the values of two resistors in series in a circuit. Figure 4.20 shows a potential divider with two separate resistors R_1 and R_2.

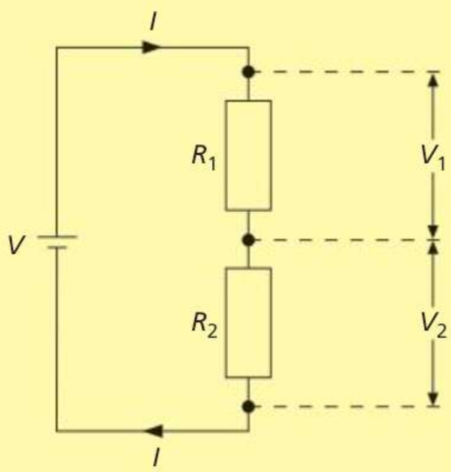
If the value of R_1 or R_2 changes, the output voltage will change.

If R_1 increases with R_2 unchanged, V_1 increases and V_2 decreases.

If R_2 increases with R_1 unchanged, V_2 increases and V_1 decreases.

Remember the sum of p.d.s for components in series is equal to the total p.d. The ratio of the voltages across the two resistors is given by:

$$\frac{R_1}{R_2} = \frac{V_1}{V_2}$$



▲ **Figure 4.20 Potential divider with two separate resistors**

Skills

Using ratios to determine the p.d. across each resistor in a potential divider arrangement

You can use this ratio to determine the p.d. across each resistor.

For example, in Figure 4.20, $R_1 = 20\,\Omega$ and $R_2 = 80\,\Omega$.

First, find the ratio of the resistors:

$$\frac{20}{80} = \frac{1}{4}, \text{ so ratio is 1:4}$$

Next, add together the parts of the ratio to find the total number of shares:

number of shares = 1 + 4 = 5

Then multiply the supply voltage by the proportion of shares required:

$$V_1 = 1 \times \frac{V}{5} \text{ and } V_2 = 4 \times \frac{V}{5}$$

Looking at another example: two resistors R_1 and R_2 are in series with an e.m.f. = 12 V. $R_1 = 10\,\Omega$ and $R_2 = 50\,\Omega$. Calculate the p.d. across R_2.

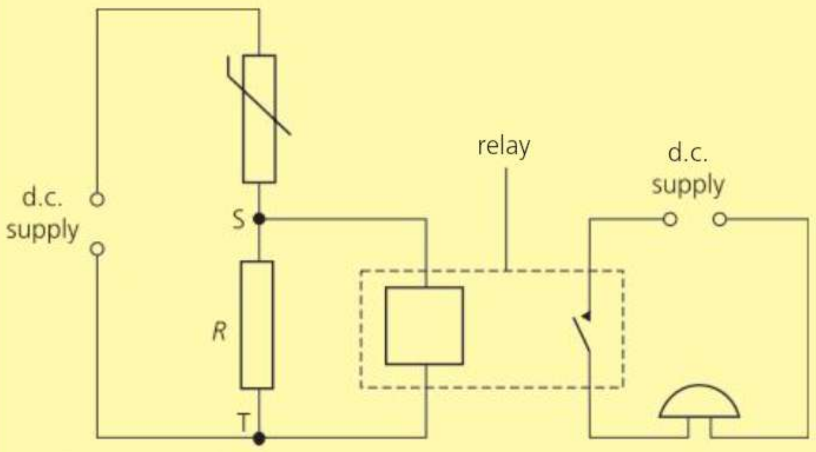
Ratio of resistors:

$$\frac{10}{50} = \frac{1}{5}, \text{ so ratio is 1:5}$$

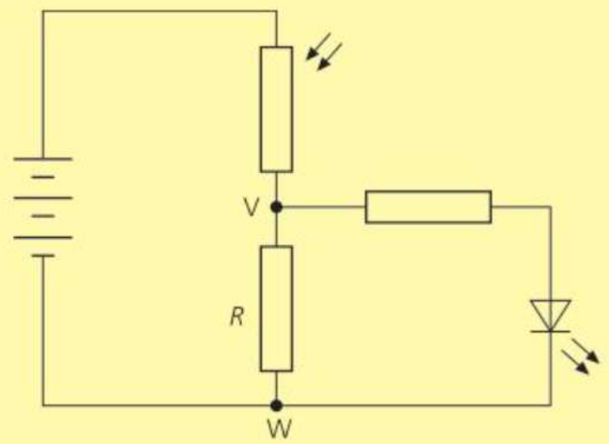
number of shares = 1 + 5 = 6

$$V_2 = 5 \times \frac{12}{6} = 10\text{ V}$$

Figure 4.21 shows a circuit that acts as a fire alarm. When the temperature of the thermistor rises, its resistance falls. The thermistor and fixed resistor R are a potential divider, so the p.d. between S and T rises and enough current flows into the relay for it to switch on the bell.



▲ **Figure 4.21 Fire alarm circuit**



▲ **Figure 4.22 Light-sensitive circuit using a remote light-emitting diode**

Figure 4.22 shows a circuit that acts as a warning when too much light enters an automated photographic laboratory. A **light-emitting diode (LED)** on the control panel outside the laboratory can light up to show the warning.

When operating correctly in the dark, the resistance of the LDR is high. The p.d. between V and W is low, so no current flows through the LED.

If light enters the laboratory, there is an increase in light level and the resistance of the LDR falls. The LDR and fixed resistor R are a potential divider, so the p.d. between V and W rises and enough current flows through the LED for it to light up and give a warning.

Light-emitting diodes (LED)

LEDs will only light when forward biased (current in direction of the arrow). LEDs must have a resistor in series with it to limit the current as diodes have low resistance in forward bias and can easily be damaged. They are very useful as indicator lights.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

17 A student has three 1.5 V cells. Describe how they could combine them to have a p.d. of 4.5 V for their circuit. [2]

18 A student has a 20 Ω resistor and a 40 Ω resistor.

a Calculate their combined resistance if they are connected in series. [1]

b Calculate their combined resistance if they are connected in parallel. [2]

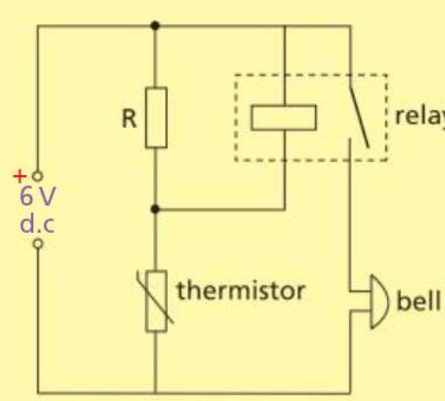
19 In Figure 4.18, the current I_1 = 0.5 A, the current I_2 = 0.3 A and the resistance of R_1 = 40 Ω.

a Calculate the p.d. across R_1. [2]

b Calculate the resistance of resistor R_2. [3]

20 The supply voltage in Figure 4.20 is 12 V and R_1 = 25 Ω and R_2 = 75 Ω. Calculate the potential difference across each resistor. [3]

21 Figure 4.23 shows a circuit. Describe what happens when the temperature increases. [4]



▲ **Figure 4.23**

4.4 Electrical safety

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Key objectives

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

- state possible hazards when using mains electricity
- understand that the mains circuit consists of three wires – live, neutral and earth – and explain why switches are placed in the live wire
- explain how trip switches and fuses work and choose appropriate settings and values for each
- explain why metal outer casings for electrical appliances are earthed
- state that for double-insulated appliances, the fuse protects the appliance from current surges even without the earth

Dangers of electricity

Some common hazards when using a mains supply are:

- Damaged insulation can lead to very high currents flowing in inappropriate places. This poses a danger of electric shock or fire.
- Cables that overheat owing to excessive current can lead to fire or damage in the appliance or in the cables and insulation.
- Damp conditions. Water lowers the resistance to earth, so damp conditions can lead to the current shorting and can cause shocks. Electrical devices for use in damp conditions must be designed to high standards of damp proofing, especially connectors and switches.
- Overloading plugs, extension leads or sockets. If you have too many appliances plugged into one outlet, then the current will be too great. This can cause overheating and so is a fire risk.

House circuits

Mains circuit wire consists of three wires: the live wire, the neutral wire and the earth wire. The mains supply is usually a.c. and the potential difference of the live wire with respect to earth varies depending on your country (lowest value of any country is 110 V a.c. and highest value is 240 V a.c.). The neutral and earth wires are at 0 V with respect to earth.

The circuits in a home are all connected in parallel across the live and neutral wires. This means they all receive the mains p.d. and can be switched on and off separately. The switch is placed in the live wire, so that when the appliance is switched off it is not connected to the mains supply.

Fuses and trip switches

A fuse is a piece of wire that melts and breaks when too much current flows through it. This switches off the circuit to protect against shock, fire or further damage. Fuses are placed in the live wire to safely switch off the device.

Trip switches or circuit breakers contain electromagnets which when the current is large enough will separate contacts and break the circuit. They operate quickly and can be easily reset by pressing a button.

Fuses come in different values and trip switches have to be set to the right setting. To choose the correct values, you need to know the maximum current expected. For example, if the maximum current is 9 A you might use a 13 A fuse or choose a 10 A trip switch.

Earthing

Appliances with metal cases have to be earthed using the earth wire. This is to protect against electric shock. For example, if the live wire became loose and touched the metal casing, the whole appliance would become live. To prevent this happening, the earth wire is connected to the metal appliance and connected to earth. If the case became live, a large current would pass through the live wire to earth through the earth wire. The fuse will melt and break, switching off the appliance.

Double insulation

Many electrical appliances have a plastic outer case, they are double-insulated. As plastic is an insulator, there is no risk of shock and these appliances do not need an earth connection. They will still have a fuse as it protects the appliance from current surges due to a short circuit.

Sample question

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9 People are gathered after dark on wet grass. Explain whether the following three situations are potentially dangerous:

- **a** A heater and several high-powered electric lamps are supplied by an old extension cable. [2]
- **b** There is a cut in the outer insulation of the cable. [2]
- **c** The devices are connected to a switch lying on the lawn. [2]

Student's answers

- *a The electrical power is likely to require too much current in the cable, leading to overheating. This could cause a fire or melting of the insulation.* [2]
- *b There is insulation on the individual wires, so the cable is safe.* [0]
- *c The dew on the cable connection could cause an electric shock.* [2]

Teacher's comments

- **a** Correct answer
- **b** Incorrect answer – using a cable with any sort of cut is unsafe practice.
- **c** Correct answer.

Correct answers

- **a** The electrical power is likely to require too much current in the cable, leading to overheating. This could cause a fire or melting of the insulation. [2]
- **b** There could also be a cut in the insulation of the individual wires, which would be difficult to see. There would be a danger of electric shock. [2]
- **c** The water on the cable switch could cause an electric shock. [2]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

22 Chose the correct fuse from 1 A, 3 A, 5 A, 13 A or 30 A for each of the following appliances. Take mains to be 220 V a.c. and remember $P = IV$.

- **a** 500 W microwave [2]
- **b** 2.5 kW heater [2]
- **c** 1.1 kW kettle [2]

Revision activity

Summarise this section into five key points about electrical safety.

4.5 Electromagnetic effects

REVISED

4.5.1 Electromagnetic induction

Key objectives

By the end of this section, you should be able to:
- understand that a changing magnetic field linked to a conductor or a conductor moving in a magnetic field can induce an e.m.f. in the conductor
- describe an experiment which demonstrates electromagnetic induction and state the changes needed to increase the induced e.m.f.
- understand the e.m.f. is induced in a direction which opposes the change causing it
- use Fleming's right-hand rule to work out the relative directions of the force, magnetic field and induced current

When the magnetic field through a conductor changes, an e.m.f is induced. This is called **electromagnetic induction**. This change can be caused by:
- a conductor moving through a magnetic field (Figure 4.24)
- a magnetic field moving relative to a conductor (Figure 4.25)

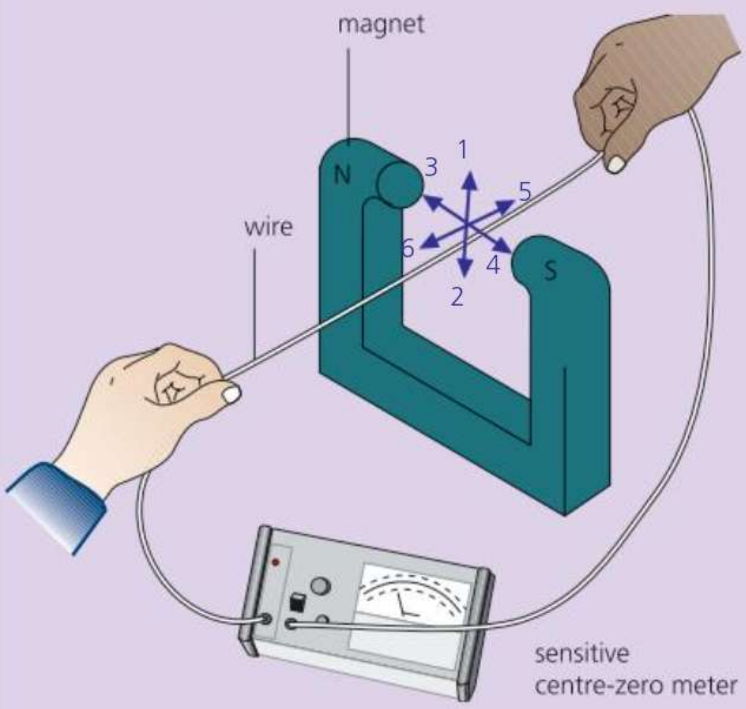
Skills

Demonstrating electromagnetic induction

You should be able to describe an experiment to demonstrate electromagnetic induction.

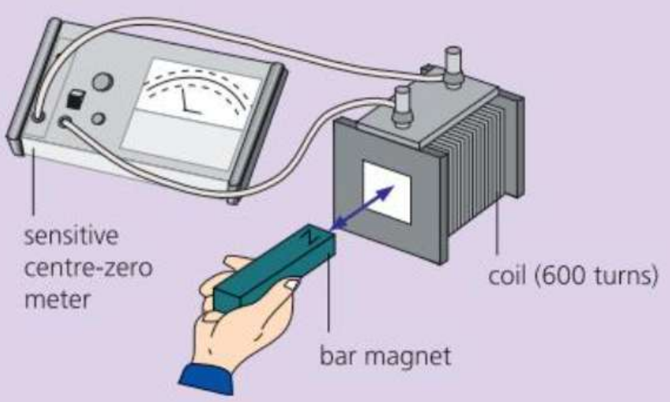
When an e.m.f. is induced in a conductor which is part of a complete circuit, there is a current. You can measure the current using a sensitive centre-zero meter. A centre-zero meter is used because the current can be induced in either direction.

Demonstrating moving conductor: In Figure 4.24, an e.m.f. is induced only when the wire moves upwards (direction 1) or downwards (direction 2). The meter deflects in opposite directions in these two cases, but only when the wire is in motion. When moved in the other directions, the wire does not cut the magnetic field, so no e.m.f. is induced.



▲ **Figure 4.24 A voltage is induced when the wire is moved up or down in the magnetic field**

Demonstrating moving magnetic field: In Figure 4.25, an e.m.f. is induced only when the magnet is moving. If the magnet is pushed in, the meter deflects one way; if the magnet is pulled out, the meter deflects in the opposite direction. You can also change the direction of the induced current by reversing the poles of the magnet.



▲ **Figure 4.25 A voltage is induced in the coil when the magnet is moved in or out**

Remember an e.m.f. is always induced when the magnetic field through a conductor changes. If there is a complete circuit, a current will also be induced.

Factors affecting the size of an induced e.m.f.

The induced e.m.f. increases with an increase in:

- speed of relative motion of the magnet or coil
- number of turns of any coil
- strength of the magnet

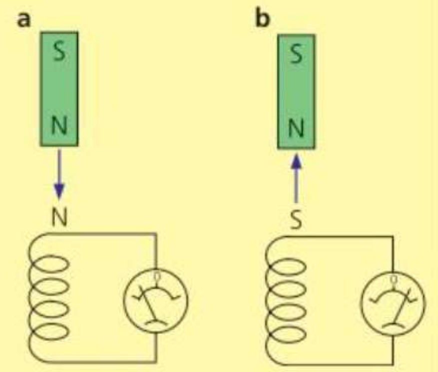
Revision activity

Try explaining to a partner how an e.m.f. is induced in a conductor.

The direction of the induced e.m.f. *opposes* the change that caused it.

In Figure 4.26, the moving magnet induces an e.m.f. in the coil, which causes a current in the coil. The current produces its own magnetic field, which opposes the movement of the magnet.

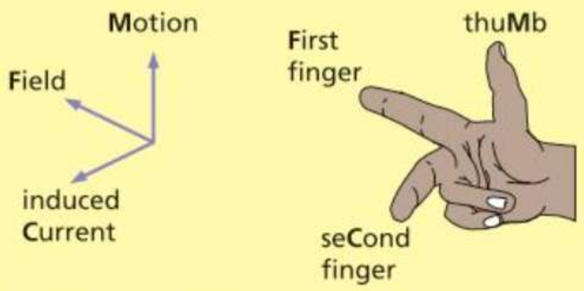
When the magnet moves down in Figure 4.26a, the top of the coil becomes a N pole. This repels the N pole of the magnet. When the magnet moves up in Figure 4.26b, the top of the coil becomes a S pole. This is to attract the N pole of the magnet



▲ **Figure 4.26 The induced current opposes the motion of the magnet**

You should be able to state and use the relative directions of force, field and induced current. For a straight wire moving at right angles to a magnetic field, you use Fleming's right-hand (generator) rule.

Remember magnetic field direction is the direction of force felt by a N pole so the lines are in the direction from N to S.



▲ **Figure 4.27 The right-hand generator rule**

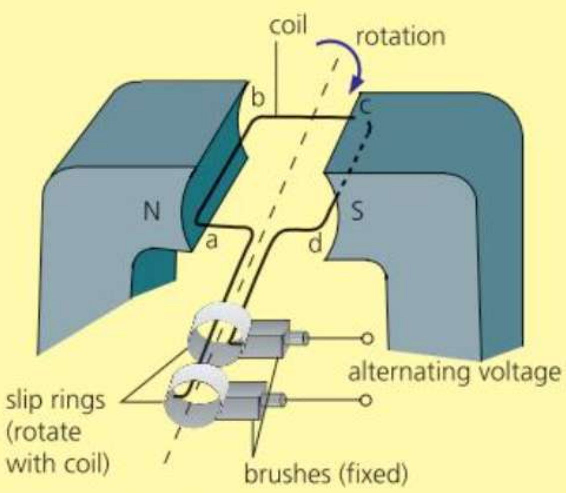
4.5.2 The a.c. generator

Key objectives

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

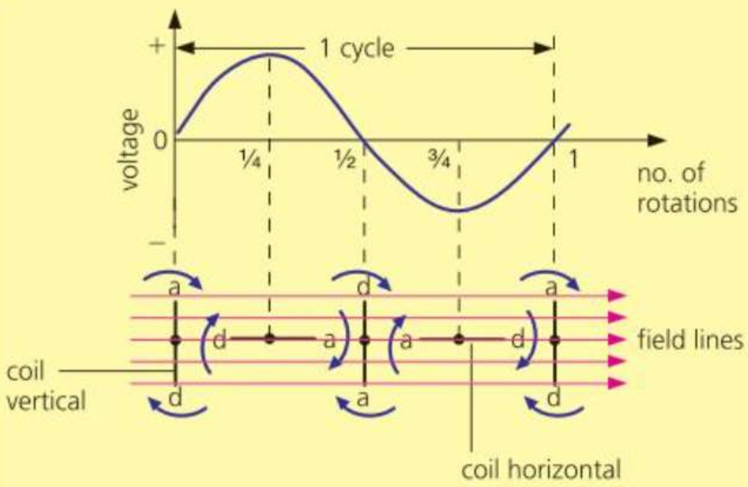
- describe the structure of an a.c generator
- sketch and interpret graphs showing how the e.m.f. varies with time and relate this to the position of the coil

Figure 4.28 shows a simple a.c. generator. It is made up of a coil which can rotate between the poles of a magnet. The coil is connected to two slip rings which rotate with the coil. These are connected to the circuit via two fixed carbon brushes.



▲ **Figure 4.28 A simple a.c. generator**

An e.m.f. is induced in the coil as it turns in the magnetic field. The wires on each side of the coil cut the field alternately moving up and down, so the e.m.f. is induced in alternating directions. You can see how the e.m.f. varies with time in Figure 4.29.



▲ **Figure 4.29 Output from a simple a.c. generator**

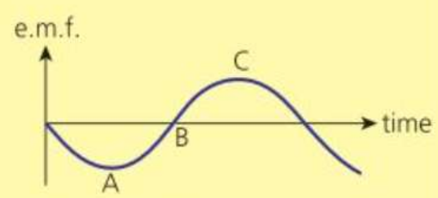
The peak e.m.f. occurs when the coil is horizontal, and the e.m.f. is zero when the coil is vertical. This is because at this point the coil is moving parallel to the magnetic field so no e.m.f. is induced. To understand why the induced e.m.f. changes direction, consider one side of the coil (ab). Initially ab is moving upwards and so induced current is in one direction. As the coil become vertical, side ab starts to move downwards and so the induced current is now in the opposite direction.

Sample question

REVISED

10 Figure 4.30 shows the output from a simple a.c. generator.

- **a** Identify a point on the graph where the induced e.m.f. changes direction. [1]
- **b** Identify a point where the coil is perpendicular to the magnetic field (vertical). [1]
- **c** Describe what you would see if the coil rotated faster [2]



▲ **Figure 4.30**

Student's answers

- *a* B [1]
- *b* A [0]
- *c* The peak e.m.f. would be higher. [1]

Teacher's comments

- **a** The student has correctly identified where the induced e.m.f. changes direction as the e.m.f. goes from negative to positive.
- **b** When the coil is vertical, the induced e.m.f. is zero. This is because the coil is moving parallel to the magnetic field.
- **c** The student realised the peak e.m.f. would be greater but they did not realise the frequency would increase. If there are two marks for a question, try to make two points.

Correct answers

- **a** B [1]
- **b** B [1]
- **c** The peak e.m.f. would be higher; the frequency would be greater. [2]

Revision activity

Draw a labelled diagram of an a.c. generator and sketch the graph of how e.m.f. varies with time. Link the two diagrams to show the position of the coil at the peaks and troughs of the e.m.f.

4.5.3 Magnetic effect of a current

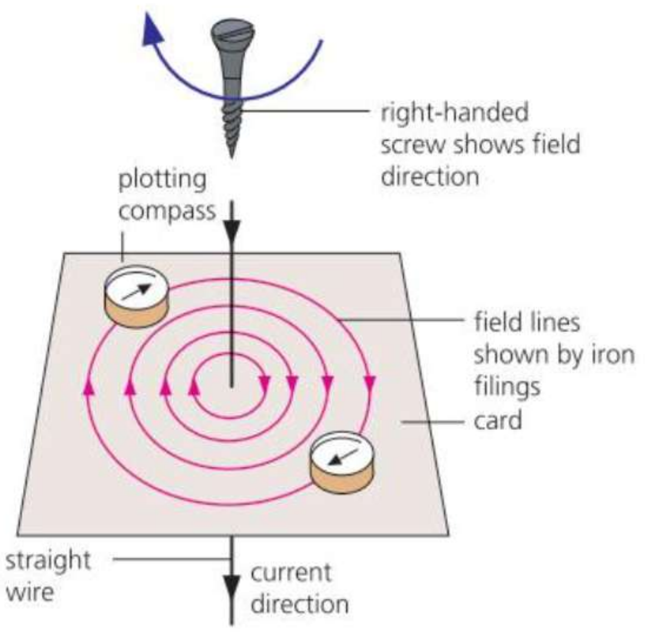
Key objectives

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

- describe the pattern of the magnetic field around a straight current-carrying wire and around a solenoid and describe an experiment to show these patterns
- describe how the magnetic effect of a current is used in loudspeakers and relays
- describe the variation in the magnetic field strength around wires and solenoids and how changing the magnitude and direction of the current affects their magnetic fields

Field due to a straight wire

A wire or coil carrying an electric current produces a magnetic field. The magnetic field pattern is a series of concentric circles, as shown in Figure 4.31. You can determine the direction of the magnetic field using the right-hand screw rule. The magnetic field lines point in the direction of rotation of the screw.

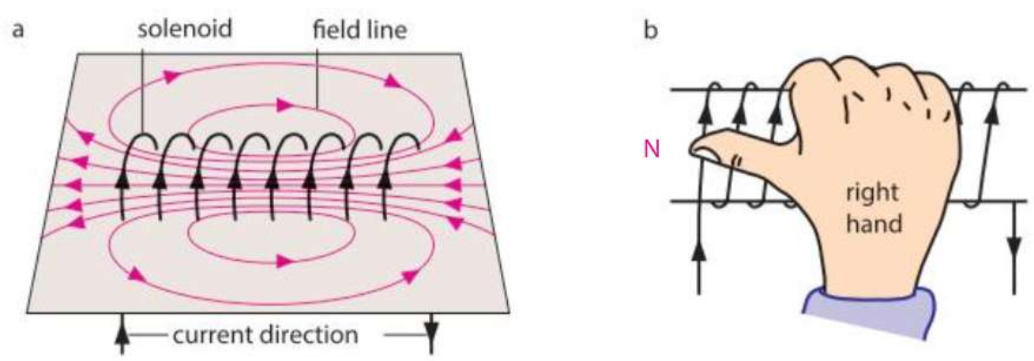


▲ **Figure 4.31 Field due to a straight wire**

Field due to a solenoid

A **solenoid** is a long cylindrical coil. When a current flows, the field pattern outside the solenoid is similar to that of a bar magnet. Inside the solenoid, there is a strong field parallel to the axis (Figure 4.32a). The right-hand grip rule gives the direction of the field.

The fingers of the right hand grip the solenoid pointing in the direction of the current and the thumb points to the N pole (Figure 4.32b).



▲ **Figure 4.32 a) Field due to a solenoid and b) the right–hand grip rule**

Skills

Plotting the magnetic field around a current-carrying wire and solenoid

To observe the magnetic field patterns of a straight current-carrying wire or a solenoid, use iron filings and a plotting compass.

Magnetic field around a wire: Thread the wire through a piece of card held horizontally by a clamp stand (Figure 4.31). Sprinkle iron filings onto the card and then tap. The iron filings will show the shape of the field. You can use a plotting compass to determine the direction of the field.

Magnetic field around a solenoid: Thread a wire through a piece of card held horizontally (as shown in Figure 4.32a). Sprinkle iron filings onto the card and then tap. The iron filings will show the shape of the field. You can use a plotting compass to determine the direction of the field.

Variation of magnetic field strength

The magnetic field strength around a current-carrying wire is not constant. The magnetic field strength decreases with distance. You can see this in the magnetic field lines in Figure 4.31, which become further apart as you move away from the wire.

The closeness of the magnetic field lines in Figure 4.32a indicates the strength of the field within the solenoid. Outside the solenoid, the further away a point is, the weaker the field.

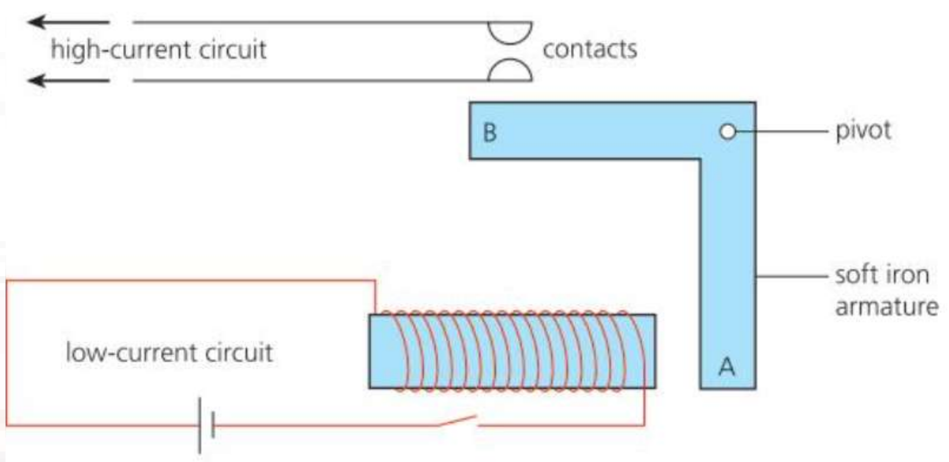
For both the straight wire and solenoid, the higher the current, the stronger the magnetic field. If the current reverses, the direction of the magnetic field is also reversed. You can also increase the strength of the solenoid's field by using more coils.

Applications of the magnetic effect of a current

A solenoid wrapped around an iron core forms an electromagnet. Electromagnets are used in cranes to lift iron objects and scrap iron, as well as in many electrical devices.

Relay

A relay is a device that enables one electric circuit to control another. It is often used when the first circuit carries only a small current (e.g. in an electronic circuit) and the second circuit requires a much higher current.

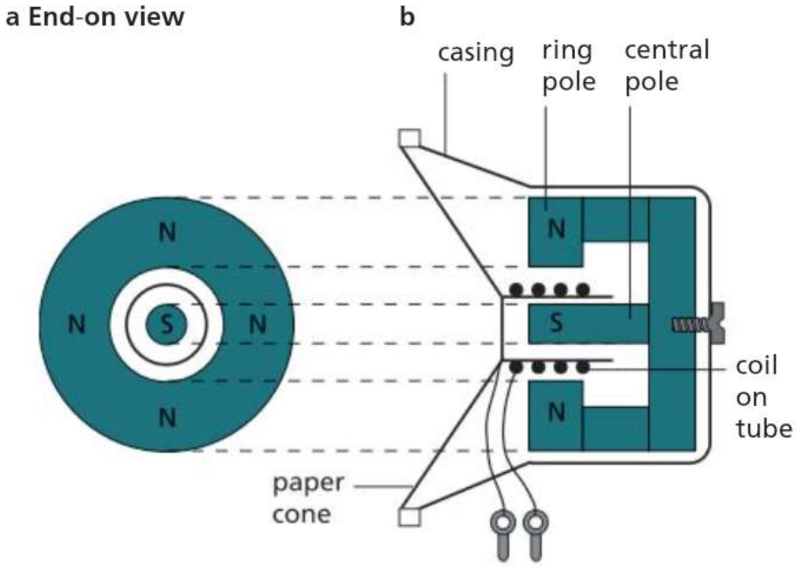


▲ **Figure 4.33 Magnetic relay**

When the switch is closed in the low-current circuit in Figure 4.33, current flows to the electromagnet, which attracts end A of the soft iron armature. The armature pivots and end B moves up to close the contacts in the high-current circuit. This circuit is now complete and the high current flows through the device, e.g. a motor, a heater or an alarm bell.

Loudspeaker

Figure 4.34 shows a loudspeaker. It consists of a circular permanent magnet with a central pole and a ring pole. A coil of wire sits over the ring pole and is attached to a paper cone.



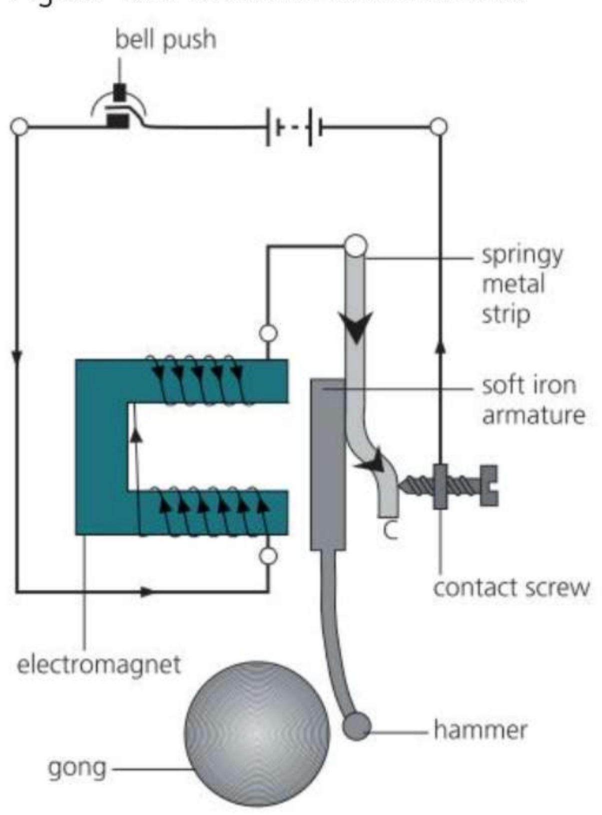
▲ **Figure 4.34 Moving-coil loudspeaker**

There is an alternating current in the coil. The changing magnetic field in this coil causes it to move up and down, making the cone vibrate and produce a sound. As the frequency of the alternating current changes so does the frequency of vibration, producing different frequency sound waves.

Sample question

REVISED

11 Figure 4.35 shows an electric bell.



▲ **Figure 4.35**

For the electric bell shown in Figure 4.35:

a Describe what happens when the bell push is pressed. [4]

b Explain why iron is used for the armature. [1]

c Choose a suitable material for the core of the electromagnet. Give your reasons. [2]

Student's answers

a When the bell is pressed, the electromagnet switches on. The iron armature is attracted and the hammer hits the gong. [2]
b A strong magnet is required. [0]
c Use soft iron, as the electromagnet must be switched on and off repeatedly. [2]

Teacher's comments

a The student has started the description well. However, they have not seen that when the hammer strikes the gong the circuit is broken. This switches off the electromagnet. The armature springs back remaking the circuit.
b The armature needs to be made from a magnetic material.
c Correct answer.

Correct answers

a When the bell push is pressed, a current flows through the electromagnet, which becomes magnetised. The armature is attracted to the electromagnet and the hammer strikes the gong. The movement of the armature breaks the circuit that applies current to the electromagnet. The armature is released and springs back. The circuit is re-made, the process repeats and the bell rings continually for as long as the bell push is pressed. [4]
b Iron is used because the armature must be attracted to the electromagnet. [1]
c Use soft iron, as the electromagnet must be switched on and off repeatedly. [2]

Revision activity

Create a revision poster on magnetic fields caused by currents – include how they are detected and how they can be used.

4.5.4 Force on a current-carrying conductor

Key objectives

By the end of this section, you should be able to:
- describe an experiment which shows how the force acting on a current-carrying wire in a magnetic field is affected by reversing the current or direction of the magnetic field
- use Fleming's left-hand rule to determine the directions of force, current and magnetic field relative to each other
- determine the direction of force on a beam of charged particles in a field

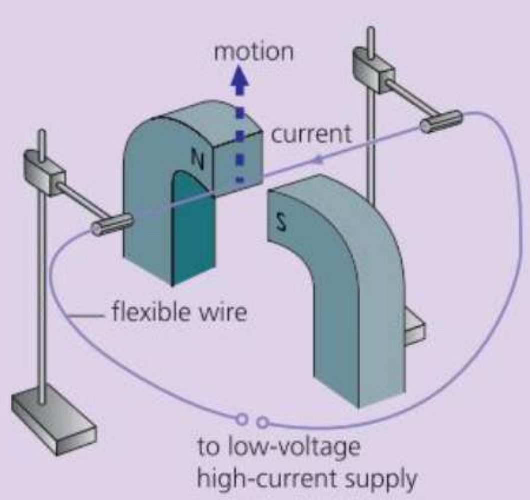
A wire or conductor carrying a current in a magnetic field experiences a force. The direction of the force depends on the direction of the magnetic field and the direction of the current.

Skills

Demonstrating force on a current-carrying wire

You can demonstrate the force on a current-carrying wire using the apparatus shown in Figure 4.36.

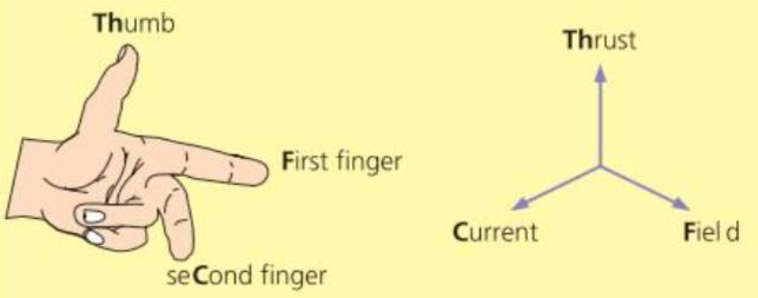
The wire is only loosely suspended and moves up when the current is switched on. The wire will move down if either the current is reversed or the magnet poles are swapped to reverse the field. If both the field and current are reversed, the wire will again move up.



▲ **Figure 4.36 Demonstrating the motor effect**

Fleming's left-hand rule

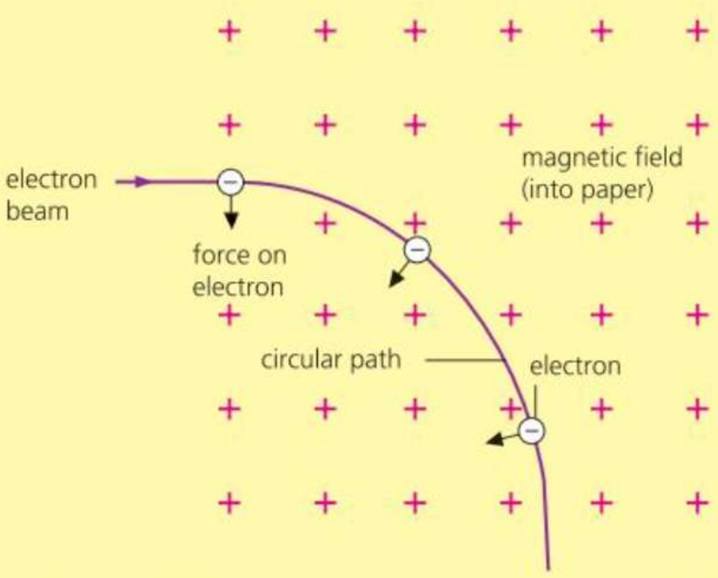
You must be able to state and use Fleming's left-hand (motor) rule to determine the relative directions of force, magnetic field and current.



▲ **Figure 4.37 Fleming's left-hand rule**

Force on beams of charged particles in a magnetic field

A beam of charged particles experiences a force in a magnetic field. Figure 4.38 shows the path of an electron beam in a uniform magnetic field. As the force acts at right angles to the beam, it follows a circular path.



▲ **Figure 4.38 The path of an electron beam perpendicular to a magnetic field**

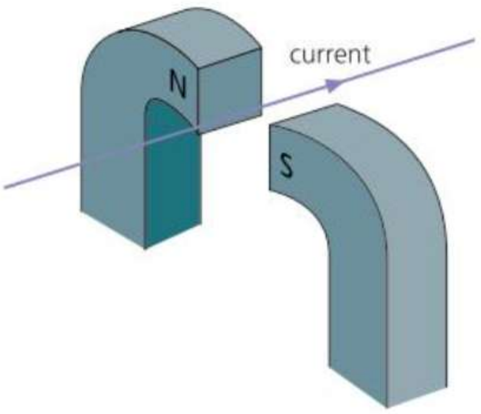
To determine the direction of the force, use Fleming's left-hand rule. The crosses show that the field is perpendicular to the paper and directed into it. They represent the back of an arrow. The important thing to remember is current direction is the direction of positive charge so point your second finger in the opposite direction to that of the electron beam – electrons are *negatively* charged.

To show the magnetic field coming out of the paper, use dots to represent the front of an arrow.

Sample questions

REVISED

12 Figure 4.39 shows a wire in a magnetic field. The current through the wire is switched on.



▲ **Figure 4.39**

a State and explain the direction of the force on the wire when the current is switched on. [2]

b For each of the following changes, made one at a time, state whether the magnitude of the force on the wire increases, stays the same, decreases or decreases to zero:

- **i** current changes direction [1]
- **ii** current drops to zero [1]
- **iii** current increases [1]
- **iv** magnetic field increases [1]
- **v** magnetic field changes direction [1]

Student's answers

a *Force is up, as in Figure 4.36.* [1]

b
- **i** *Changes direction.* [0]
- **ii** *Becomes zero.* [1]
- **iii** *Increases.* [1]
- **iv** *Increases.* [1]
- **v** *Changes direction.* [0]

Teacher's comments

a The student did not observe that the current is reversed from Figure 4.36.

b The student seems in places to have committed the classic error of answering the question that was expected not what was asked.

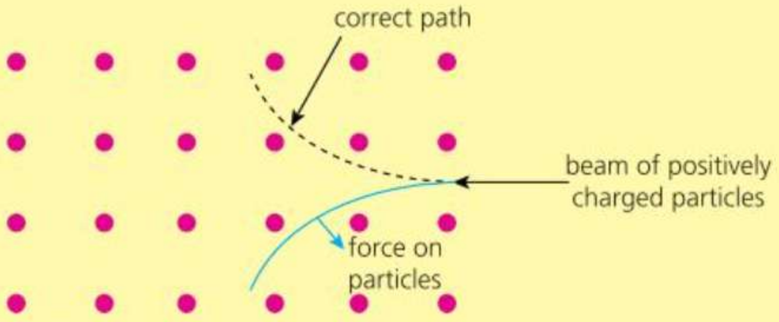
- **i** The student answered a different question.
- **ii** Correct answer.
- **iii** Correct answer.
- **iv** Correct answer.
- **v** The student answered a different question.

Correct answers

a Force is down by Fleming's left-hand rule. [2]

b
- **i** Force stays the same. [1]
- **ii** Force decreases to zero. [1]
- **iii** Force increases. [1]
- **iv** Force increases. [1]
- **v** Force stays the same. [1]

13 Figure 4.40 shows a beam of positively charged particles entering a magnetic field at right angles to it. Sketch the path of the beam and explain your answer. [3]



▲ **Figure 4.40**

Student's answer

The student's answer is shown by the blue line in Figure 4.40. The magnetic field is out of the page. The positively charged particles feel a force at right angles to their direction [1] so curve downward [0]. Using the left-hand rule [1 mark for diagram ignoring direction].

Teacher's comments

The student's statement about the magnetic field is correct, and they understand that there is a force at right angles to the direction of the beam. The blue line shows a curved path. The beam is positively charged and so direction of the current is to the left. The student knew they had to apply the left-hand rule to their directions but made a mistake.

Correct answer

The magnetic field is out of the page. The current is to the left, so according to Fleming's left-hand rule [1] the charges feel a force upwards [1] as they enter the magnetic field. The force is always perpendicular to the motion, so the path is curved as shown in Figure 4.40 by the black dotted line. [1]

4.5.5 The d.c. motor

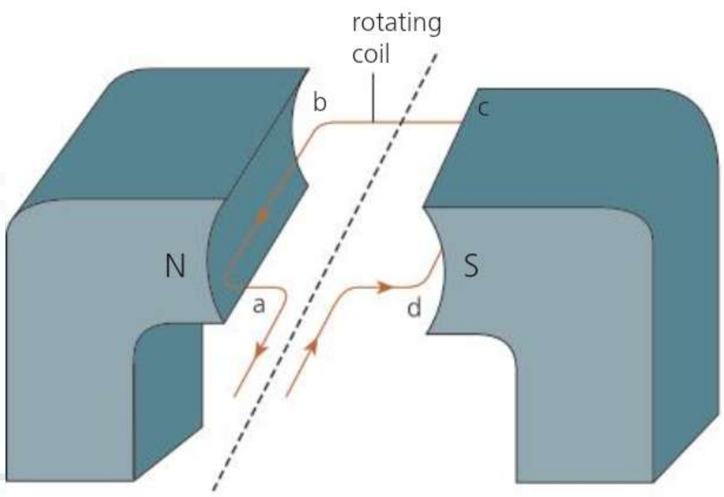
Key objectives

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

- state that a current-carrying coil can experience a turning effect in a magnetic field and know the factors that increase the turning effect
- describe the structure of an electric motor and how it works

Turning effect on a coil

A straight wire in a magnetic field feels a force. If you make the wire into a rectangular coil and place it in a magnetic field, one side feels a force upwards as the other feels a force downwards. This causes a turning effect. Figure 4.41 shows a single coil in a magnetic field.



▲ **Figure 4.41 A single coil in a magnetic field**

You can see the current flows in opposite directions either side of the coil. The turning effect is increased by:

- increasing the number of turns on the coil
- increasing the current
- increasing the strength of the magnetic field

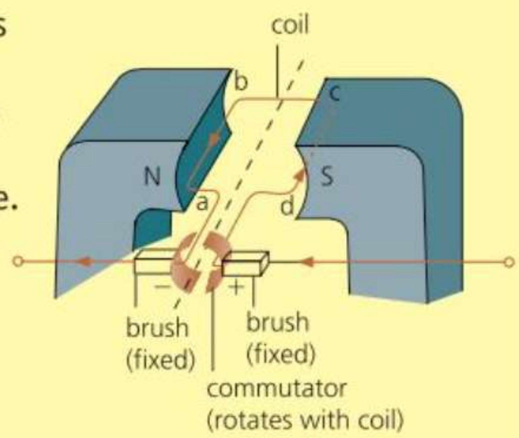
Revision activity

Explain to a partner how a motor works. You may need to draw diagrams or use a simple model to help explain.

Simple d.c. electric motor

The directions of the forces on the coil are worked out using Fleming's left-hand (motor) rule. In Figure 4.42 there is an upwards force from the magnetic field on the wire ab. The current in the wire cd is in the other direction, so it experiences a force in the opposite direction (downwards). These two forces cause the coil of wire to turn clockwise.

The commutator and brushes act as a switching mechanism that changes the direction of the current every half turn to allow continuous rotation. When the coil is vertical the gaps in the split ring commutator line up with the brushes and there is no longer a current in the coil. The coil keeps moving as there is no force acting to stop it. Wire ab is now on the right, so moves down. Similarly, wire cd is now on the left and moves up.



▲ **Figure 4.42 The commutator and brushes of a d.c. motor**

4.5.6 The transformer

Key objectives

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

- describe the construction of a simple transformer and explain how it works
- recall and use the transformer equation and use the terms *primary* and *secondary*, *step up* and *step down*
- recall and use the equation for 100% efficiency in a transformer
- describe how transformers are used for high-voltage transmission and state their advantages
- recall and use the correct power loss equation to explain why power losses are less at higher voltages

A **transformer** transforms (changes) an alternating voltage from one value to another of greater or smaller value. It consists of two coils wound on the same soft iron core. The primary coil is supplied with an alternating current and the secondary coil provides an alternating current to another circuit.

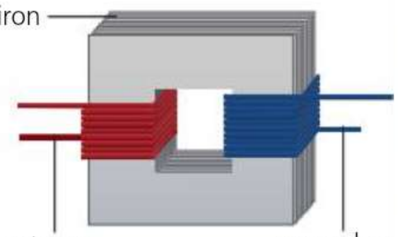


Figure 4.43 Primary and secondary coils of a transformer

The a.c. in the primary coil sets up a changing magnetic field in the soft iron core. As the changing magnetic field cuts through the secondary coil, it induces an alternating e.m.f. in the secondary coil.

Transformers will only work with a.c. This is because if d.c. is used the current remains constant and so does the magnetic field. You need a changing magnetic field to induce an e.m.f.

Transformer equation

A step-up transformer has more turns on the secondary coil than the primary coil and the V_s is greater than V_p. In a step-down transformer, there are fewer turns on the secondary than the primary coil and V_s is less than V_p.

The relationship between the number of coils on the primary (N_p) and the number of coils on the secondary (N_s) is given by the equation:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

When the p.d. is increased in a step-up transformer, the current is decreased by the same proportion. In an ideal transformer which has 100 % efficiency:

power in the primary = power in the secondary

$$I_p V_p = I_s V_s$$

As you can see, if the p.d. is halved then the current is doubled.

Transmission of electrical power

Electricity is transmitted over large distances at very high voltages, in order to reduce the energy losses due to the resistance of the transmission lines. This is achieved by having a step-up transformer at the power station to increase the voltage to several hundred thousand volts. Where the electricity is to be used, there is a series of step-down transformers to reduce the voltage to values suitable for use in factories or homes.

The advantages of high voltage transmission are:

- less power loss in the cables as the heating effect in the cables is less
- lower current in the cables means that thinner/cheaper cables can be used

Power loss in transmission cables

All power cables have some resistance. This means some energy is transferred to thermal energy as it is transmitted. The power loss in a cable (P) is given by the equation:

$$P = I^2R$$

When the voltage is stepped up the current is stepped down. Power is therefore transmitted at the highest possible voltage in order to reduce the current and thus the losses in the cables.

Sample question

REVISED

14 A transformer used by students in a school laboratory has 5500 turns on the primary coil and is supplied with 110 V a.c. The secondary coil has 500 turns.

a Calculate the output voltage. [3]

b Explain the principle of operation of a transformer. [3]

Student's answers

a $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

$\frac{110}{V_s} = \frac{500}{5500}$

$V_s = \frac{5500 \times 110}{500} = 1210\,V$ [1]

b The primary coil acts as an electromagnet supplied with an alternating current. This flows in the soft iron core. Therefore, the secondary coil has an alternating current. [1]

Teacher's comments

a The student started with the correct equation, but muddled up the primary and secondary coil when they substituted the numbers into the equation. The student should have realised that students in a laboratory would never have access to such a high voltage, so something must have gone wrong in the calculation.

b The student knows that there is a magnetic field but completely fails to use this information. The answer also gives the impression that current flows through the core to the secondary coil, which is completely wrong.

Correct answers

a $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

$\frac{110}{V_s} = \frac{5500}{500}$

$V_s = \frac{500 \times 110}{5500} = 10\,V$ [3]

b The alternating current in the primary coil produces an alternating magnetic field in the soft iron core. The secondary coil is in this alternating magnetic field, so an alternating e.m.f. is induced. [3]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

23 The wire in Figure 4.24 is moved upwards.

a Describe how to increase the e.m.f. induced in the wire. [3]

b State whether the induced current is in a clockwise or anticlockwise direction in the wire. [1]

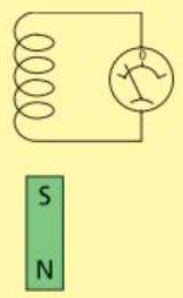
24 The magnet in Figure 4.44 is released and falls away from the coil. The needle on the centre-zero meter moves to the left.

Describe what would happen to the needle on the centre-zero meter if:

a the S pole of the magnet is moved upwards [1]

b the N pole of the magnet is moved upwards [1]

c the coil is moved down over the magnet as it is shown in Figure 4.44 [1]



▲ **Figure 4.44**

25 A loudspeaker is made up essentially of a stationary magnet that is close to a small coil fixed to a paper cone. The signal from the amplifier is a small alternating current supplied to the coil. Describe briefly:

a the variation of the magnetic field produced by the coil [1]

b the variation of the magnetic force on the coil [1]

c the motion of the paper cone [1]

26 Describe an experiment to show that a force acts on a current-carrying wire in a magnetic field and what happens if the current is reversed. [3]

27 Figure 4.45 shows a coil with several turns carrying a current in a magnetic field.

a State the effect that the current has on the coil. [1]

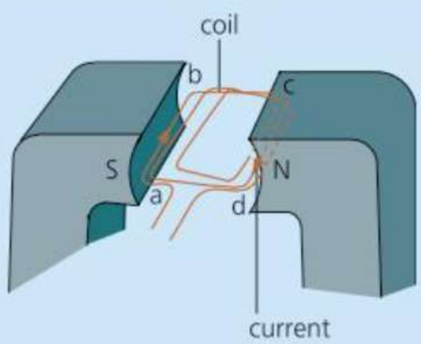
b State whether the size of this effect is increased, the same, decreased or decreased to zero when:

i the current is reversed

ii the current is increased

iii the magnets are removed

iv the number of turns is increased [4]



▲ **Figure 4.45**

28 Figure 4.46 shows a coil that can rotate in a magnetic field.

a State the direction of any forces on:

i wire ab

ii wire cd [2]

b The coil is rotated so that it is vertical. State the direction of any forces now acting on:

i wire ab

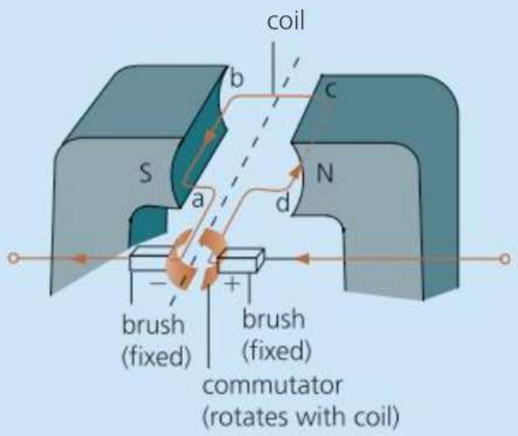
ii wire cd

Explain how you reached your answers. [4]

Revision activity

Create a spider diagram about the transformer. Write down these words and find links between them: transformer, step up, step down, high-voltage transmission, power losses.

c The coil is rotated so that it is again horizontal with wire ab on the right and wire cd on the left. State the direction of any forces now acting on:
   i wire ab
   ii wire cd [2]



▲ **Figure 4.46**

29 A transformer is used to provide an a.c. 6 V supply for a laboratory from 240 V a.c. mains. The secondary coil of the transformer has 100 turns. Calculate the number of turns on the primary coil. [3]

30 A transformer has 1200 turns on the primary and 20 turns on the secondary coil. The input voltage is 120 V a.c and the current in the primary coil is 10 mA. Calculate the current in the secondary coil. [4]

31 Transmission cables have a resistance of 400 Ω. Calculate the power loss in the cables:
   a when the current is 2.5 A [2]
   b when the current is 250 A [2]

5 Nuclear physics

Key terms

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Term	Definition
Alpha-particle (α)	Radiation consisting of helium ions with a double positive charge ($^{4}_{2}He$)
Atom	Tiny constituent of matter
Background radiation	Ever-present radiation resulting from cosmic rays from outer space and radioactive materials in rocks, the air, buildings
Beta-particle (β)	Radiation consisting of high-speed electrons ($^{0}_{-1}e$)
Electron	Negatively charged elementary particle ($^{0}_{-1}e$)
Gamma-radiation (γ)	High-frequency, very penetrating electromagnetic waves
Half-life	The average time for half the nuclei in a radioactive sample to decay
Ion	Charged atom or molecule that has lost or gained one or more electrons so that it is no longer neutral
Isotope	One form of an element that has the same number of protons but a different number of neutrons in the nucleus from other isotopes of the same element
Neutron	An uncharged subatomic particle found in the nucleus of an atom (except that of hydrogen)
Nucleon number, *A*	Number of protons and neutrons in the nucleus
Proton	Positively charged particle found in the nucleus of an atom
Proton number, *Z*	Number of protons in the nucleus
Fission	The break-up of a large nucleus into smaller parts
Fusion	The union of light nuclei into a heavier one

5.1 The nuclear model of the atom

REVISED

5.1.1 The atom

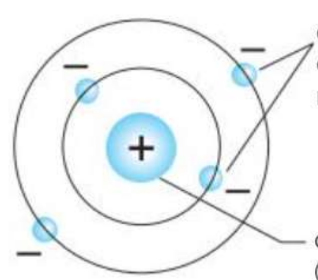
Key objectives

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

- describe the structure of an atom
- state how positive and negative ions are formed
- describe how the alpha scattering experiment supports the nuclear model of the atom

The atom

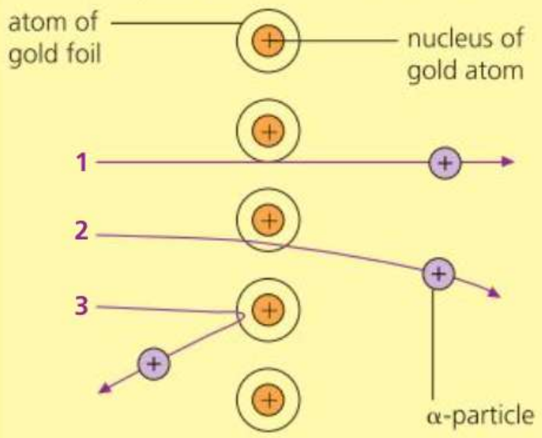
The **atom** is the smallest particle of an element. It is made up of a central nucleus, with all the positive charge and nearly all the mass, and negatively charged electrons in orbit. The nucleus is very much smaller than the electron orbits, so the majority of every atom is empty space.



▲ **Figure 5.1 The nuclear atom**

The model of a nuclear atom was confirmed by observing a beam of α-particles (positively charged particles) travelling towards a sheet of thin metal foil.

- The vast majority of α-particles passed straight through without being deflected. This is evidence that most of the atom is empty space and the nucleus is very small.
- A few α-particles were deflected, some through a large angle, and a very small proportion bounced back (see Figure 5.2). This is evidence that the nucleus is positively charged because the positively charged alpha particles were strongly repelled. The small number deflected shows that all the mass and positive charge is concentrated in a small part of the atom – the nucleus.



▲ **Figure 5.2 Scattering of α-particles by thin gold foil**

Path 1 is a long way from any nucleus and the α-particle is undeflected.

Path 2 is close to a nucleus and there is some deflection.

Path 3 heads almost straight for a nucleus and the α-particle rebounds back.

Ions

Atoms are neutral. They contain an equal number of positively charged **protons** and negatively charged **electrons**. An atom with a charge is called an **ion**. If an atom gains electrons, it becomes negatively charged and is called a negative ion. If an atom loses electrons, it becomes positively charged and is called a positive ion.

5.1.2 The nucleus

Key objectives

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

- define proton number Z and nucleon number A and calculate the number of neutrons in the atom
- use nuclide notation
- explain what is meant by an isotope
- describe the processes of nuclear fission and fusion including the nuclide equations
- relate the relative charge and relative mass of a nucleus to the proton and nucleon number, respectively

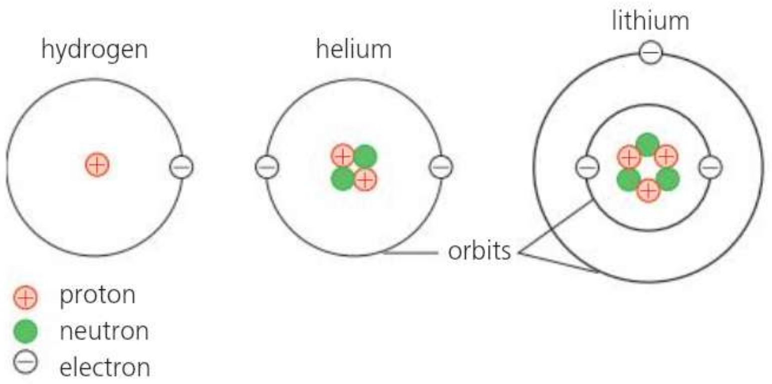
Protons and neutrons

A nucleus contains **protons** and **neutrons** which are known as the **nucleons**. To compare the particles inside an atom, you consider their mass and charge relative to each other. Table 5.1 shows relative mass, relative charge and their position.

▼ **Table 5.1 The relative mass, charge and position of the subatomic particles**

Particle	Relative mass	Relative charge	Position
Proton	Approximately 2000	+1	Inside the nucleus
Neutron	Approximately 2000	0	Inside the nucleus
Electron	1	–1	Outside the nucleus

Figure 5.3 shows a model of how the particles are arranged.



▲ **Figure 5.3 Protons, neutrons and electrons in atoms**

The number of protons in a nucleus is called the **proton number (*Z*)** and is the same as the number of electrons in orbit.

The number of nucleons (protons and neutrons) is called the **nucleon number (*A*)**. The difference between the nucleon number *A* and the proton number *Z* gives the number of neutrons in the nucleus ($A - Z$).

The nuclide (type of nucleus) of an element can be written with the notation $^{A}_{Z}X$, where X is the chemical symbol for the element.

Mass and charge on a nucleus

Different atoms have different masses. The **relative mass** of a nucleus depends on the number of nucleons. You use the nucleon number, *A*, to determine the relative mass. For example, oxygen, $^{16}_{8}O$ has a relative mass of 16.

The **relative charge** of a nucleus is always positive and depends on the number of protons in the nucleus. You use the proton number *Z* to determine the relative charge. For example, an oxygen nucleus has a relative charge of +8.

Isotopes and nuclides

Isotopes of the same element are different forms that have the same number of protons but different numbers of neutrons in the nucleus. An element may have more than one naturally occurring isotope.

Some radioactive isotopes occur naturally, e.g. carbon-14 is produced in the atmosphere by cosmic rays.

Many radioactive isotopes are produced artificially in nuclear reactors and have a wide range of practical uses, e.g. as a source of radiation to kill cancers (see p. 144) or as tracers in the human body or in a pipeline.

Skills

Determining the number of neutrons in a nucleus

Aluminium has the symbol Al and is written as $^{27}_{13}Al$. Calculate the number of neutrons in the nucleus of an aluminium atom.

$A = 27$, $Z = 13$

number of neutrons = $A - Z = 27 - 13 =$ 14 neutrons

Energy from nuclear reactions

In **fission**, a heavy nucleus is split into smaller nuclei and some neutrons. In **fusion**, smaller nuclei join together to make a larger nucleus. In both processes, the mass of the starting atoms is greater than the products. The missing mass or mass defect is converted into energy.

Nuclear fission

In fission, a neutron strikes a large nucleus and it splits into two smaller nuclei, approximately the same size, and two or three more neutrons, for example,

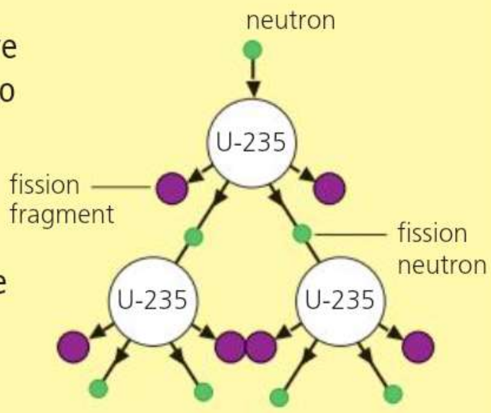
$$^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \longrightarrow {}^{144}_{56}\text{Ba} + {}^{90}_{36}\text{Kr} + 2\,{}^{1}_{0}\text{n}$$

▼ **Table 5.2 Nucleon and proton numbers of each nuclei in the fission reaction**

A	235	1	= 236	144	90	2	= 236
Z	92	0	= 92	56	36	0	= 92

Notice that the total values of *A* and *Z* on both sides of the equation are equal. As more neutrons are released in the reaction, these can go on to fission other uranium nuclei and start a chain reaction (Figure 5.4).

In an atomic bomb, the chain reaction is uncontrolled and leads to an explosion. In a nuclear reactor, the number of neutrons is carefully controlled. The lighter nuclei produced are themselves highly radioactive nuclear waste, which is difficult and expensive to dispose of.



▲ **Figure 5.4 Chain reaction**

Nuclear fusion

Fusion occurs under conditions of extremely high temperature and pressure when light nuclei can join together. The nuclei need enough kinetic energy to overcome their electrostatic repulsion. Remember nuclei are positively charged and so will repel strongly. Fusion releases a large amount of energy.

The following reaction occurs in the Sun and other stars, as well as in the hydrogen bomb:

$$^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He}$$

Research reactors are currently experimenting into ways of maintaining controlled fusion reactions for possible power stations of the future

Sample question

REVISED

1 The most common isotope of carbon is carbon-12, written $^{12}_{6}\text{C}$ in nuclide notation.

- **a** Write down the nucleon and proton numbers of carbon-12. [2]
- **b** Write down the number of electrons in a neutral atom of carbon-12. [1]
- **c** Carbon-14 is a radioactive isotope that exists in small quantities in the atmosphere. Write down the nucleon and proton numbers of carbon-14. [1]
- **d** Write down the nuclide notation for carbon-14. [2]
- **e** Work out the number of neutrons in a nucleus of carbon-14 and state the difference between the nuclei of carbon-12 and carbon-14. [2]

Student's answers

a nucleon number, $A = 12$
proton number, $Z = 6$ [2]
b number of electrons = 12 [0]
c nucleon number, $A = 14$
proton number, $Z = 6$ [1]
d $^{6}_{14}C$ [0]
e A carbon-14 nucleus is bigger, with more particles. [0]

Teacher's comments

a Correct answers.
b The student has incorrectly thought that the number of electrons is the same as the number of nucleons.
c Correct answer.
d The student has mixed up the nucleon and proton numbers – care needs to be taken here!
e The first part of the question has not been answered and the rest of the answer is too vague.

Correct answers

a nucleon number, $A = 12$
proton number, $Z = 6$ [2]
b number of electrons = number of protons = 6 [1]
c nucleon number, $A = 14$
proton number, $Z = 6$ [1]
d $^{14}_{6}C$
e number of neutrons in carbon-14 nucleus
= nucleon number – proton number [2]
$= A - Z = 14 - 6 = 8$
number of neutrons in carbon-12 nucleus = 12 – 6 = 6
A carbon-14 nucleus has two extra neutrons. [2]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

1 Copy and complete the table to indicate the composition of an atom of each of the isotopes of strontium given. [6]

Isotope	Number of protons	Number of neutrons	Number of electrons
$^{88}_{38}Sr$			
$^{90}_{38}Sr$			

2 Sodium (symbol Na) has 11 protons and 12 neutrons.
a Write down the nuclide notation for sodium. [3]
b A sodium atom loses one electron. State the charge of the ion formed. [1]
c Write the relative mass and relative charge of a sodium nucleus. [2]

3 a Explain the difference between nuclear fission and nuclear fusion. [4]
b State one significant similarity between them. [1]
c State where a fission reaction occurs. [1]
d State where a fusion reaction occurs. [1]

4 Copy the nuclear equation for the fission of uranium-236 and fill in the gaps to balance the equation. [2]

$$^{236}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{\_\_}Ba + ^{\_\_}_{36}Kr + 3\,^{1}_{0}n$$

Revision activity

Create a poster showing the structure of an atom and how this is represented using nuclide notation. Include descriptions of how positive and negative ions are formed and what an isotope is.

Create a table to match the descriptions of a nuclear model to the evidence from the alpha scattering experiment. Describe how energy is released in nuclear fission and fusion.

5.2 Radioactivity

REVISED

5.2.1 Detection of radioactivity

Key objectives

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

- state what is meant by background radiation and the main sources
- state how a detector connected to a counter is used to measure ionising nuclear radiation and the units of count rate are counts/s or counts/minute
- determine the corrected count rate using measurements of background radiation

There is radiation all around you all of the time. This is called **background radiation**. This is mainly due to natural sources such as radon gas in the air, cosmic rays, rocks and buildings and from food and drink. The value varies depending on where you live.

In collisions between radioactive particles and molecules in the air, the radioactive particles knock electrons out of the atoms, leaving the molecules positively charged. This is called **ionisation**. This ionising effect is used to detect radiation.

In a Geiger–Müller tube, the ionising radiation causes a pulse of current to flow between the electrodes. The tube is connected to a counter which counts these pulses of current and gives the total in a set amount of time. This is used to calculate the count rate which is measured in counts per second or counts per minute.

If you are measuring the count rate for a radioactive source, you need to correct for background radiation. To do this you simply subtract the count rate due to background radiation from your reading. To measure the background count, take a reading using the detector for a few minutes when the radioactive source is not in the room. Divide the total count by the time to determine the background count rate.

5.2.2 The three types of nuclear emission

Key objectives

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

- describe the emission of radiation from a nucleus as spontaneous and random in direction
- identify alpha, beta and gamma emissions from their basic characteristics
- describe the deflection of α-particles, β-particles and γ-radiation in electric and magnetic fields
- explain the relative ionising effects of each type of emission

Alpha, beta and gamma radiation

Radioactivity occurs when an unstable nucleus decays and emits one or more of the three types of radiation: **α (alpha)-particles**, **β (beta)-particles** or **γ (gamma)-radiation**. Radioactivity is a random process. It is impossible to know when an individual radioactive nucleus will decay and in what direction. It is also a spontaneous process. This means it happens on its own and is not affected by factors such as temperature or pressure.

Table 5.3 shows how you can identify the different types of radiation from their properties

▼ **Table 5.3 The properties of α, β and γ radiation**

Emission	Nature	Charge	Penetration	Ionising effect
α-particle	Helium nucleus (two protons and two neutrons)	+2	Stopped by thick paper or a few centimetres of air	Very strong
β-particle	High-speed electron	–1	Stopped by a few millimetres of aluminium	Weak
γ-radiation	Electromagnetic radiation	None	Only stopped by many centimetres of lead	Very weak

Explaining range and ionising effect of alpha, beta and gamma

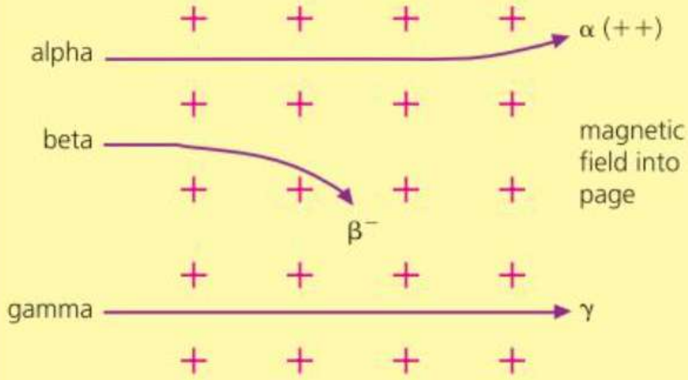
Alpha-particles have the largest mass and the highest charge. This means they are much more likely to interact with matter and so they cannot penetrate very far. In collisions, the positive charge easily knocks outer electrons from atoms and so they have a high ionising power. In each collision, the α-particle transfers energy from its kinetic energy store and so slows down and has a short range.

Beta-particles have less mass than α-particles and so are less likely to interact with matter. This means they can penetrate further. The single negative charge means they are able to knock out electrons from atoms as the particles pass them and so have ionising ability. As they make fewer collisions, they can travel a greater distance (a few metres through air) before all of their kinetic energy has been transferred through collision.

Gamma-radiation has no charge as it is electromagnetic radiation. It has very little interaction with matter. Gamma-radiation can still knock an outer electron from an atom and ionise it. However, it is the least likely to ionise. As it has the least interaction with matter, it travels a long distance before transferring all its energy.

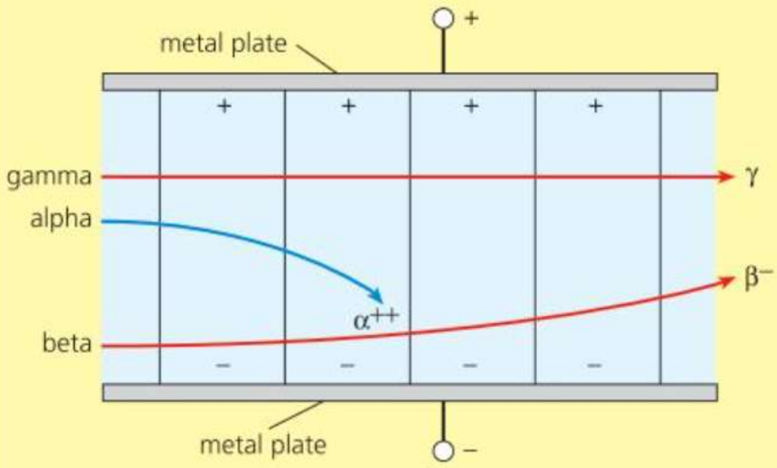
Deflection of alpha, beta and gamma in magnetic and electric fields

In a magnetic field, alpha and beta are deflected according to their charge. You can use Fleming's left-hand rule to determine the direction. Remember, conventional current is in the direction of flow of positive charge. Gamma, as it is uncharged, is unaffected by the magnetic field. Their deflections in a magnetic field are summarised in Figure 5.5a. Use Fleming's left-hand rule to check the directions shown.



▲ **Figure 5.5a Deflection of α- and β-particles and γ-rays in a magnetic field**

In an electric field, α-particles are attracted towards the negative plate, β-particles towards the positive plate and γ-rays pass through with no deflections. The deflections are summarised in Figure 5.5b.



▲ **Figure 5.5b Deflection of α- and β-particles and γ-rays in an electric field**

5.2.3 Radioactive decay

Key objectives

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

- state that radioactive decay is a change to an unstable nucleus and can lead to emission of alpha, beta or gamma radiation and that it is both random and spontaneous
- know that during alpha and beta decay the nucleus changes to that of a different element
- understand that isotopes may be radioactive because of an excess of neutrons and/or because the nucleus is too heavy
- describe how the changes to a nucleus improve its stability and to use radioactive decay equations using nuclide notation

Radioactive decay is when an unstable nucleus emits radiation. When the nuclei emit α-particles or β-particles, the nuclei change to a different element. This element may also be unstable and emit radiation.

Alpha-decay

An α-particle is a helium nucleus. It consists of two protons and two neutrons. During α-decay, the nucleus loses two neutrons and two protons. The nucleon number goes down by four. The proton number goes down by two, so the nuclide changes to another element. An example of α-decay can be shown by a word equation:

radium-226 → radon-222 + α-particle

The same example of α-decay can be shown by an equation in nuclide notation:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He}$$

Note that, because an α-particle is the same as a helium nucleus, it is shown as He in nuclide notation.

Beta-decay

In β-decay, a neutron in the nucleus changes to a proton and an electron, which is emitted at high speed as a β-particle. The nucleon number is unchanged. The proton number goes up by one, so the nuclide also changes to another element.

An example of β-decay can be shown by word and nuclide equations:

carbon-14 → nitrogen-14 + β-particle

$$^{14}_{6}\text{C} \rightarrow {}^{14}_{7}\text{N} + {}^{0}_{-1}\text{e}$$

Note that, because a β-particle is an electron, it is shown as e in nuclide notation, with a nucleon number of 0, because it has negligible mass, and a proton number of –1, because of its negative charge.

Gamma-emission

Gamma-radiation is an electromagnetic wave and so does not change the structure of the nucleus. However, γ-radiation is usually given off during both α-decay and β-decay, and can be added to the equations, for example:

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\text{He} + \gamma$$

Skills

Writing a decay equation

Each nuclide equation of a radioactive decay balances. The sum of the nucleon number and proton number on the left-hand side of the equation is the same as on the right-hand side. You can use this to determine the nucleon and proton number of the nucleus after the decay.

For example, the nuclear equation shows the decay of an isotope of polonium. Calculate the values of *A* and *Z*.

$$^{210}_{84}\text{Po} \rightarrow {}^{A}_{Z}\text{Pb} + {}^{4}_{2}\text{He}$$

nucleon number: $210 = A + 4$

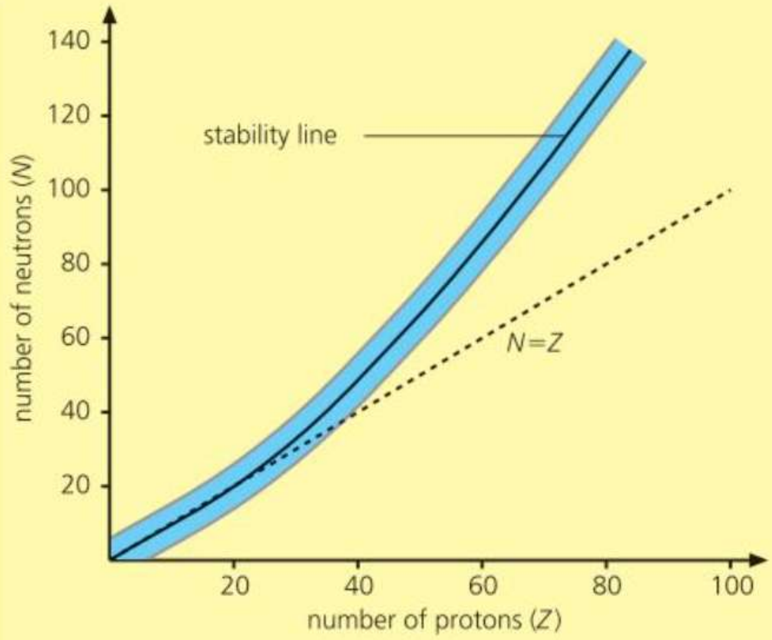
$A = 206$

proton number: $84 = Z + 2$

$Z = 82$

Nuclear stability

An isotope of an element may be unstable because it has too many neutrons or because it is too heavy (has too many nucleons). Figure 5.6 shows a graph of the number of neutrons (*N*) against the number of protons (*Z*). The stable nuclei lie on the stability line.



▲ **Figure 5.6 Stability of nuclei**

For unstable nuclides, a decay helps them move closer to the stability line. If the isotope lies above the line, then it needs to reduce the number of neutrons. It can do this through β-decay. Large nuclei often decay via α-emission to reduce the mass of their nucleus and become more stable.

Gamma-emission often happens after α- or β-decay as the nucleus is left in an excited state. Gamma-emission makes the nucleus more stable by releasing this excess of energy.

Sample question

REVISED

2 Radioactive strontium-90 (Sr, proton number 38) decays to yttrium (Y), emitting a β-particle and γ-radiation. Show this decay reaction as a nuclide equation. [4]

Student's answer

$^{90}_{38}Sr \rightarrow ^{89}_{39}Y + ^{0}_{-1}e + \gamma$ [3]

Teacher's comments

The student has mostly got the answer right. The nuclide symbol for strontium is correct, as are the symbols for the β-particle and γ-radiation. The student has also correctly deduced that the proton number of yttrium is 39, one more than that of strontium. However, the nucleon number must stay the same in β-decay, as the nucleus has lost a neutron and gained a proton.

Correct answer

$^{90}_{38}Sr \rightarrow ^{90}_{39}Y + ^{0}_{-1}e + \gamma$ [4]

Revision activity

Create flash cards with a question on one side and answer on the reverse. Questions should cover the sources of background radiation, the nature, properties and ionising effects of alpha, beta and gamma radiation, and the meaning of random and spontaneous. Use the cards to test yourself. Include decay equations for supplemental.

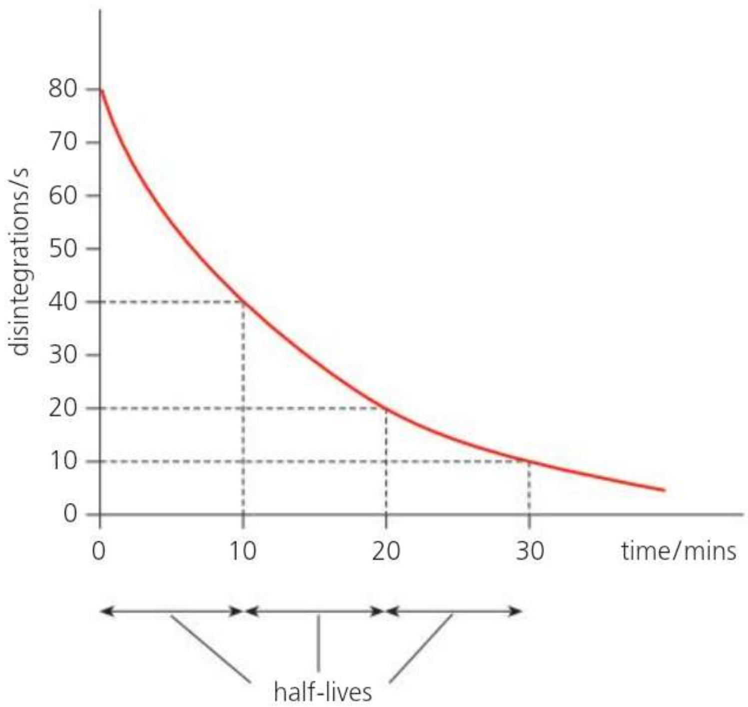
5.2.4 Half-life

Key objectives

By the end of this section, you should be able to:
- define half-life and use this definition to perform half-life calculations including using data from table or decay curves
- perform half-life calculations taking into account background radiation
- explain how a radioactive isotope can be suitable for a particular use

Radioactive decay is a random process. It is impossible to predict when an individual nucleus will decay. However, *on average,* there is a definite decay rate for each isotope.

The decay rate is expressed as the **half-life**, which is the time for half the nuclei in a sample to decay. As it is hard to count the number of nuclei, you can determine the half-life by monitoring the disintegrations per second (activity) from a radioactive source. In Figure 5.7 the half-life is 10 minutes. This is because the disintegrations per second halves every 10 minutes.



▲ **Figure 5.7 The half-life of a material can be found by using a graph (decay curve)**

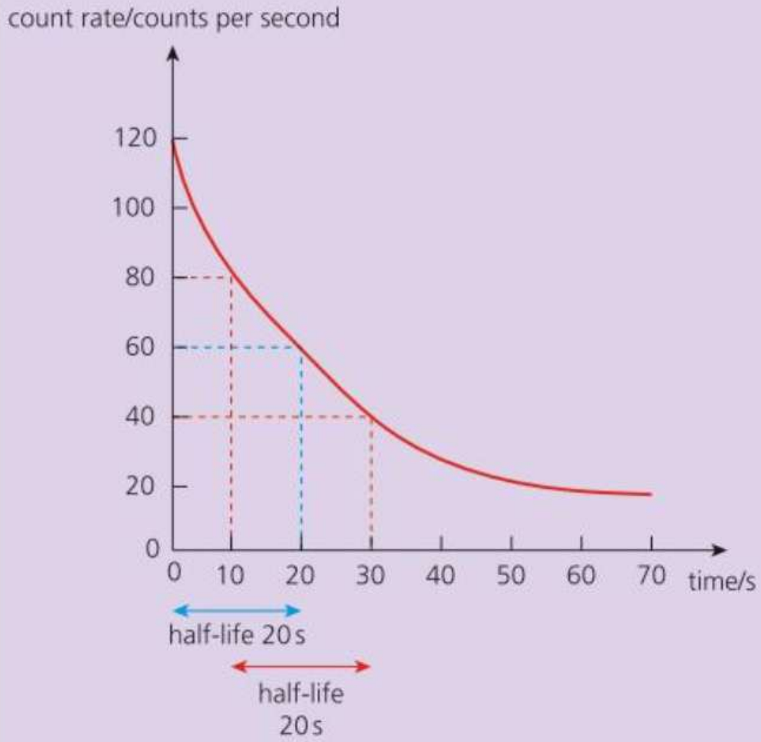
Extended candidates need to be able to carry out half-life calculations allowing for background radiation.

Skills

Plotting a decay curve

You need to know how to plot and interpret decay curves to determine the half-life of an isotope.
- When you plot a decay curve, the time is always on the x-axis and the number of disintegrations per second or count rate is on the y-axis.
- Choose a scale so you can plot the points easily and so you use as much of the graph paper as possible.
- The line of best fit must be a smooth curve.
- You can then use the curve to find the half-life. Check the value by finding the time taken to halve the activity in more than one place.

- To correct for background radiation, subtract the background count rate from each value before you plot the curve.



▲ **Figure 5.8 Finding the half-life from a decay curve**

Uses of radioactivity

The type of radiation emitted and the half-life of the radioactive isotope determine how it can be used.

Smoke alarm

Inside a smoke alarm, there is a small radioactive source which emits α-particles. The α-particles ionise the air and a small current flows between electrodes. When there is smoke, the ions cannot flow freely between the electrodes. The current decreases and this is detected by a circuit, which sounds the alarm. An α-emitting source is chosen because α-particles are highly ionising and not very penetrating. This means the smoke alarm is not dangerous to anyone nearby. A source with a long half-life is used so that the activity remains constant.

Irradiation and sterilisation

Radiation causes ionisation and can kill living cells. This makes radiation useful for killing bacteria on food to make it last longer. This is called irradiation. The food is not radioactive as there is no radioactive material on the food. Radiation is also used to sterilise medical instruments. Gamma-radiation is used because it is the most penetrating so can pass through the packaging. A source with a long half-life is used so that the activity remains constant.

Thickness monitoring

A radioactive source is placed on one side of a strip of paper, plastic or metal during its manufacture. A radiation detector on the other side of the strip monitors how much has been absorbed. This indicates the thickness of the strip. Beta-emitters are used for thinner materials and γ-emitters for thicker materials as they can penetrate further and can still be detected on the other side. A source with a long half-life is used so that the activity remains constant.

Diagnosis and treatment of cancer

Radioactive tracers can be used to detect cancer cells. The tracer is injected into the body and its progress through the body can be detected by a gamma camera. If there is a problem, a higher concentration of γ-radiation will be detected in that area. The radioactive isotopes used are gamma as it is low ionising and can penetrate the body, so can be detected from the outside. The half-life will be short so that it will have a low activity soon after the test is over but long enough for the readings to be taken. Usually about four hours.

High-energy beams of γ-radiation are used to kill cancer cells. Careful arrangements are made to concentrate the radiation on the cancer cells and not kill other healthy cells in the body. Extensive shielding is also needed to protect the medical staff operating the equipment. A source with a long half-life is used so that the activity remains constant.

Sample question

REVISED

3 A radioactive sample gives a detector reading of 700 counts per second. The half-life of the sample is seven days.

a Work out the expected detector reading two weeks later. [2]

b The background count is 100 counts per second. Calculate the expected detector reading taking background into account. [2]

Student's answer

a *After 1 week, detector reading* $= \frac{700}{2} = 350$ *counts/s*

After 2 weeks, detector reading $= \frac{350}{2} = 175$ *counts/s* [2]

b *background count is 100 counts/s so detector reading* $= 175 + 100 = 275$ [0]

Teacher's comments

a The student has correctly calculated the count rate after two weeks.

b The student has not allowed for the background count correctly. You have to subtract background count from the initial reading. Determine the count rate after two weeks and then add background count on to the value.

Correct answers

a After 1 week, detector reading = $\frac{700}{2}$ = 350 counts/s

After 2 weeks, detector reading = $\frac{350}{2}$ = 175 counts/s [2]

b Initial detector reading due to sample = 700 − 100 = 600 counts/s

After 1 week, detector reading due to sample = $\frac{600}{2}$ = 300 counts/s

After 2 weeks, detector reading due to sample = $\frac{300}{2}$ = 150 counts/s

Final detector reading including background = 150 + 100 = 250. [3]

Revision activity

Check you understand what is meant by half-life, and you can do simple half-life calculations by creating flash cards to test these out in your class and then switching with a partner.

Work in a group of three. Each of you choose alpha, beta or gamma and then prepare a 30 second presentation on a practical use of your radioactive source. The presentation must include an explanation of why that type of radiation is chosen and whether a long or short half-life is needed. Give the presentation to your group.

5.2.5 Safety precautions

Key objectives

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

- state the effects of ionising nuclear radiation on living things
- describe precautions for handling, using and storing radioactive materials safely and explain these precautions.

Radioactive emissions are ionising radiation. Ionising radiation can be very harmful to living things. It either kills cells outright or mutates cells, which can lead to cancers. To reduce the risk of harm from ionising radiation, a number of simple precautions can be taken.

The following safety precautions should therefore be taken:

- Whenever possible, radioactive samples are in sealed casings so that no radioactive material can escape.
- Samples are stored in lead-lined containers in locked storerooms.
- Samples are handled only by trained personnel and must always be supervised when not in store.
- Radioactive samples are shielded and kept at as great a distance as possible from people. In the laboratory, they are handled with long tongs and students are kept at a distance. In industry, they are usually handled by remote-controlled machines.
- Workers in industry are often protected by lead and concrete walls, and wear film badges that record the amount of radiation received.

The safety precautions are designed to reduce exposure to the ionising radiation by:

- reducing the time people spend near the sources
- keeping the distance from the source and the person as large as possible
- by using suitable shielding to absorb the radiation

Sample question

REVISED

4 An extremely strong source of α-particles and γ-rays is used in an experiment being demonstrated to a group of student observers. The source is held and moved by a robot arm controlled by a technician who is always at least 1 m away from the source. The observers are always at least 3 m away from the source.

a These precautions are insufficient for the technician and for the students. Explain this. [2]

b Suggest practicable improvements that would permit the demonstration to continue and be observed in a safe way. [2]

Student's answers

a The students would be safe at that distance but the technician needs to move further away. [0]

b The technician could use a video camera. [1]

Teacher's comments

a This answer makes no distinction between α- and γ-radiation. There is no risk of harm from the alpha-source. But 3 m of air will not protect from the gamma-source.

b The answer shows some awareness of the possibility of remote observation but does not address the issue of appropriate shielding.

Correct answers

a The robotic handling and distance from the source protects the technician and students observers from the α-radiation. [1] Because of the strong γ-radiation, even at 3 m distance, this is extremely unsafe for both the technician and the observers. [1]

b The source should be shielded by thick lead or concrete from all humans. [1] The experiment could be viewed by video camera. A remote screen behind the shielding would allow the technician to control the robot and the students to observe in complete safety. [1]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

5 State what is meant by background radiation and name two natural sources. [3]

6 A Geiger–Müller tube is used to measure the background radiation in the room before an experiment. The total count from the detector after 2 minutes is 24.

a Calculate the count rate in counts/s due to background radiation. [2]

b A radioactive source has a count rate of 40 count/s. Calculate the corrected count rate. [1]

7 The penetration of two radioactive samples is tested by measuring the count rate with various types of shielding between the sample and the counter. The numbers in the table below indicate the count rate (CR) with each type of shielding in place: no shielding, thick card, 3 mm of aluminium (Al), 20 cm of lead (Pb).

Revision activity

Create a simple poster explaining the dangers of ionising radiation and describing how to move, use and store radioactive sources in a safe way.

Explain how these reduce the risk.

Copy the table and tick the appropriate boxes in the right-hand three columns to show the type or types of emission from that sample. [3]

Sample	CR (none)	CR (card)	CR (Al)	CR (Pb)	α	β	γ
1	6000	1000	1000	20			
2	3000	3000	20	20			

8 A positron is a subnuclear particle with the same mass as an electron but with a positive charge. A certain nuclear reaction emits positrons and γ-rays, which are directed to pass parallel to and between two horizontal plates in a vacuum. The upper plate has a very high positive potential relative to the lower plate. Describe the path between the plates of:

- **a** the positrons [1]
- **b** the γ-radiation [1]

9 Radioactive uranium-238 (U, proton number 92) decays to thorium (Th), emitting an α-particle and γ-radiation. Show this decay reaction as a nuclide equation. [4]

10 Caesium $^{137}_{55}Cs$ decays by an emission of a β-particle to an isotope of barium (Ba). Write down the nuclide equation for this decay. [3]

11 Describe how the emission of a β-particle can increase the stability of a radioactive isotope. [3]

12 The results in the table below came from an experiment to determine the half-life of a radioactive sample.

Time/min	0	2	4	6	8
Counts/s	400	280	200	140	100

- **a** Use the data in the table to determine the half-life of the radioactive isotope. [1]
- **b** Calculate the fraction of the sample left after 12 minutes. [1]

13 In an experiment to find the half-life of protactinium, a student gained the results given in the table below.

Time/s	0	30	60	90	120
Count/s	1200	895	670	504	377

- **a** Plot a graph to show the decay curve for this data. [4]
- **b** Use your graph to determine the half-life of protactinium. [2]

14 The table below shows the half-life and type of emissions from three radioactive sources A, B and C.

Radioactive isotope	Type of emission	Half-life
A	β-particles	25 years
B	γ-radiation	28 years
C	γ-radiation	3 hours

- **a** Explain which source could be used as a medical tracer. [3]
- **b** Explain which source could be used to monitor the thickness of thin sheets of aluminium. [3]

15 A teacher is using a radioactive source to demonstrate the absorption of γ-radiation in air. The source is shielded so radiation is only emitted from one side.

- **a** Describe some precautions the teacher could take to keep themselves and the students safe. [2]
- **b** Explain how these precautions keep the teacher and students safe. [2]

6 Space physics

Key terms

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Term	Definition
Big Bang Theory	Violent explosion of the Universe from a single point at the beginning of time
Comets	Small objects that orbit the Sun in highly elliptical orbits
Dwarf planets	Smaller objects and asteroids which orbit the Sun, e.g. Pluto
Earth	Our planet, orbits round the Sun approximately every 365 days
Galaxy	A group of billions of stars
Light-year	Distance travelled in space by light in one year
Milky Way	Our galaxy containing the Solar System
Moon	Natural satellite orbiting the Earth in approximately 1 month
Natural satellites	Moons which orbit planets
Orbital period	Time for an object in space to complete one orbit
Phases of the Moon	Changes in appearance of the Moon as it orbits the Earth
Planets	Eight large objects, which orbit the Sun
Redshift	Increase of wavelength of light from a receding star or galaxy
Solar System	The Sun, the eight major planets, minor planets, asteroids and other bodies
Stars	Consist mainly of hydrogen and helium, release energy from nuclear fusion reactions
Sun	Our star at the centre of the Solar System
Universe	Hundreds of billions of galaxies that make up all the matter that exists
CMBR	Cosmic microwave background radiation
Hubble constant (H_0)	Symbol H_0, ratio of the speed at which a galaxy is moving away from the Earth to its distance from the Earth
Red giant	State of most stars near the end of their life
Red supergiant	State of largest stars near the end of their life before they explode as supernovas

6.1 Earth and the Solar System

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6.1.1 The Earth

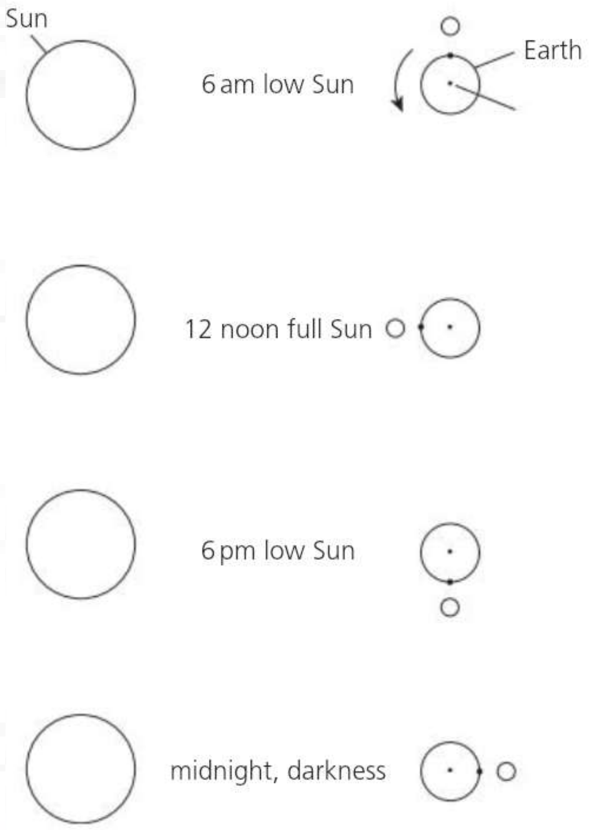
Key objectives

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

- know how the Earth orbits the Sun
- explain how the tilt of the Earth's axis of rotation causes the seasons
- define average orbital speed and recall and use the equation: $v = 2\pi r/T$
- know that the Moon orbits the Earth in about one month and use this to explain the Moon's phases.

Motion of the Earth

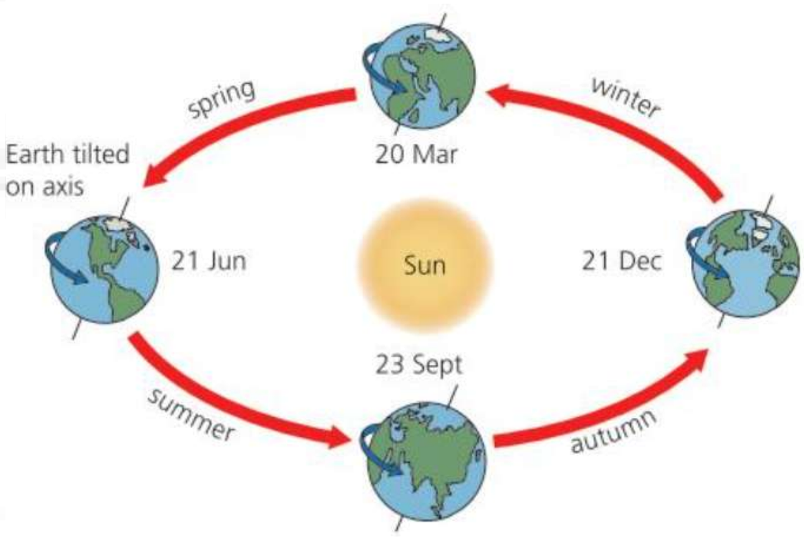
The **Earth** is a planet which rotates on its axis once in approximately 24 hours. The **Sun** appears to move when observed from a point on the Earth's surface. Figure 6.1 is a simplified view, not to scale, from above the North Pole of the Earth of how the Sun is seen at a point labelled O at 6 am, noon, 6 pm and midnight.



▲ **Figure 6.1 The Sun as seen from the Earth**

When point O is on the side of the Earth facing the Sun, it is day. Then point O moves to the side of the Earth away from the Sun and it is night.

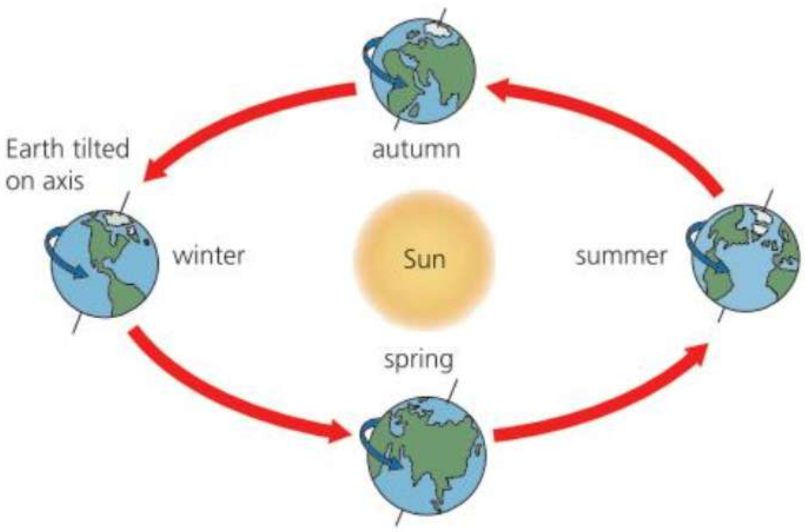
The axis of the Earth's rotation is not at right angles to the plane of its rotation around the Sun but it is tilted at an angle of about 20°, as shown by Figure 6.2.



▲ **Figure 6.2 The tilt of the Earth's axis**

It can be shown that because of this tilt, the lengths of day and night are not equal and vary during the year.

The Earth orbits the Sun once in approximately 365 days. This together with the tilt of the axis of rotation explains the seasons. Figure 6.3 shows the seasons for the Southern hemisphere.



▲ **Figure 6.3 Seasons for the Southern hemisphere**

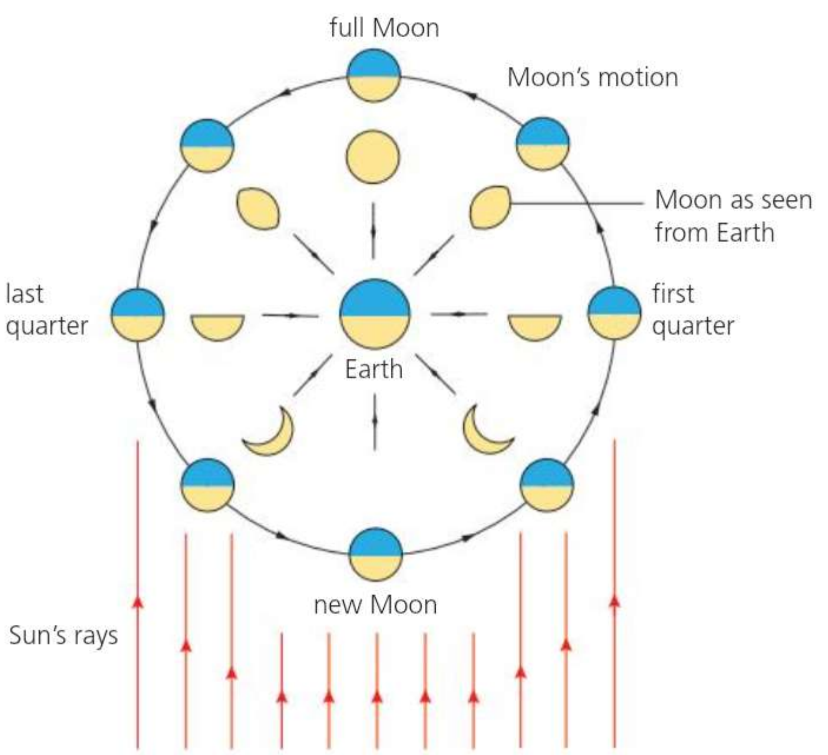
From autumn through winter to spring, the Southern hemisphere is tilted away from the Sun so it receives daylight for a shorter time every day. It receives less solar radiation so it is cooler.

Revision activity

Draw the appearance of the Moon in two different phases.

Motion of the Moon

The **Moon** takes about one month to orbit the Earth. As the moon orbits the Earth, its appearance changes between full circle and thin crescent, with other shapes in between. These are called the **phases of the Moon**.



▲ **Figure 6.4 Phases of the moon**

Figure 6.4 shows how parts of the Moon's surface are illuminated by the Sun to change the appearance of the Moon.

The average orbital speed v of any object is given by the equation $v = 2\pi r/T$ where r is the average radius of the orbit and T the **orbital period**. This equation applies to all orbits, e.g. the Earth or any other planet around the Sun, the Moon around the Earth or any moon around its planet.

Revision activity

The phases of the Moon

You should prepare yourself to observe the Moon every day for a month. Initially you will observe just after sunset and later it will have to be shortly before dawn. It will not matter if you miss a few days. If you live in a part of the Earth where the weather is cloudy, you will miss a few or possibly several observations.

- Find out the date of the next new Moon from an app, the internet or your teacher.
- One or two days after that, the Moon will be visible as a very thin crescent shortly after sunset. Sketch the appearance of the Moon and record the number of days after the new Moon you made the observation.
- Continue to observe and record the appearance of the Moon every day for a month if you can. You will have to be flexible with the time you observe. When the Moon becomes fuller than a semicircle, it is often possible to see it during daylight.
- By observing regularly, you will discover the pattern and timing of the Moon's phases. Maybe it will help to repeat for another month later using your experience of the first attempt to time your observations better.
- Compare your observations with Figure 6.4 and note any comments you have about this comparison.

Skills

Rearranging the orbital speed equation

You need to be able to rearrange the equation $v = 2\pi r/T$ to make any of the variables the subject.

- Write down the equation when r is the subject.

$$v = \frac{2\pi r}{T}$$

$$\frac{2\pi r}{T} = v$$

$$2\pi r = vT$$

$$r = \frac{vT}{2\pi}$$

- Write down the equation when T is the subject.

$$v = \frac{2\pi r}{T}$$

$$\frac{2\pi r}{T} = v$$

$$2\pi r = vT$$

$$vT = 2\pi r$$

$$T = \frac{2\pi r}{v}$$

Sample questions

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1 Draw a line from each description in the left column to one of the time durations in the right column.

Description	Time duration
hours of daylight in every 24 hours in spring	12 hours
time taken by the Earth to orbit the Sun	24 hours
time taken by the Moon to orbit the Earth	1 month
time taken by the Earth to turn one revolution on its axis	365 days

[4]

Student's answer

Description	Time duration
hours of daylight in every 24 hours in spring	12 hours
time taken by the Earth to orbit the Sun	24 hours
time taken by the Moon to orbit the Earth	1 month
time taken by the Earth to turn one revolution on its axis	365 days

[3]

Teacher's comments

The student has failed to follow instructions and drawn two lines from 'time taken by the Earth to turn one revolution on its axis' on the left and no line from 'hours of daylight in every 24 hours in spring' on the left.

Correct answer

Description	Time duration
hours of daylight in every 24 hours in spring	12 hours
time taken by the Earth to orbit the Sun	24 hours
time taken by the Moon to orbit the Earth	1 month
time taken by the Earth to turn one revolution on its axis	365 days

[4]

2 The orbital speed of the Earth around the Sun is 30 000 m/s. Calculate the average radius of the Earth's orbit. [4]

Student's answer

$$r = \frac{v}{2\pi T}$$

$$r = \frac{3 \times 10^4}{365 \times 2\pi} = 13\text{ m}$$

[1]

Correct answer

$$v = \frac{2\pi r}{T}$$

$$r = \frac{v}{2\pi T}$$

$T = 365$ days $= 365 \times 24 \times 3600$ s

$v = 3.0 \times 10^4$ m/s.

$$r = \frac{3.0 \times 10^4 \times 365 \times 24 \times 3600}{2\pi} = 1.5 \times 10^{11}\text{ m}$$

[4]

Teacher's comments

The student incorrectly rearranged the equation and substituted a time in days not seconds. The student should have considered the answer and realised that 13 m was quite impossible for the radius of the Earth's orbit.

6.1.2 The Solar System

Key objectives

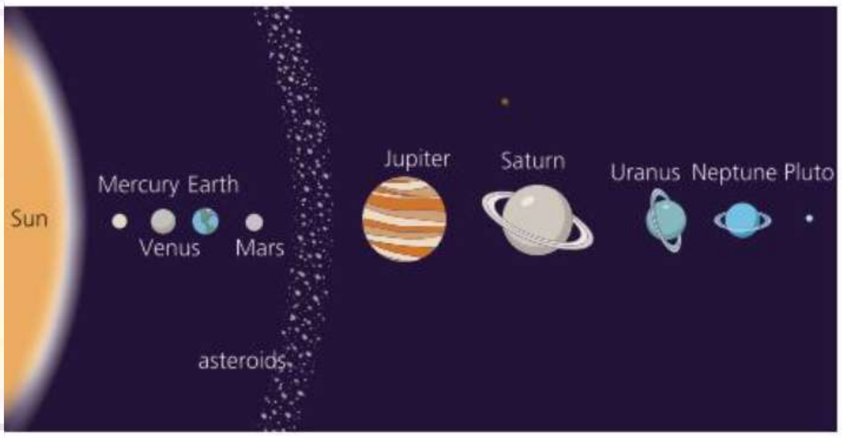
By the end of this section, you should be able to:

- describe the Solar System as containing the Sun, the eight named planets including their order from the Sun, minor planets and other bodies
- understand the elliptical nature of orbits around the Sun
- know the different compositions of the inner and outer planets and explain this using the accretion model
- analyse and interpret planetary data
- know how the strength of a gravitational field of an object depends on the mass of the object and the distance from the object
- calculate the time it takes for light to travel between objects in the Solar System
- know that the Sun contains most of the mass of the Solar System and the force that keeps objects in orbit around the Sun is gravitational attraction
- know that orbital speeds of planets vary with distance from the Sun and position in an elliptical orbit

The Solar System

The Sun is a **star** at the centre of the **Solar System**.

The main objects of the Solar System orbiting the Sun are shown in Figure 6.5.



▲ **Figure 6.5 The Solar System (distances from the Sun not to scale)**

The first four **planets** in order of distance from the Sun are rocky and small: Mercury, Venus, Earth and Mars.

The next four planets in order of distance from the Sun are gaseous and large: Jupiter, Saturn, Uranus and Neptune.

There are also smaller Solar System bodies: asteroids, **comets** and **dwarf planets** such as Pluto which may orbit in the asteroid belt or further from the Sun than Neptune.

Many of the planets have moons or **natural satellites** which orbit around them.

All objects orbiting the Sun have elliptical orbits, although some are approximately circular. Except in the cases of circular orbits, the Sun is not at the centre of the orbit.

▼ Table 6.1 Data for the planets

Planet	Av distance from Sun/ million km	Orbit time around Sun/ days or years	Surface temperature/ °C	Density/ kg/m³	Diameter/ 10^3 km	Mass/10^{24} kg	Gravitational field strength/ N/kg	Number of moons
Mercury	57.9	88 d	350	5427	4.8	0.330	3.7	0
Venus	108.2	225 d	460	5243	12.1	4.87	8.9	0
Earth	149.6	365 d	20	5514	12.8	5.97	9.8	1
Mars	227.9	687 d	–23	3933	6.8	0.642	3.7	2
Jupiter	778.6	11.9 y	–120	1326	143	1898	23.1	79
Saturn	1433.5	29.5 y	–180	687	120	568	9.0	82
Uranus	2872.5	84 y	–210	1271	51	86.8	8.7	27
Neptune	4495.1	165 y	–220	1638	50	102	11.0	14

The four planets closest to the Sun, Mercury, Venus, the Earth and Mars, are rocky and smaller than the outer four planets. You can see in Table 6.1 their smaller diameter and higher density. The outer four planets are not only much larger but also have a lower density as they are gaseous.

The **accretion model** for the Solar System explains these differences.

- The Solar System was formed about 4.5 billion years ago from clouds of hydrogen gas and dust and heavier elements produced from a supernova which exploded.
- Hydrogen and some helium were drawn together by gravitational attraction to form the Sun.
- The remaining small particles joined together to form a disc in an accretion process as the material rotated.
- All the planets orbit the Sun in the same direction and lie in roughly the same plane, which is only likely if they were all in the accretion disc.
- As the Sun grew in size and temperature, light molecules such as hydrogen could not exist in a solid state.
- Heavier elements gradually accreted by gravitational attraction to grow into the inner planets.
- The lighter elements drifted further from the Sun and eventually grew by gravitational attraction to be large enough to attract even the lightest elements to form the gaseous outer planets.

Revision activity

Work in pairs. Choose a planet for your partner. Your partner chooses a different planet for you. Use Table 6.1 to look up the average distances of your two planets from the Sun. Each of you calculate the time it would take for light from the Sun to reach your planet. When you have finished, compare your answers and check for consistency.

Gravitational field strength of a planet

Table 6.1 shows that the gravitational field strength at the surface of a planet depends on the mass of the planet and its density.

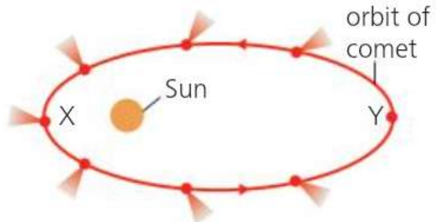
The strength of the gravitational field of any object decreases as the distance from the object increases. So the gravitational field around a planet decreases as the distance from the planet increases. Most of the mass of the Solar System is in the Sun, so planets orbit the Sun, kept in orbit by gravitational attraction of the Sun.

The strength of the Sun's gravitational field decreases as the distance from the Sun increases. The orbital speeds of the planets decrease as the distance from the Sun increases. This can be confirmed by calculation using the data from Table 6.1.

The time it takes for light to travel between the objects can be calculated using the velocity equation from Topic 1 and the velocity of light 3.0×10^8 m/s from Topic 3.

When an object travels in an elliptical orbit around the Sun, its velocity is greater when it is closer to the Sun. The gravitational potential energy is greater the further the object is from the Sun. However, its kinetic energy increases, as the velocity increases when it is closer to the Sun. Energy is conserved so the total energy is the same at all points of the orbit.

Figure 6.6 shows a comet moving round the Sun in an elliptical orbit. At point X, the gravitational potential energy is least, and the velocity and kinetic energy are greatest. At point Y, the gravitational potential energy is greatest, and the velocity and kinetic energy are least.



▲ **Figure 6.6 Elliptical orbit of a comet**

Revision activity

Write down the energy changes of a comet as it moves from its furthest to its closest distance from the Sun.

Sample questions

REVISED

3 What are the main common characteristics of the composition and size of the inner four planets? [2]

4 What are the main common characteristics of the composition and size of the outer four planets? [2]

5 State two objects other than the eight main planets which orbit the Sun. [2]

Student's answers

3 *Rocky and hot* [1]
4 *Gaseous and far from the Sun* [1]
5 *Comets and satellites* [1]

Correct answers

3 Rocky and relatively small [2]
4 Gaseous and relatively large [2]
5 Comets and dwarf planets [2]

Teacher's comments

3 Rocky is correct; hot is not about the composition or size.
4 Gaseous is correct; far from the Sun is not about the composition or size.
5 Students should write any **two** of: dwarf planets, comets or asteroids.

6 This question is about the accretion model for the formation of the Solar system.
- **a** Which materials accreted to form the Solar System? [2]
- **b** Which force caused this accretion? [1]
- **c** Explain why it is likely that the material was in a rotating disc at one stage. [2]

Student's answers

a *Hydrogen and plutonium* [1]
b *Electrostatic attraction* [0]
c *All of it goes the same way round.* [1]

Teacher's comments

a Hydrogen is correct; plutonium incorrect.
b Incorrect answer.
c 1 mark awarded for the right idea of orbiting in the same direction.

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Correct answers

a Hydrogen, dust and heavier elements [2]
b Gravitation [1]
c All the planets orbit roughly in a plane and in the same direction. [2]

7 a State with a reason how the gravitational fields on the surface of Mars and Neptune compare. [2]

b State with a reason how the orbital speeds of Mars and Neptune compare. [2]
c Confirm your answer to part a using the data from Table 6.1. [3]

Student's answers

a *Neptune because it is bigger.* [0]

b *The orbital speed of Mars is greater because its year is shorter.* [1]
c *orbital speed of Mars = 24 000 m/s*
orbital speed of Neptune = 2700 m/s
so orbital speed of Mars is greater [1]

Teacher's comments

a The student possibly meant that the gravitational field on the surface of Neptune was larger, but did not say so. The size of the planet is not the decisive factor.

b Correct answer about orbital speed, but the orbit time around the Sun follows from the speed and distance and is not the reason.
c The orbital speed of Mars is correct. The candidate possibly forgot the '2' in calculating the orbital speed of Neptune, but with no working no partial credit can be given. As it is based on a wrong number, the comment about the greater orbital speed of Mars is invalid.

Correct answers

a The gravitational field on Neptune is greater because it more massive. [2]

b The orbital speed of Mars is greater because it is closer to the Sun. [2]
c orbital speed of Mars $= \dfrac{2\pi \times 230 \times 10^9}{687 \times 24 \times 3600} = 24000\,\text{m/s}$

orbital speed of Neptune $= \dfrac{2\pi \times 4500 \times 10^9}{165 \times 365 \times 24 \times 3600} = 5400\,\text{m/s}$

So the orbital speed of Mars is greater. [3]

8 a A student states that it takes light 8 minutes to travel from the Sun to the Earth. Using data from Table 6.1, calculate the velocity of light based on this time. Note: Extension students need to know the value of the velocity of light in a vacuum. [3]

b Comment on the accuracy of this value of the velocity of light and the student's statement. [1]

c The average distance from the Earth to Neptune is 4500 million km and the velocity of light is 3×10^8 m/s. Calculate the time in hours light takes to travel from Neptune to the Earth. [2]

Student's answers

a *velocity = distance/time = $1.5 \times 10^{11}/8 \times 60 = 3.1 \times 10^5$ m/s* [2]

b *They are nearly right.* [0]

c *time = distance/velocity = $4.3 \times 10^{12}/3.0 \times 10^8 = 1.4 \times 10^4$ s = 4.0 h* [1]

Teacher's comments

a The student made an error of factors of 10 in the calculation, so loses a mark.

b As the comment is based on a wrong calculation, no mark is scored.

c The student used a slightly wrong value in the correct equation.

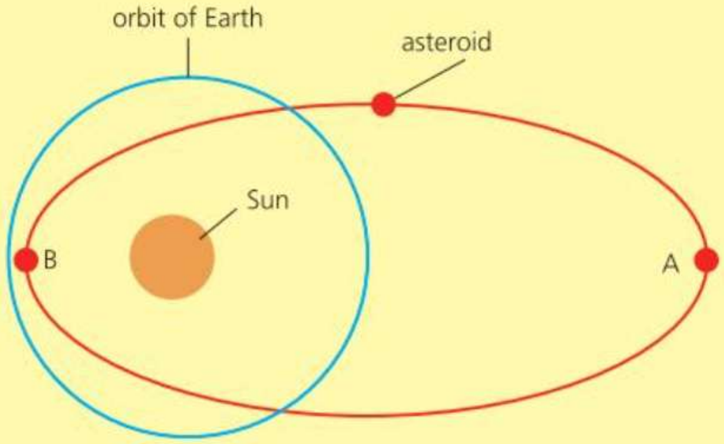
Correct answers

a velocity = distance/time = $1.5 \times 10^{11}/8 \times 60 = 3.1 \times 10^8$ m/s [3]

b The velocity of light is close to the correct value, so the time for light to travel from the Sun is fairly accurate. [1]

c time = distance/velocity = $4.5 \times 10^{12}/3.0 \times 10^8$
$= 1.5 \times 10^4$ s = 4.2 h [2]

9 Figure 6.7 shows the elliptical orbit of an asteroid.



▲ **Figure 6.7**

Describe the change of the following quantities as the asteroid moves from point A to point B:
distance from the sun, velocity, gravitational potential energy, kinetic energy, total energy [5]

Student's answer

distance from the sun decreases, velocity increases, gravitational potential energy increases, kinetic energy increases [3]

Teacher's comments

Correct answers for distance from the Sun, velocity and kinetic energy. The answer for gravitational potential energy is incorrect and the student failed to write anything about total energy.

Correct answer

distance from the sun decreases, velocity increases, gravitational potential energy decreases, kinetic energy increases, total energy stays the same [5]

Revision activity

Make flash cards to revise and rearrange the equation connecting orbital speed, radius of orbit and orbital period. Include what the symbols in the equation represent and rearrange the equation with r on its own on the left of the equals sign and then with T on its own on the left.

Revision activity

Observing planets in the night sky

Three of the planets Venus, Jupiter and Mars appear as bright 'stars' and can easily be observed at the right time of year and time of day. Saturn and Mercury can also be seen with the naked eye but can be hard to see, especially Mercury.

You should prepare yourself to observe the planets every week for a few months. Again, if you live in a part of the Earth where the weather is cloudy, you will miss a few or possibly several observations.

- Find out which of Venus, Jupiter and Mars are visible where you live and at what time of night from an app, the internet or your teacher.
- See if you can observe these planets at times that are reasonable for you. Don't let it disturb your sleep!
- Make notes and record the date and time of observing any planet. Try to record where you observed it in the sky and how high up.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

1 a Sketch a labelled diagram to show:
   i the orbit of the Earth around the Sun [2]
   ii the Earth's axis of rotation [1]
  b Describe the angle of the axis of rotation. [1]

2 In the table below, which describes the planet Venus?

A	gaseous and large
B	gaseous and small
C	rocky and large
D	rocky and small

[1]

3 In the table below, which compares properties of the Earth and Jupiter?

	Property of the Earth	Property of Jupiter
A	relatively low density	relatively high density
B	relatively low mass	relatively high mass
C	relatively high diameter	relatively low diameter
D	relatively high density	relatively low mass

[1]

4 a The planet Mercury has an orbital radius of 58 million km and an orbital speed of 48 000 m/s.
  Show that the orbital period of Mercury is 88 days. [3]
  b Without calculation, write down how the following properties for the planet Uranus compare with the properties for the planet Mercury:
   i orbital speed [1]
   ii strength of the Sun's gravitational field [1]

5 Using data from Table 6.1:
  a State and explain the differences of orbit time, average distance from the Sun and surface temperature of the planets Uranus and Neptune. [4]
  b Considering density, diameter and mass, explain the difference between gravitational field strength on the surface of the planets Mars and Jupiter. [2]

6 a State the differences in nature of the four inner planets in the Solar System from the four outer planets and why there are these differences. [2]
  b Use the accretion model to explain why there are these differences. [4]

7 Light travels at 3.0×10^8 m/s in space. The distance of the Moon from the Earth is 390 000 km. Calculate the time it takes for light to travel from the Moon to the Earth. [3]

8 a Make a labelled sketch of the typical orbit of a comet going round the Sun. Label two points X and Y at two points on the orbit. [3]
  b State the difference in velocity, gravitational potential energy and total energy between X and Y. [4]

6.2 Stars and the Universe

REVISED

6.2.1 The Sun as a star

Key objectives

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

- know that the Sun is a medium-sized star containing mostly hydrogen and helium
- the Sun radiates energy mostly in the infrared, visible and ultraviolet regions of the electromagnetic spectrum
- know that stars are powered by nuclear fusion reactions with hydrogen

The Sun is a medium-sized star. It is made up almost entirely of hydrogen: there is some helium and other elements. It radiates energy over the whole electromagnetic spectrum but mostly in the infrared, visible and ultraviolet regions.

Stars are powered by nuclear fusion reactions. Stable stars produce helium from the fusion of hydrogen.

Sample question

REVISED

10 a What two elements are the main constituents of the Sun? [2]

b Name one of the main types of radiation from the Sun in addition to visible light. [1]

c Describe the nuclear reaction that takes place in the Sun. [3]

Student's answers

a *hydrogen and deuterium* [1]

b *X-rays* [0]

c *Nuclear explosion of hydrogen.* [1]

Teacher's comments

a Hydrogen is correct, but deuterium is an isotope of hydrogen. A different element was required.

b X-rays are given off by the Sun, but the main electromagnetic radiations in addition to visible light are infrared and ultraviolet.

c This answer is much too vague.

Correct answers

a hydrogen and helium [2]

b infrared (or ultraviolet) [1]

c nuclear fusion of hydrogen to form helium [3]

6.2.2 Stars

Key objectives

By the end of this section, you should be able to:
- know that galaxies are groups of hundreds of billions of stars and the Solar System is in a galaxy called the Milky Way
- be able to calculate the value in metres of the astronomical distance 1 light-year, the distance light travels in a year
- know that 1 light-year = 9.5×10^{15} m
- describe the life cycle of a star

Galaxies

Galaxies are groups of hundreds of billions of stars. The Solar System is in a galaxy called the **Milky Way**. The other stars of the Milky Way are much further from the Solar System than the distances between the Sun and the planets of the Solar System.

An astronomical unit of distance is the **light-year**, the distance travelled in space by light in one year.

One light year is equal to 9.5×10^{15} m.

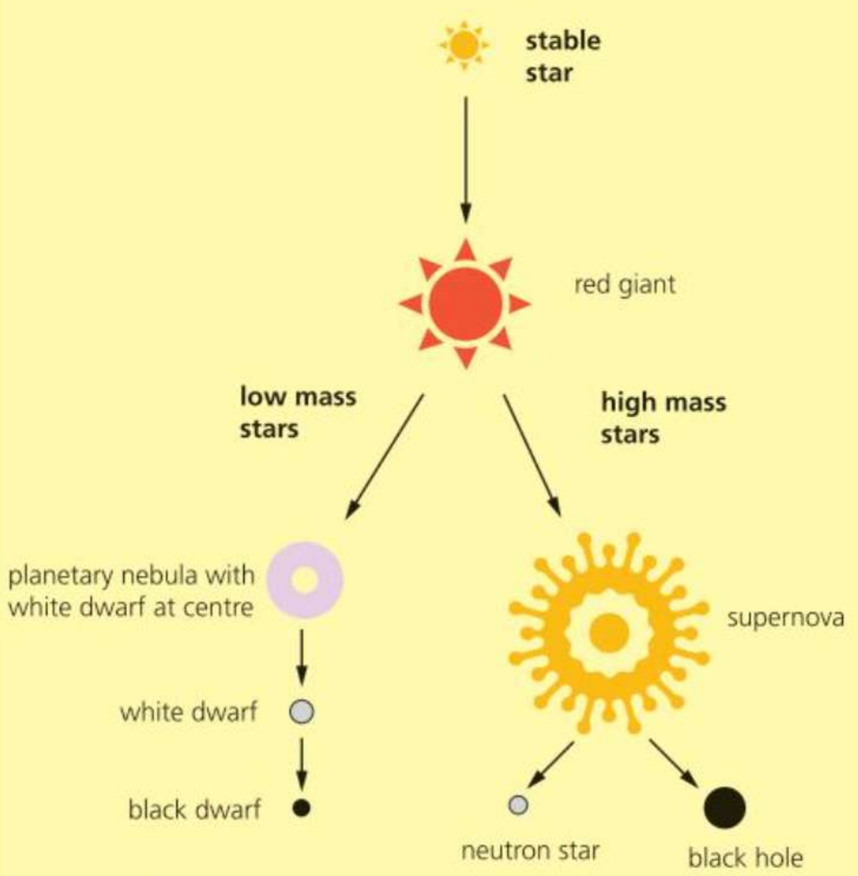
Skills

Calculating the value of the astronomical distance 1 light-year in metres

$$\text{distance} = \text{speed} \times \text{time}$$
$$= 3 \times 10^8 \times 365 \times 24 \times 3600$$
$$= 9.5 \times 10^{15}\ \text{m}$$

Life cycle of stars

The life cycle of a star shown in Figure 6.8.



▲ **Figure 6.8 Life cycle of stars**

- The materials which form stars are interstellar clouds of gas and dust containing hydrogen.
- The interstellar clouds collapse due to gravitational attraction, increase in temperature and form protostars.

Revision activity

Make flash cards to revise information about galaxies. Include the name of the galaxy containing the Earth, how many stars are in this galaxy, the diameter of this galaxy and how many galaxies are in the Universe.

- Stable stars form from protostars when the inward gravitational forces balance the outward forces as the temperature of the star increases. The high kinetic energy at high temperatures causes a large pressure, producing the outward forces.
- All stars eventually use up all the hydrogen for fusion reactions.
- When this happens, most stars become **red giants**.
- Red giants become planetary nebulas with a white dwarf at the centre.
- Massive stars expand to form **red supergiants**.
- A red supergiant explodes as a supernova, forming a nebula of hydrogen and new heavier elements created in the explosion.
- The explosion of a supergiant leaves behind a neutron star or a black hole.
- The nebula from a supernova may form new stars with orbiting planets.

Sample questions

REVISED

11 Calculate the distance of a light-year in metres. The velocity of electromagnetic waves in a vacuum is 3.0×10^8 m/s. [4]

Student's answer

light-year = $3.0 \times 10^8 \times 365 \times 3600 = 3.9 \times 10^{14}$ m [3]

Teacher's comments

The student used the correct equation correctly, but left out the factor 24 for the number of hours in a day.

Note: Extension students are expected to know that 1 light-year = 9.5×10^{15} m and that the velocity of electromagnetic waves in a vacuum is 3.0×10^8 m/s.

Correct answer

One light-year = distance travelled by light in a year

$= v \times t$

$= 3.0 \times 10^8 \times 365 \times 24 \times 3600 = 9.5 \times 10^{15}$ m [4]

12 Choose words from the following list that describe what stars of normal size can become or produce after using up all their hydrogen.

red giant | red supergiant | white dwarf | red dwarf
heavier elements | neutron star | black hole [2]

13 Choose words from the following list that describe what massive stars much greater than normal size can become after using up all their hydrogen.

red giant | red supergiant | white dwarf | red dwarf
heavier elements | neutron star | black hole [3]

Student's answers

12 <u>red giant</u> red supergiant <u>white dwarf</u> red dwarf <u>heavier elements</u> neutron star black hole [1]

13 red giant <u>red supergiant</u> white dwarf red dwarf <u>heavier elements</u> <u>neutron star</u> <u>black hole</u> [2]

Correct answers

12 <u>red giant</u> red supergiant <u>white dwarf</u> red dwarf heavier elements neutron star black hole [2]

13 red giant <u>red supergiant</u> white dwarf red dwarf <u>heavier elements</u> <u>neutron star</u> OR <u>black hole</u> [3]

Teacher's comments

12 Red giant and white dwarf are correct answers, but the only correct answers. Heavier elements are not formed in stars of normal size. One mark is lost for the incorrect additional answer.

13 Red supergiant and heavier elements are correct answers. Either a neutron star or a black hole is formed. One mark is lost for stating both.

6.2.3 The Universe

Key objectives

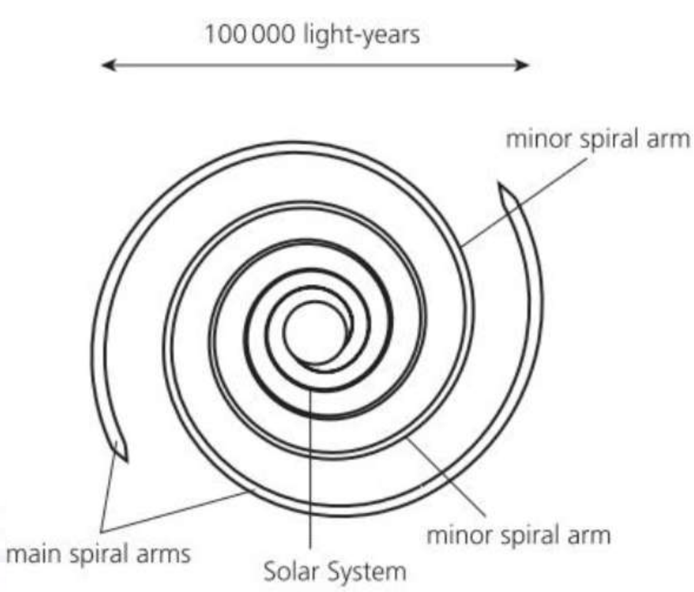
By the end of this section, you should be able to:

- know that the Milky Way is one of hundreds of billions of galaxies in the Universe and the diameter of the Milky Way is about 100 000 light-years
- describe redshift as an increase of wavelength of light from receding stars and galaxies compared with light from a stationary source
- know that redshift is evidence for the Big Bang Theory
- explain what is meant by cosmic microwave background radiation (CMBR)
- know how the speed at which a galaxy is moving away from Earth and the distance to a far galaxy can be found
- define the Hubble constant H_0 and know its current estimated value is $2.2 \times 10^{-18}\,s^{-1}$
- know the equation containing the Hubble constant for the age of the Universe.

The Universe

The Milky Way is one of hundreds of billions of galaxies in the **Universe**. The Milky Way is one large disc with spiral arms of diameter about 100 000 light-years, containing hundreds of billions of stars. The Solar System is in one of the minor spiral arms.

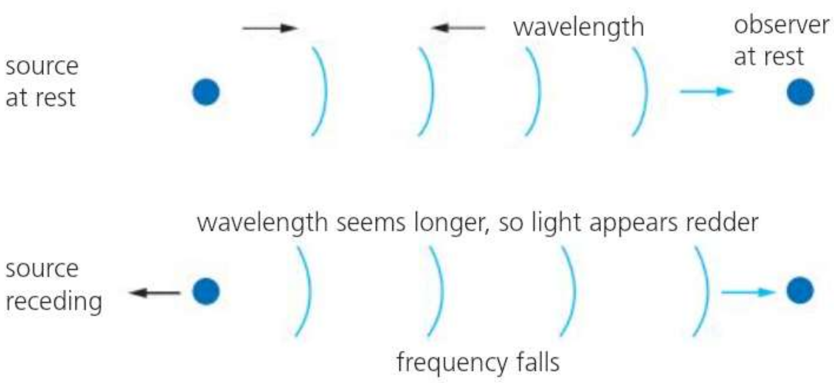
Figure 6.9 shows a simplified diagram of the Milky Way galaxy.



▲ **Figure 6.9 The Milky Way**

The expanding Universe and the Big Bang Theory

Nearly all the stars and galaxies of the Universe are moving away from the Earth at high speed. This increases the wavelength of light and other electromagnetic radiation observed on Earth emitted from receding stars and galaxies, so the light appears redder than when emitted. This is called **redshift** and is illustrated in Figure 6.10.



▲ **Figure 6.10 Redshift**

Redshift of this light shows that the Universe is expanding. This is consistent with the **Big Bang Theory** that the Universe was initially packed in a single point, which exploded over 10 billion years ago.

Electromagnetic radiation from the Big Bang is still observed in the microwave region today, everywhere in space. It was produced shortly after the Universe was formed and this radiation has been expanded into the microwave region of the electromagnetic spectrum as the Universe expanded. It is called cosmic microwave background radiation (**CMBR**).

The speed (v) of a galaxy's recession from the Earth can be worked out by measuring the amount of redshift. The brightness of a supernova in a far galaxy enables its distance (d) from the Earth to be worked out.

The ratio of v and d equals the **Hubble constant (H_0)** as given by the equation:

$$H_0 = \frac{v}{d}$$

The value of H_0 is currently estimated to be $2.2 \times 10^{-18}\,s^{-1}$.

Skills

Rearranging the equation with the Hubble constant

You need to be able to rearrange the equation $H_0 = v/d$ to make any of the variables the subject.

- Write down the equation when v is the subject:

$$H_0 = \frac{v}{d}$$

$$\frac{v}{d} = H_0$$

$$v = dH_0$$

- Write down the equation when d is the subject:

$$H_0 = \frac{v}{d}$$

$$dH_0 = v$$

$$d = \frac{v}{H_0}$$

Age of the Universe

An estimate for the age of the Universe from when all matter was at a single point is given by d/v. So rearranging the previous equation gives:

$$\frac{d}{v} = \frac{1}{H_0} = \text{age of the Universe}$$

Skills

Rearranging the equation for the age of the Universe

You need to be able to rearrange the equation for the age of the Universe in terms of v and d to make any of the variables the subject.

$$\frac{d}{v} = \text{age of Universe}$$

- Write down the equation when d is the subject:

$$d = v \times \text{age of Universe}$$

- Write down the equation when v is the subject:

$$d = v \times \text{age of Universe}$$

$$v \times \text{age of Universe} = d$$

$$v = \frac{d}{\text{age of Universe}}$$

Sample questions

REVISED

14 A galaxy is 40 million light-years distant from the Solar System. Calculate the speed it is moving away from the Earth. [3]

Student's answer

$v = H_0 d = 2.1 \times 10^4$ m/s [1]

Correct answer

$v = H_0 d = 2.2 \times 10^{-18} \times 40 \times 10^6 \times 9.5 \times 10^{15} = 8.4 \times 10^5$ m/s [3]

Teacher's comments

The answer is too small by a factor of 4. Possibly the candidate forgot the number 40 and also made a factor of 10 error. The examiner cannot see what the candidate did, so is not able to give any credit beyond that for the correct equation.

Although the basic mathematics is straightforward, the working out is often complex in Space physics questions. Candidates for the Extended paper are expected to be able to do such calculations.

15 Use the value of the Hubble constant to estimate the age of the Universe in billions of years. [3]

Student's answer

age of the Universe $= 1/H_0 = 1/2.2 \times 10^{-18} = 4.5 \times 10^{17}$ s [1]

Correct answer

age of the Universe $= 1/H_0 = 1/2.2 \times 10^{-18} = 4.5 \times 10^{17}$ s

$$= \frac{4.5 \times 10^{17}}{365 \times 24 \times 3600}$$

$= 1.4 \times 10^{10}$ years

$= 14$ billion years [3]

Teacher's comments

The student's answer is correct as far as it goes, but is incomplete. The question asked for the answer in billions of years not in seconds.

Revision activity

Make flash cards to revise about CMBR. Include what CMBR stands for and what CMBR means in relationship to the Big Bang.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

9 In the table below, which is the name of the Sun's galaxy and the distance of most other stars in the galaxy from the Sun compared with the distance of the Earth from the Sun? [1]

	Name of the Sun's galaxy	Distance of other stars in the galaxy from the Sun
A	Solar System	about the same
B	Milky Way	much further
C	Solar System	much closer
D	Milky Way	about the same

10 a State how the size of the Sun compares to most stars in the Universe. [1]

b State which elements make up most of the Sun. [2]

c State what powers the Sun. [2]

d State what is contained in a galaxy. [1]

e State the name of the galaxy where the Earth is situated. [1]

11 The diameter of the Milky way is 100 000 light years. Calculate the diameter of the Milky Way in metres. [4]

12 a State what is redshift. [2]

b Explain the connection between redshift and the Big Bang Theory. [2]

13 Choose from the table below what most stars form as the next stage in their life cycle after running out of hydrogen.

A	red giant
B	red supergiant
C	white dwarf
D	neutron star

[1]

14 a What do the letters CMBR stand for. [2]

b State and explain if CMBR radiation is part of the electromagnetic spectrum. [2]

c Explain the connection between CMBR and the Big Bang Theory. [2]

d Write down the distance of 1 light-year in metres. [1]

15 a Explain how the speed of a galaxy moving away from the Earth can be determined. [2]

b State how the distance away from the Earth of a far galaxy can be determined. [2]

16 a Write down an equation which defines the Hubble constant. Use the normal symbols for all quantities in your equation and explain what these quantities represent. [5]

b Write down the current estimate for the value of the Hubble constant and its unit. [2]

17 a Write down the equation which estimates the age of the Universe. Use the normal symbols for all quantities in your equation and explain what these quantities represent. [5]

b Work out an estimate for the age of the Universe in years. [3]

c Write down a statement about all the matter in the Universe being at a single point. [2]

Index

Note: page numbers in bold refer to the location where a key definition is *first* defined.

G

H

I

K

L

M

N

O

P

R

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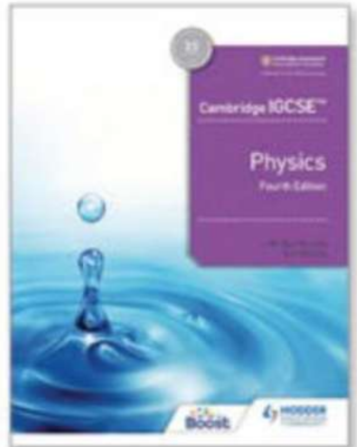

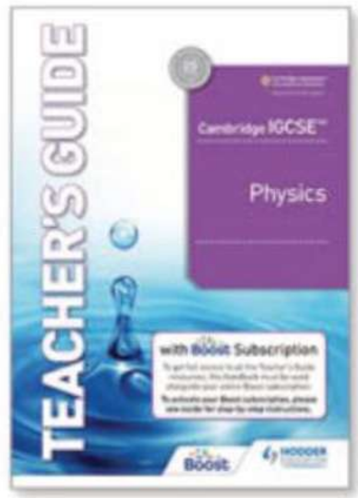

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