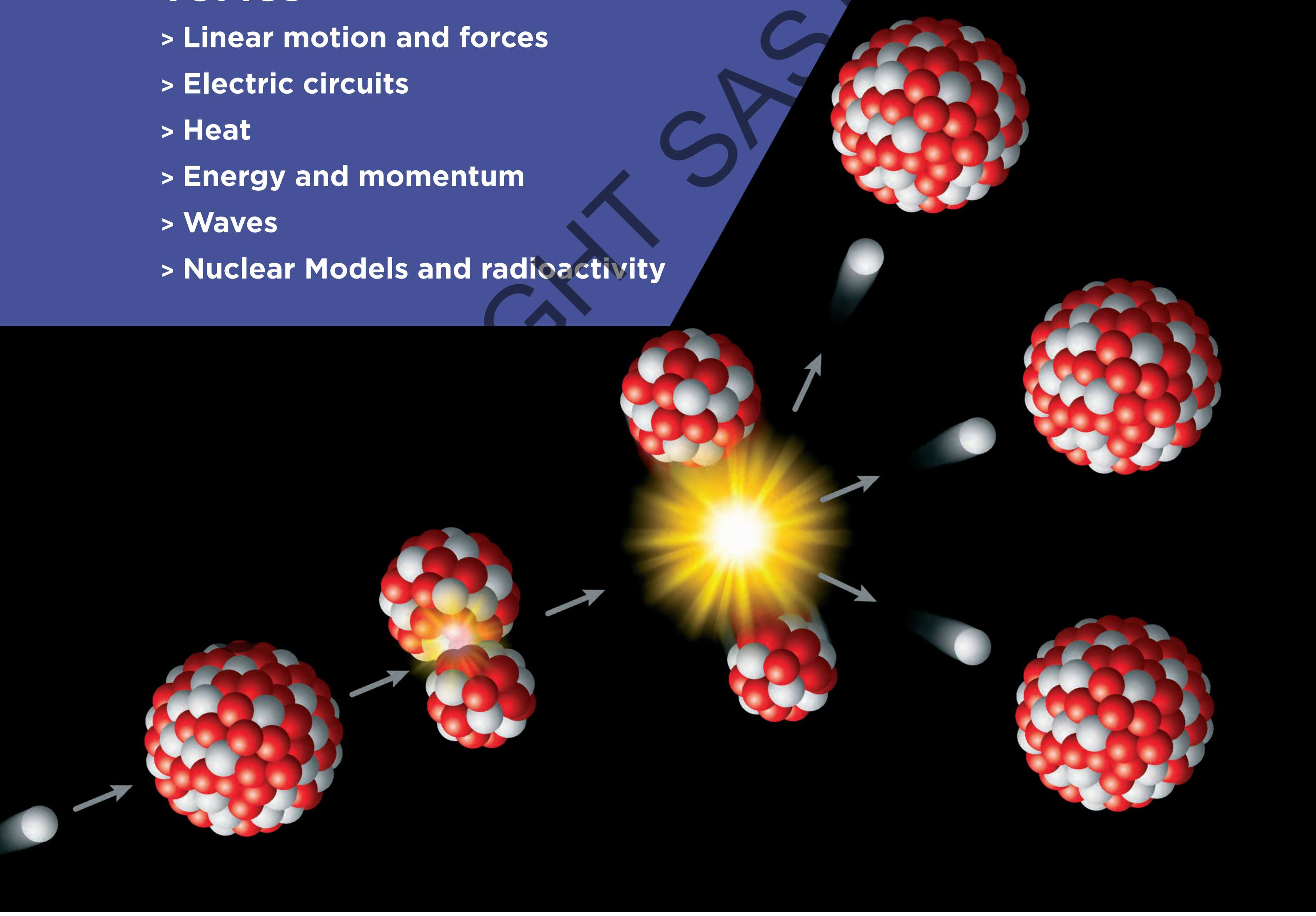
SACE STAGE 1
Australian Curriculum

WORKBOOK

Physics

TOPICS

- > Linear motion and forces
- > Electric circuits
- > Heat
- > Energy and momentum
- > Waves
- > Nuclear Models and radioactivity



SASTA South Australian Science Teachers Association
Supporting Teachers of Science
Advancing Science Education

SECOND EDITION
Rhys Lewis

Contents

CHAPTER 2

TOPIC 2: ELECTRIC CIRCUITS

2.1: Potential difference and electric current

Atoms contain positively charged protons and negatively charged electrons.

Objects become charged when electrons are transferred from one object to another or redistributed on one object.

Two like charges exert repulsive forces on each other, whereas two opposite charges exert attractive forces on each other.

- Describe electric forces between like charges and between opposite charges.
- Explain various phenomena involving interactions of charge.
- Explain how electrical conductors allow charges to move freely through them, whereas insulators do not.

All materials are composed of atoms. Atoms have a central **nucleus** containing **protons** and **neutrons** surrounded by a cloud of **electrons.** Figure 2.01 shows a simplified model of an atom showing the position of protons, neutrons and electrons.

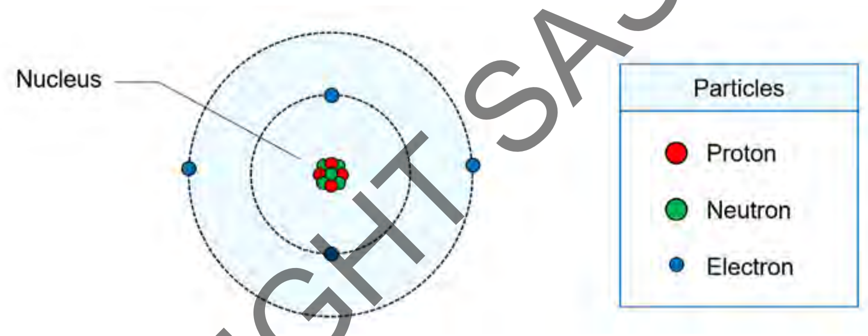


Figure 2.01: Simple atomic structure.

Protons, neutrons and electrons are defined as **subatomic particles** as they comprise the substructure of an atom. Some properties of the subatomic particles are provided in the table below.

Subatomic particle	Mass (kg)	Electric charge (*e*)*	Position in an atom
Proton	1.673×10^{-27}	+1	Inside the nucleus
Neutron	1.675×10^{-27}	0	Inside the nucleus
Electron	9.11×10^{-31}	−1	Outside the nucleus

*the magnitude of *e* is 1.6×10^{-19} C.

The table identifies protons and electrons as particles possessing a quantity of electric charge.

Electric Forces

The **electric force** (F) is a mutual force of attraction or repulsion between two charged particles or objects. The electric force is repulsive between like-charges and attractive between opposite charges as shown in the table below.

Between:	Nature of electric force
Two positive charges	Repulsion
Two negative charges	Repulsion
Positive and negative charge	Attraction

The electric forces exerted by two charges are equal in magnitude but opposite in direction which is consistent with Newton's Third Law of Motion. Figure 2.04 shows the magnitude and direction of the mutual electric forces of attraction and repulsion between charges.

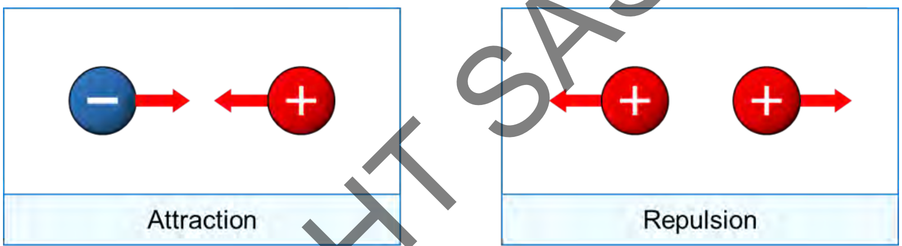


Figure 2.04: Mutual forces of attraction (left) and repulsion (right) between charges

Charge Transfer

Atoms are electrically neutral as they contain equal numbers of positively charged protons and negatively charged electrons. Electrons are bound to the nucleus of an atom by a mutual electric force of attraction. However, the electric force between the nucleus and electron(s) in an atom is very weak (10^{-8} to 10^{-10} N) and this allows electrons to be removed from atoms by the application of a net force in a direction away from the atomic nucleus. Objects become charged when electrons are transferred from one object to another. The table below identifies the net charge on an object that was initially neutral due to different types of charge transfer.

Charge transfer	Net charge due to transfer
Electrons added	Negative
Electrons removed	Positive

Various phenomena involving interactions of charge are described in Examples 2.01 to 2.03.

Example 2.01

Figure 2.05 shows the charge transfer that occurs when hair is brushed with a plastic comb. Electrons are transferred from hair to the plastic comb by friction. After combing, hair has a net positive charge (electrons removed), and the comb has a net negative charge (electrons added).

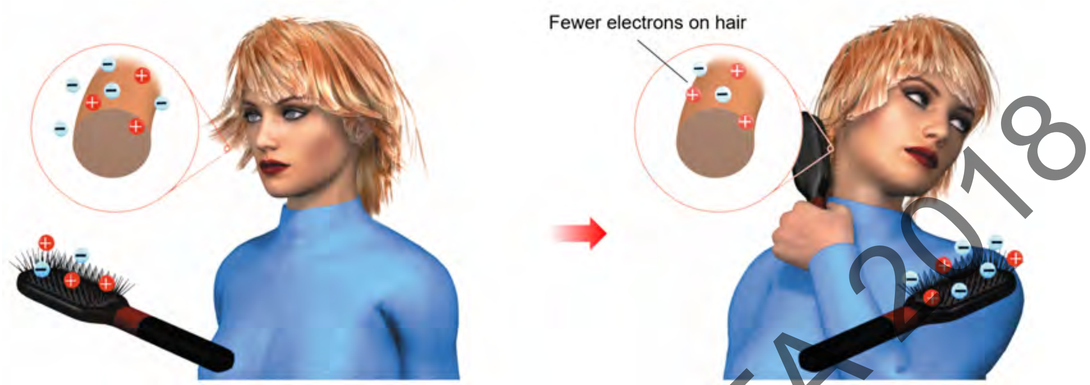


Figure 2.05: Transfer of electrons from hair to comb.

Example 2.02

Charge transfer is utilised in the operation of a laser printer (Figure 2.06).

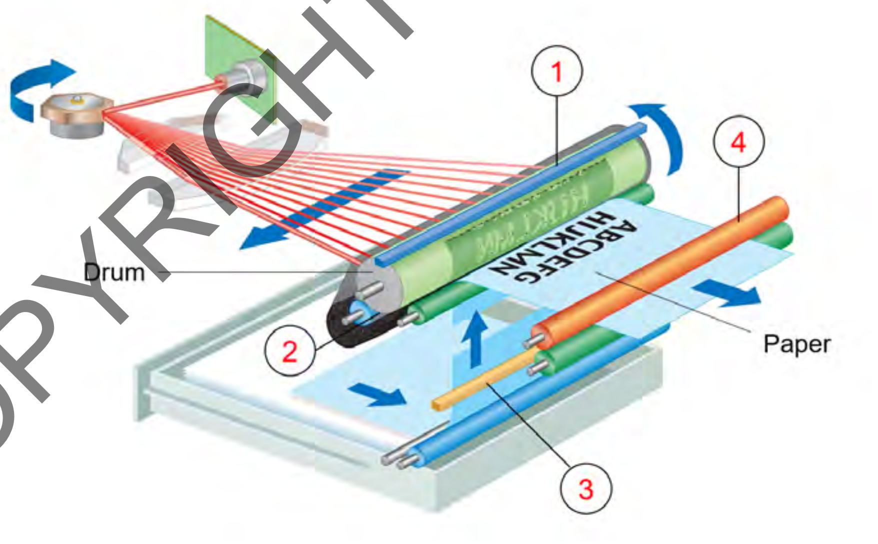


Figure 2.06: Laser printer.

The operation of the laser printer is described below.

1. Electrons are removed from the drum by a positively charged wire.
2. Negatively charged toner particles are attracted to the surface of the positively charged drum.
3. Electrons are removed from the paper by a positively charged wire.
4. Negatively charged toner particles are transferred from the drum to the positively charged paper.

Example 2.03

Lightning is an electrical phenomenon caused by the movement of different types of ice crystals within a cloud. Electrons are transferred through collisions between lighter ice crystals moving upwards and heavier crystals moving downwards towards the base of the cloud (Figure 2.07).

Figure 2.07: Charge transfer between moving ice crystals.

The transfer of electrons between ice crystals causes a build-up of negative charge at the base and a build-up of positive charge at the top of a cloud. The ground located beneath the cloud becomes positively charged as electrons on the surface are repelled deep into the Earth. Charges flow between the base of the cloud and the Earth producing a large electrical discharge called a **lightning strike** (Figure 2.08).

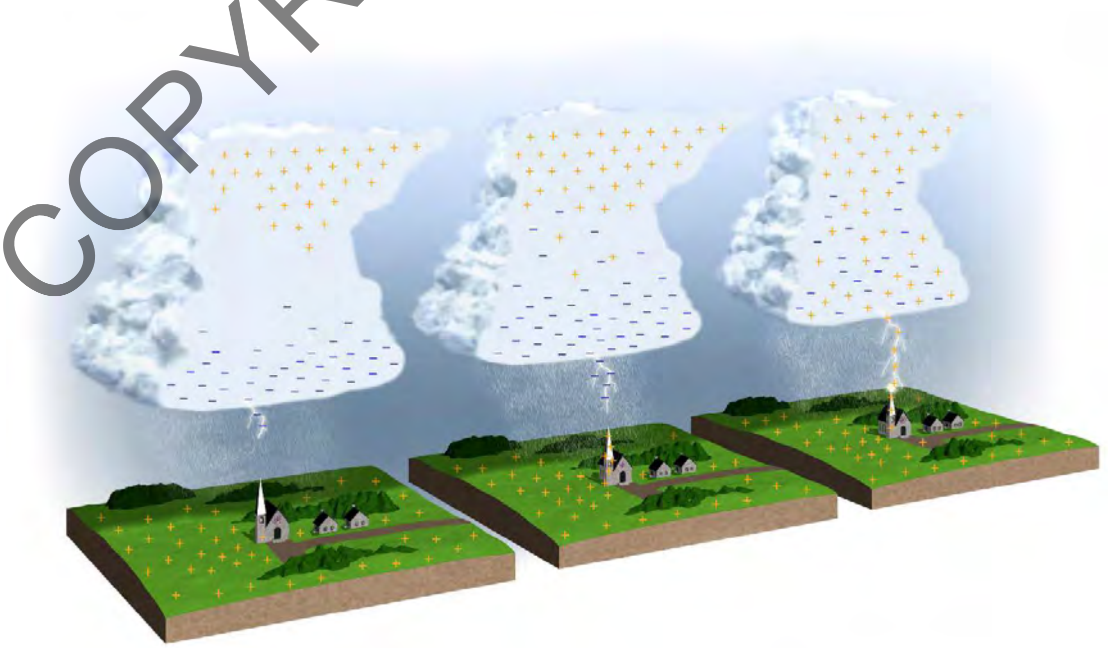
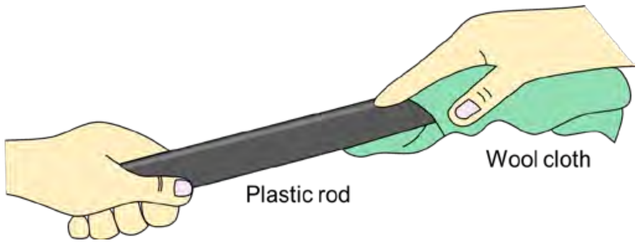


Figure 2.08: Movement of charges during a lightning strike.

Question 33

The diagram below shows a plastic rod being rubbed with a wool cloth.



(a) The rod becomes negatively charged after rubbing.

(1) Describe and explain the rod becomes negatively charged.

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____ (2 marks) KA2

(2) State the charge on the cloth after rubbing and give a reason for your answer.

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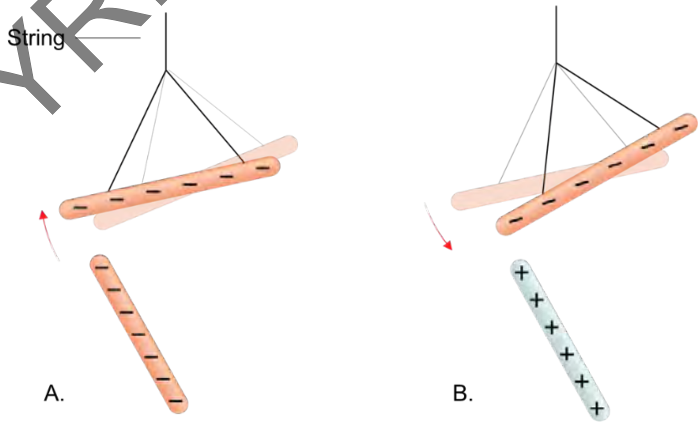
____ (2 marks) KA2

(b) The diagrams below show interactions between charged rods.



Describe and explain the movements of the charged rods in diagrams A and B above.

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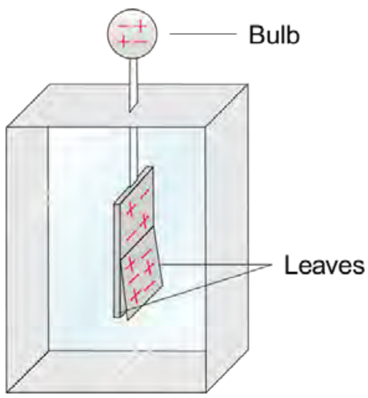
____ (2 marks) KA1

Question 34

An electroscope is a device that is used to determine if an object is electrically charged.

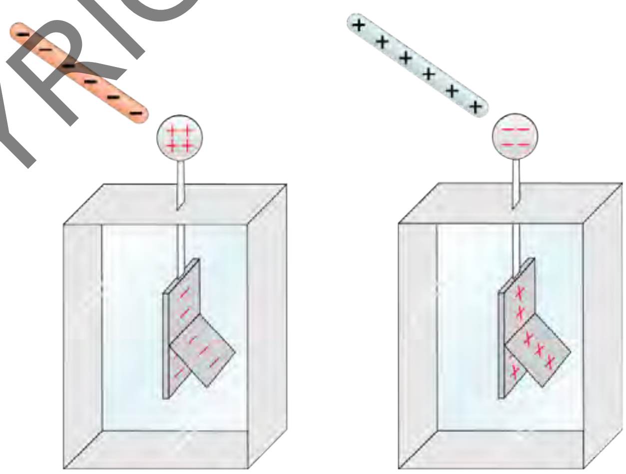
The diagram shows an electroscope that is electrically-neutral.



(a) Explain how both the bulb and leaves of an electroscope can be electrically-neutral when each contains positive and negative charges.

(2 marks) KA2

(b) The leaves of the electroscope separate when a charged rod is placed near the bulb of a neutral electroscope.



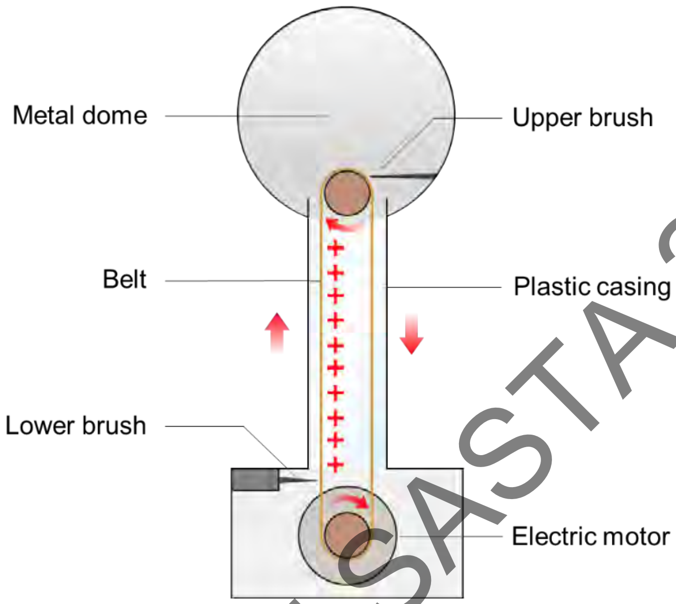
Describe and explain the separation of the leaves due to the charged rod.

(2 marks) KA2

Question 35

A Van de Graaff generator is a laboratory device used in the production of high voltages and static electric charge.

The diagram below shows some components of a Van de Graaff generator.



(a) Electrons are transferred from the upper brush to the surface of the belt during operation.

Electrons then move from the outer surface of the metal dome to the upper brush.

State and explain the charge on the surface of the metal dome.

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__________________________________ (2 marks) **KA2**

(b) The charge on the surface of one Van de Graaff generator is 5×10^{-5} C.

Calculate the number of electrons removed from the surface of the metal dome.

The charge on an electron is 1.6×10^{-19} C.

(2 marks) **KA4**

Electrical conductors and insulators

All materials are classified as **electrical conductors** or **electrical insulators**.

An electrical conductor is a material containing electrically-charged particles that are free to move when connected to a source of **electric potential difference** (ΔV). A source of electric potential difference such as a battery or power supply produces an electric field within a material that causes free moving charges to flow in the direction of either the positive or negative terminals.

Example 2.04

Metals are materials with good electrical conductivity. Metals contain free moving electrons which move in the direction of the positive terminal when the material is connected to a source of electric potential difference. Figure 2.09 shows the flow of electrons on a copper wire that is connected to a source of electric potential difference. The free electrons in the metal flow in the direction of the positive terminal of the source of electric potential difference.

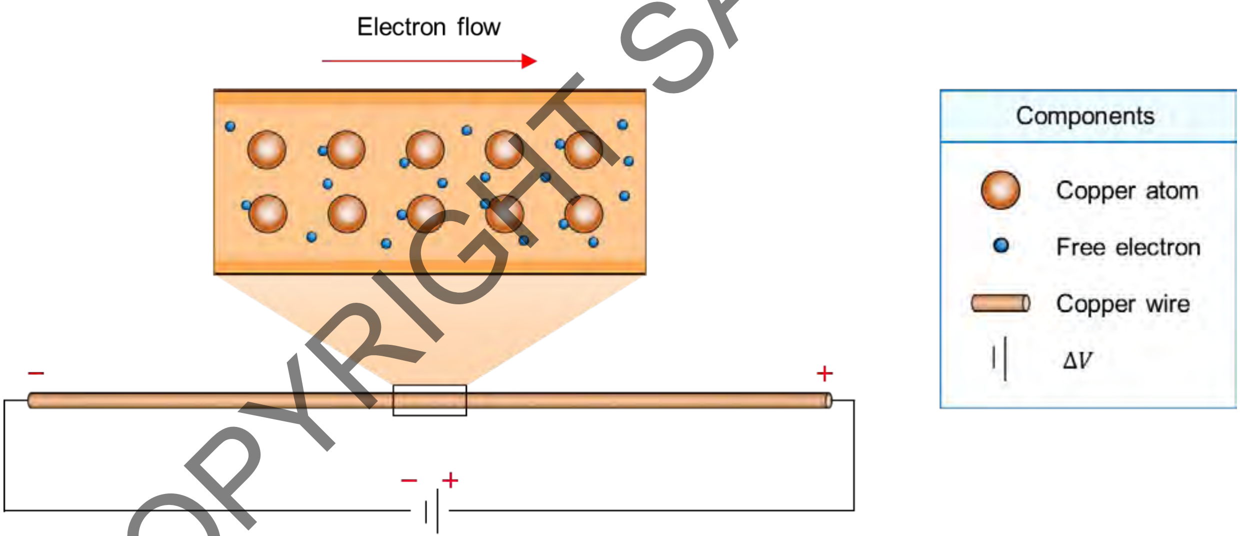


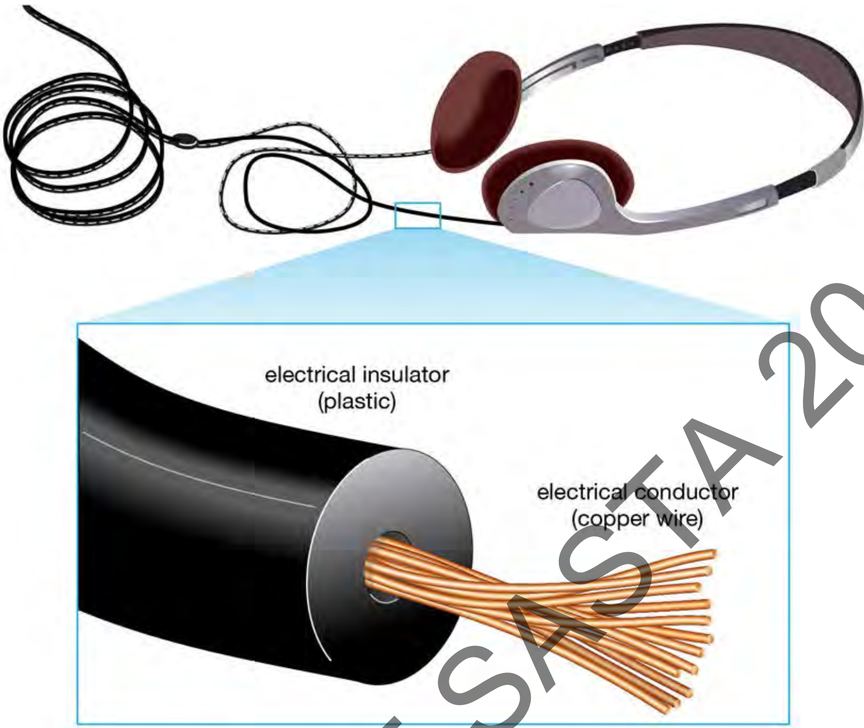
Figure 2.09: Flow of electrons in a copper metal wire.

Other examples of electrical conductors include molten salts, salt solutions and tap water. These materials contain free-moving charged particles called **ions** that flow when the material is connected to a source of electric potential difference.

An electrical insulator is a material that does not contain electrically-charged particles that are free to move when connected to a source of electric potential difference. Examples of electrical insulators include glass, air, wood, plastic, and rubber.

Question 37

The diagram below shows two different materials used in the manufacture of headphones.



(a) The plastic material is an electrical insulator.

(1) Define the term electrical insulator using the plastic covering as an example.

(2 marks) KA1

(2) State one function of the plastic covering in the electrical cable above.

(1 mark) KA2

(b) Explain why copper wire is an electrical conductor.

(2 marks) KA1

Electric potential difference

Electric potential or **voltage** (V) is a measure of the electric potential energy (E_p) per unit charge (q) at a certain position in an electric circuit or electric field.

$$V = \frac{E_p}{q}$$

The movement of charge between two positions (A and B) in an electric circuit or field results in a change in both the electric potential and electric potential energy of a charge. The difference in electric potential of a charge at positions A and B is called **electric potential difference** (ΔV) and is calculated using the formula below.

$$\Delta V = \frac{\Delta E_p}{q}$$

The change in electric potential energy of a charge (ΔE_p) is equal to the work done (W) in moving it between positions A and B in an electric circuit or field.

Electric potential difference is calculated using the formula below.

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

Symbol	Variable	SI unit
ΔV	Electric potential difference	V
ΔE_p	Change in electric potential energy	J
W	Work done	J
q	Charge	C

The SI unit of measurement of voltage and electric potential difference is the **Volt** (V) which is named after Italian physicist Alessandro Volta (Figure 2.11).

Figure 2.11: Alessandro Volta (1745- 1827)

Voltmeter

The potential difference between two points in an electric circuit is measured using a device called a **voltmeter**. The purpose of the voltmeter is to determine the magnitude of the potential difference across a component such as a load or battery to ensure that it is functioning correctly in a circuit.

Example 2.07

A car will not start if the potential difference across the battery is not high enough to supply the starter motor and ignition system with sufficient current to start the engine. A voltmeter is used to determine the potential difference across the two terminals of a car battery as shown in Figure 2.13.

Figure 2.13: Voltmeter measuring the potential difference across a car battery.

A voltmeter is connected in **parallel** (discussed in Topic 2.3) with the component to be measured as components connected in parallel have the same potential difference. Figure 2.14 shows a voltmeter that is measuring the potential difference across a light bulb in a simple electric circuit.

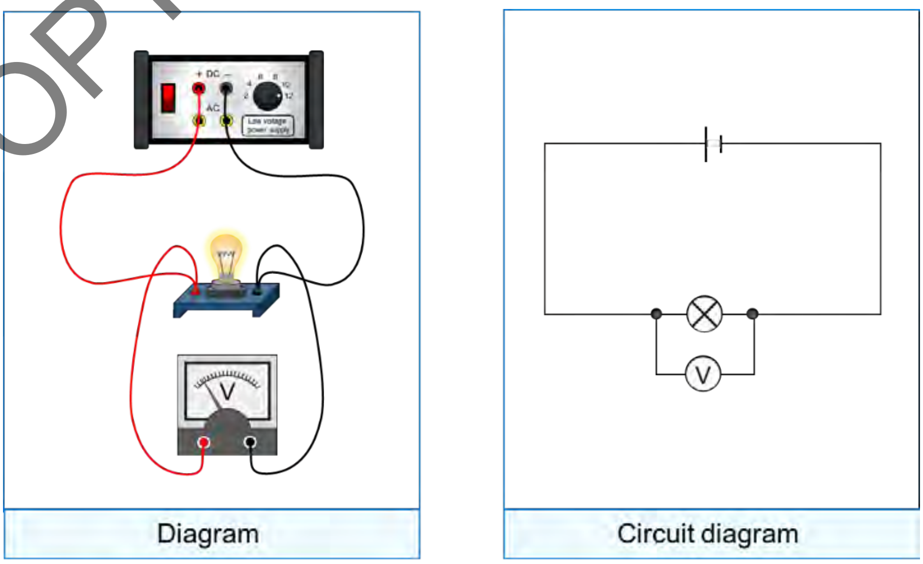


Figure 2.14: Voltmeter measuring the potential difference across a light bulb.

Ammeter

The electric current at a point in an electric circuit is measured using a device called an **ammeter**. The purpose of the ammeter is to determine the current (or resistance) across a component such as a load or battery to ensure that it is functioning correctly in a circuit.

An ammeter is connected in series (see Topic 2.3) with the components of the circuit because two components in series have the same current. Figure 2.17 shows an ammeter that is measuring the current flow in a light bulb in a simple electric circuit.

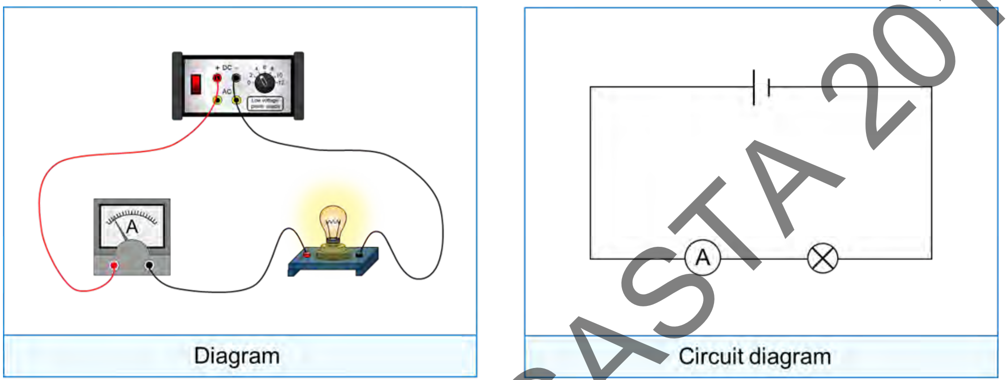


Figure 2.17: Ammeter measuring the electric current in a light bulb in a simple circuit.

Electrical safety

Electric current powers electrical appliances in the home. Electric current flows in conducting wires to electric loads including lights, computers, televisions and kitchen appliances. The flow of electric current in conducting wires produces heat which can initiate the combustion of floors, curtains, and rugs surrounding the wire and start a fire (Figure 2.18).

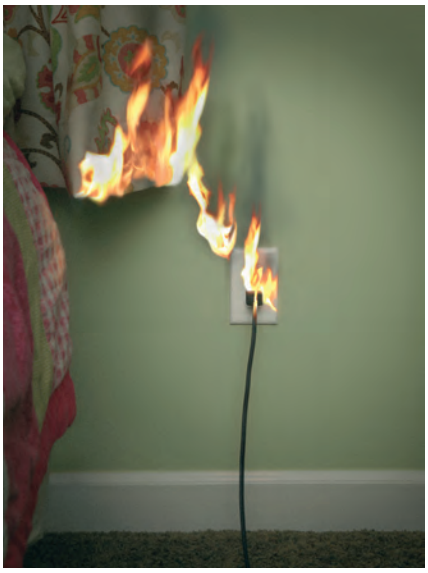


Figure 2.18: Heat from electrical wiring initiates combustion of curtains.

Electrical fuses and circuit breakers are safety devices used to prevent electrical wires from becoming overheated due to the flow of electric current.

Fuse

A fuse is an electrical safety device that protects electrical wires and loads in a circuit from overheating due to excess current. A simple household fuse is shown in Figure 2.19 below.

Figure 2.19: Simple household fuse.

A fuse contains a thin wire that melts in response to high current flow in a circuit which prevents current flow and protects wires and loads from overheating and causing a fire (Figure 2.20).

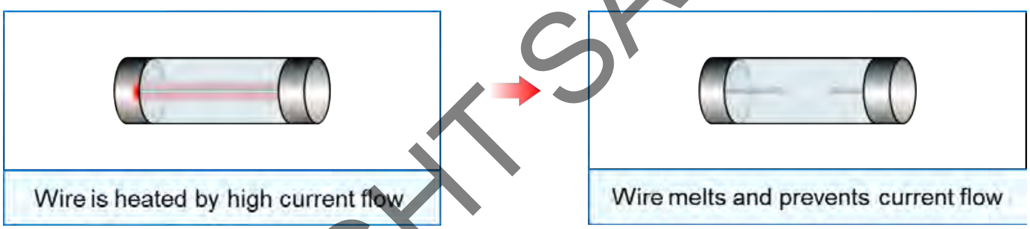


Figure 2.20: A simple fuse melts when the current in the circuit is too high.

Circuit breaker

A circuit breaker is a device that breaks (opens) the electric circuit in response to high current flow. One type of circuit breaker is shown in Figure 2.21.

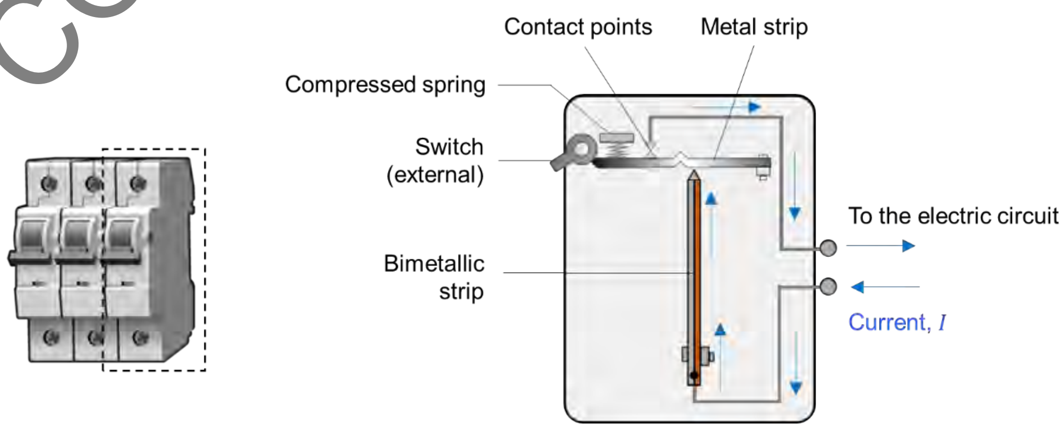


Figure 2.21: Circuit breaker.

The bimetallic strip of the circuit breaker bends and the contact points separate in response to high current flow in a circuit which prevents the flow of charge and protects wires and loads from overheating and causing a fire (Figure 2.22).

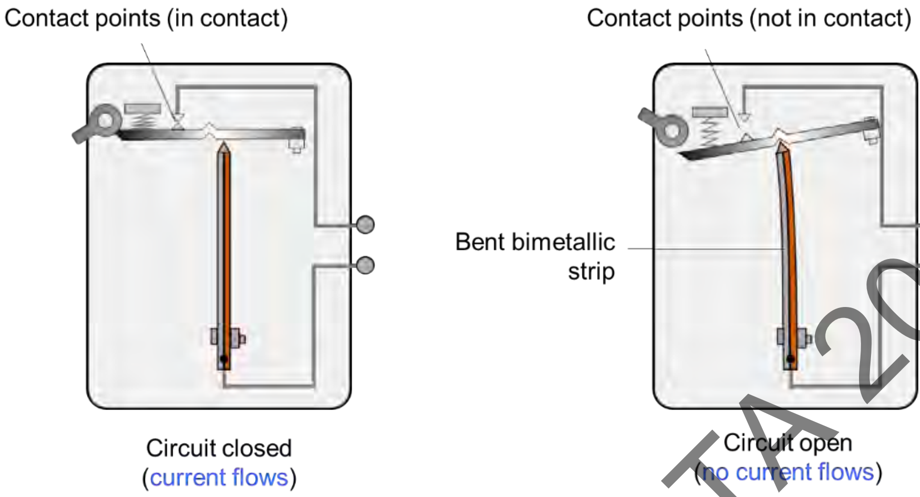


Figure 2.22: Circuit breaker mechanism of operation.

Residual-current devices

A residual-current device (RCD) is a device that instantly breaks (opens) an electric circuit to prevent electric shock. An RCD is designed to rapidly open a circuit when it detects that the electric current is not balanced between the active and neutral conducting wires in the power cable of an electronic device (Figure 2.23).

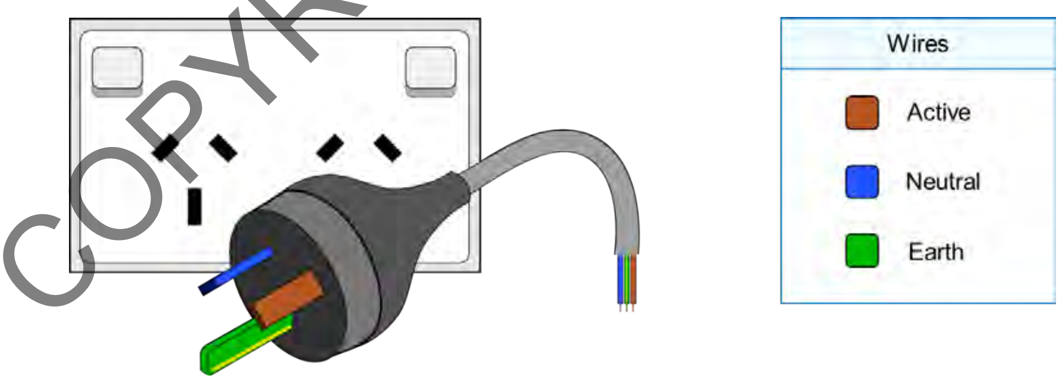


Figure 2.23: Australian power cable showing three wires.

The current in the active and neutral wires is identical when a device is functioning correctly, and any difference can indicate a short circuit or another electrical anomaly that can harm an individual by causing electric shock. An RCB detects any difference in current between the active and neutral wires and uses an electromagnet to open the circuit if the current difference becomes too large.

2.2: Resistance

Resistance for ohmic and non-ohmic components is defined as the ratio of potential difference across the component to the current in the component.

The resistance of a conductor depends on its length, area of cross-section, temperature, and the type of the material of which it is composed.

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

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

- Solve problems involving $R = \frac{V}{I}$

Resistance is a measure of the opposition to the flow of charge in an electrical conductor. Resistance is caused by collisions between moving charges and the particles in a conductor. Figure 2.24 shows collisions between free electrons and metal atoms in a metal wire.

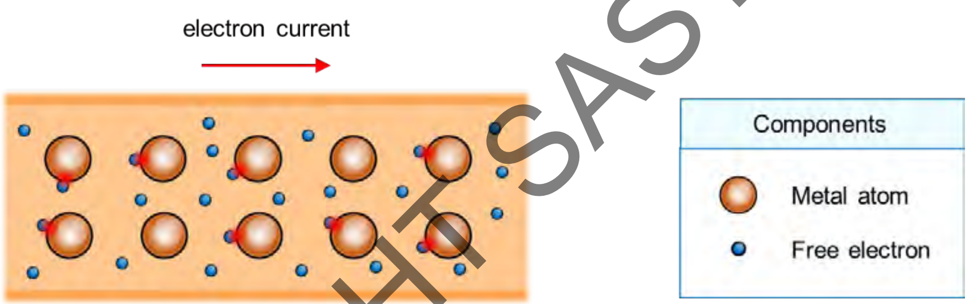


Figure 2.24: Resistance to the flow of electrons in a metal wire.

The resistance of an electric conductor is dependent on factors including temperature, the length and cross-sectional area of the conductor, and a property called the **resistivity**.

Length

The resistance of a conductor is proportional to its length (L) as there are more stationary particles to resist the flow of charge in a greater length of conductor (Figure 2.25).

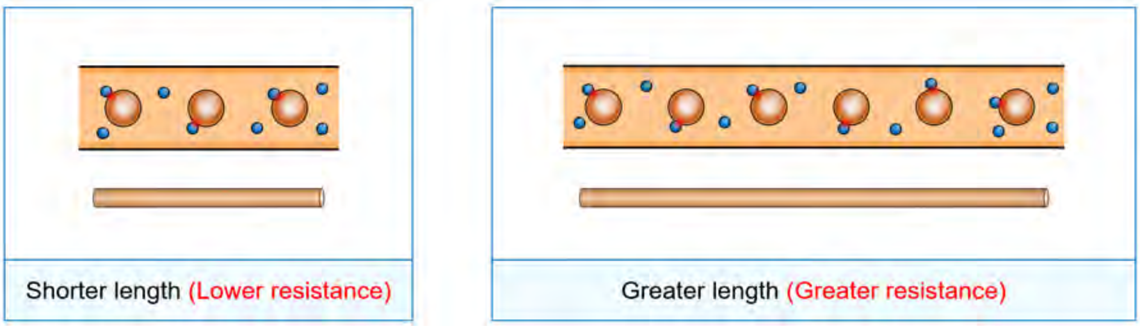


Figure 2.25: Relationship between resistance and the length of a conductor.

Cross-sectional area (thickness)

The resistance of a conductor is inversely proportional to its cross-sectional area (A).

Resistance decreases as charges flowing through a greater area are less likely to collide with stationary particles in the conductor as depicted in Figure 2.26.

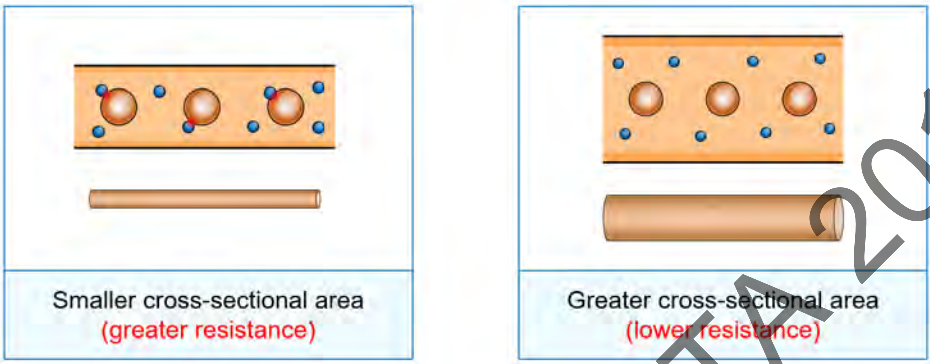


Figure 2.26: Relationship between resistance and the cross-sectional area of a conductor.

Temperature

The resistance of a conductor increases with temperature.

Kinetic energy is transformed into heat when charges collide with stationary particles in a conductor. The vibrational kinetic energy of stationary particles in the conductor increases when the particles absorb heat released from the collisions. Stationary particles vibrate more rapidly around their fixed positions which increases the frequency of collisions with moving charges in the conductor.

Heating a metal wire increases its resistance and results in metal atoms vibrating more rapidly and impeding electron flow as depicted in Figure 2.27.

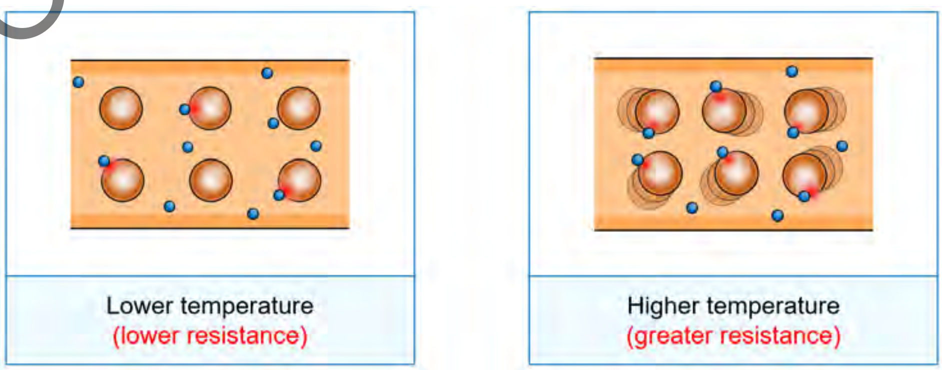
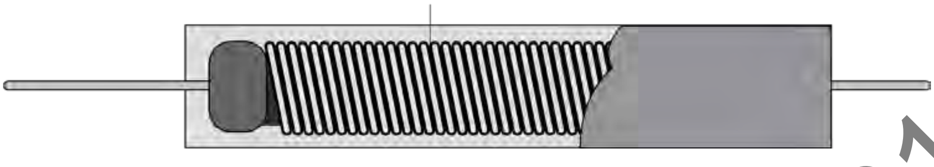


Figure 2.27: Relationship between resistance and the temperature of a conductor.

Question 44

A wire-wound resistor is a device used to reduce current flow in an electric circuit.

The resistor is prepared by winding a length of metal wire around a solid core.



An electrician is preparing a wire-wound resistor using nichrome wire of diameter 1.0 mm.

(a) The cross-sectional area (A) of the nichrome wire is calculated using πr^2.

Show that the cross-sectional area of the wire is approximately 7.9×10^{-7} m^2.

(2 marks) KA4

(b) The resistivity of the nichrome wire is 1.1×10^{-6} $\Omega.\text{m}$.

(1) Define the term resistivity using nichrome wire as an example.

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__________________________________ (1 mark) KA1

(2) Calculate the length of nichrome wire required to prepare a wire-wound resistor with a resistance of 2.2 Ω.

(2 marks) KA2

(c) State and explain one method of increasing the resistance of the wire-wound resistor.

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__________________________________ (2 marks) KA2

Ohm's Law

Electrical resistance decreases the current in a conductor. Charged particles transfer kinetic energy during collisions with stationary particles in a conductor. The transfer of kinetic energy results in a decrease in both the velocity of the charges and the current in the conductor.

Current (I) is therefore inversely proportional to resistance (R) if the potential difference across the conductor is constant.

$$I \propto \frac{1}{R} \quad \text{(if } \Delta V \text{ is constant)}$$

Electric current increases with potential difference across a conductor. Increasing the potential difference results in more work being done per unit of charge which increases the average kinetic energy and velocity of charges flowing in the conductor. The current increases with velocity as charges flow at a greater rate through the conductor.

Current (I) is therefore directly proportional to potential difference (ΔV) if the resistance across the conductor is constant.

$$I \propto \Delta V \quad \text{(if } R \text{ is constant)}$$

German physicist Georg Ohm (Figure 2.29) first identified the proportional relationship between potential difference and current in 1827.

Figure 2.29: Georg Ohm (1789–1854)

Ohm's law states that current is directly proportional to the potential difference across a conductor if the temperature is constant.

The formula for Ohm's law is given below.

Formula	$\Delta V = IR$

Symbol	Variable	SI unit
ΔV	potential difference	V
I	current	A
R	resistance	Ω

The unit of measurement for electrical resistance is the ohm (Ω) which is named after Georg Ohm. It is important to note that Ohm's law is an approximate law which is only valid for certain materials.

Example 2.10

A current of 4.0 A flows when a potential difference of 2.0 V is applied across a length of copper wire.

Determine the resistance in the wire.

$$\Delta V = IR$$
$$R = \frac{\Delta V}{I}$$
$$R = \frac{2.0}{4.0}$$
$$R = 0.5\ \Omega$$

Example 2.11

The heating element in a hairdryer consists of a long coil of nichrome wire with a resistance of 60 Ω.

Determine the maximum current that flows in the wire when operating at 240 V.

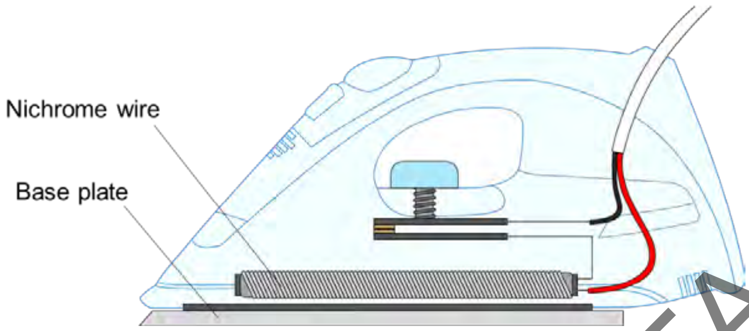
$$\Delta V = IR$$
$$I = \frac{\Delta V}{R}$$
$$I = \frac{240}{60}$$
$$I = 4\ \text{A}$$

Question 48

A clothes iron is an electrical appliance used to iron clothes and fabrics.

A clothes iron generates heat by passing an electric current through a coil of nichrome wire.

Heat is transferred to the base plate which is pressed against clothes to remove creases.



The potential difference (p.d), current and resistance across the nichrome wire at different operating temperatures are provided in the table below.

Temperature (°C)	p.d (V)	Current (A)	Resistance (Ω)
110	5.20	0.13	
150	6.40		42
200		0.20	45

(a) Calculate the resistance when the temperature of the wire is 110°C.

(2 marks) **IAE3**

(b) Calculate the current in the wire when the temperature is 150°C.

(2 marks) **IAE3**

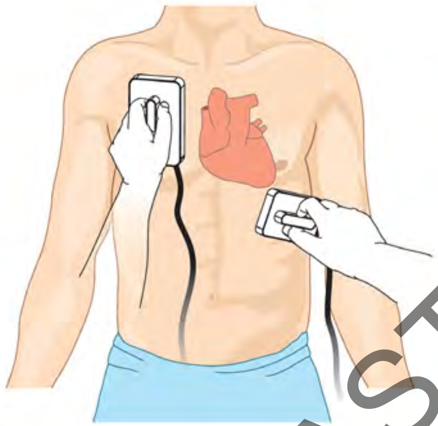
(c) Calculate the potential difference across the wire when the temperature is 200°C.

(2 marks) **IAE3**

Question 49

A defibrillator is a medical device that uses electric current to restore the normal rhythm of the heart during a medical emergency.

A large potential difference causes current to flow through the body between two electrode pads applied to the chest as shown below.



(a) 70 mC of charge passes through the body during a single discharge of the defibrillator which lasts for 2.3 ms.

Show that the average current through the body during a single discharge is 30 A.

(2 marks) **KA2**

(b) 210 J of energy is transferred to the body in a single discharge.

Show that the potential difference across the two electrodes of the defibrillator is approximately 3 kV.

(2 marks) **KA2**

(c) Use Ohm's law to determine the total resistance of the body during a single discharge.

(2 marks) **KA2**

Ohmic conductors

Ohmic conductors are materials in which current is directly proportional to potential difference.

Example 2.12

A resistor is an example of an ohmic conductor. The resistance of an ohmic conductor is determined from a graph of potential difference against current (Figure 2.30).

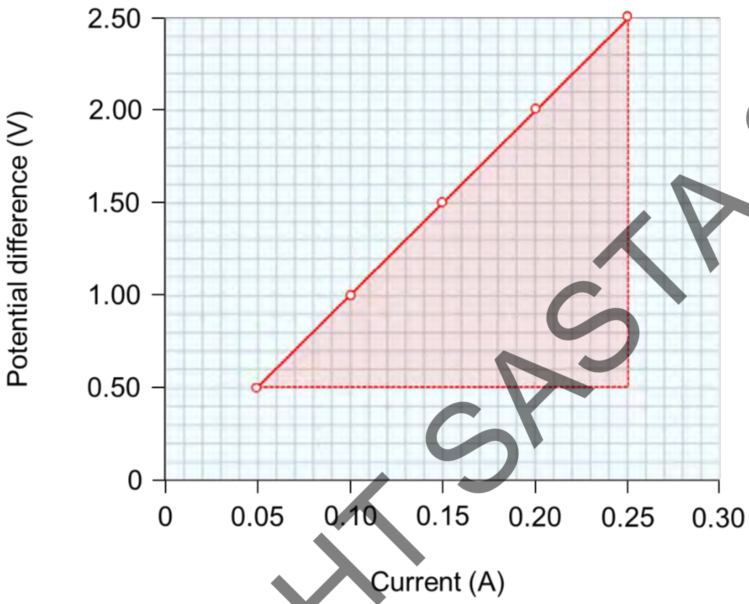


Figure 2.30: Potential difference-current graph for an ohmic conductor.

The gradient of the line (m) in a graph of potential difference against current represents the resistance of the ohmic conductor.

$$m = \frac{\Delta y}{\Delta x}$$

$$m = \frac{2.50 - 0.50}{0.25 - 0.05}$$

$$m = 10\ \Omega$$

Current increases uniformly with potential difference in Figure 2.30 reflecting that resistance is constant in an ohmic conductor at a constant temperature.

Non-ohmic conductors

Non-ohmic conductors are materials in which current is **not** directly proportional to potential difference.

Example 2.13

The filament in an incandescent light bulb is an example of a non-ohmic conductor as resistance in the filament increases with current. The resistance of a non-ohmic conductor is also determined using a graph of potential difference against current (Figure 2.31).

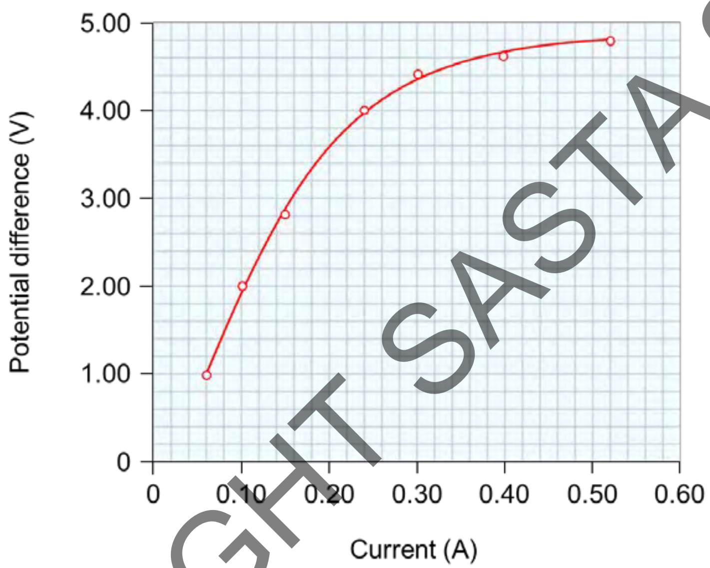
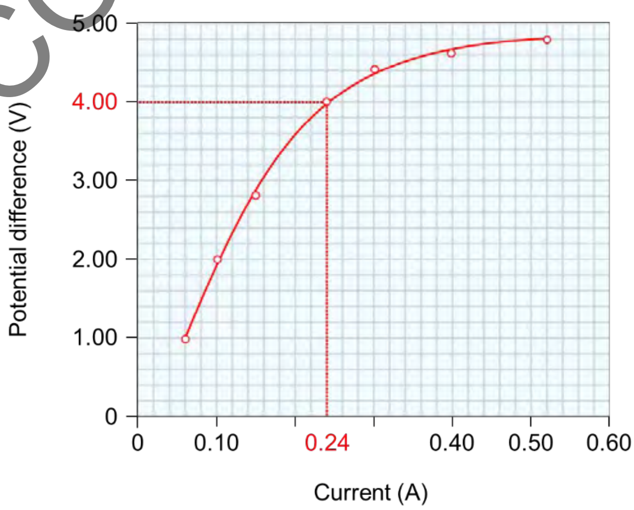


Figure 2.31: Potential difference-current graph for an incandescent light bulb.

The resistance of a non-ohmic conductor is calculated for a given potential difference and current. The resistance of the filament in the light bulb when the current is 0.24 A is calculated below.



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

$$R = \frac{4.00}{0.24}$$

$$R = 16.67\ \Omega$$

2.3: Circuit Analysis

Circuit analysis and circuit design involve calculation of the potential difference across, the current in, and the power supplied to components in series, parallel, and composite circuits.

The current is equal in each series component.

- Solve problems involving $V_t = V_1 + V_2 \dots V_n$ and $R_t = R_1 + R_2 \dots R_n$ for components in series.

A **circuit diagram** is a pictorial representation of the connections between the components, loads and source of electric potential difference in an electric circuit. A circuit diagram for a simple electric circuit is shown in Figure 2.32.

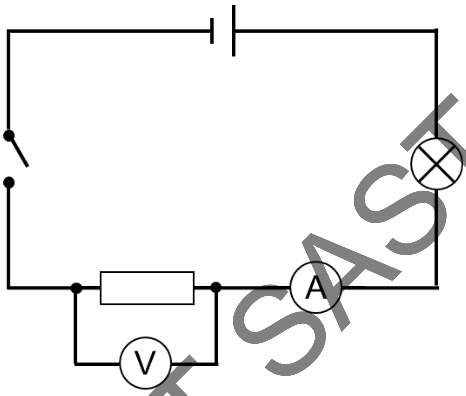
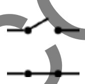
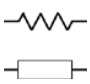
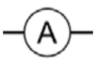
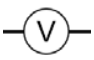


Figure 2.32: Circuit diagram for a simple electric circuit.

The components of an electric circuit are represented in circuit diagrams using a standardised set of symbols. Some common symbols are identified in the table below.

Symbol(s)	Component	Description
	ΔV	Source of electric potential difference in the circuit. The longer of the two vertical lines is the positive terminal.
	Switch	Opens and closes the circuit to allow or prevent the flow of charge.
	Light bulb	Converts electric potential energy into visible light.
	Resistor	Resists the flow of electric charge in a circuit.
	Ammeter	Measures the current in the components of the circuit.
	Voltmeter	Measures the potential difference across a component.

Kirchhoff's First Law

In 1845, German physicist Gustav Kirchhoff described two physical laws used to determine the current and electric potential (voltage) at any point in an electric circuit (Figure 2.33).

Figure 2.33: Gustav Kirchhoff (1824-1887)

Kirchhoff's First Law is used when calculating the current at a point in an electric circuit and is based on the principle of conservation of electric charge.

Kirchhoff's First Law states that the sum of all currents entering a junction in an electric circuit is equal to the sum of all currents exiting the junction.

Example 2.14

Figure 2.34 shows the current flowing into and out of a junction in an electric circuit.

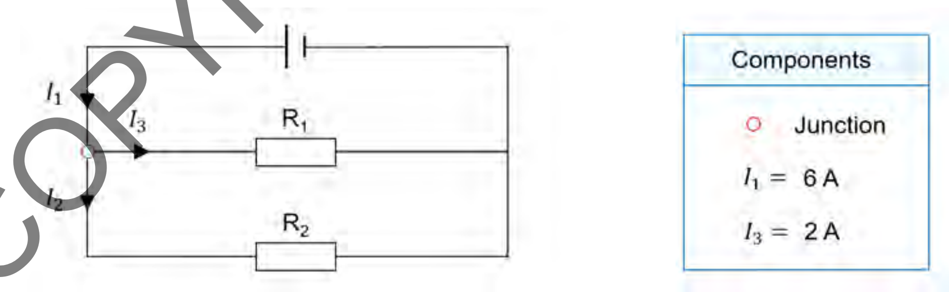


Figure 2.34: Current flowing into and out of a junction in a simple electric circuit

The current I_2 exiting the junction is calculated using Kirchhoff's First Law.

$$\begin{aligned} I_1 &= I_2 + I_3 \\ I_2 &= I_1 - I_3 \\ I_2 &= 6 - 2 \\ I_2 &= 4\text{ A} \end{aligned}$$

Kirchhoff's Second Law

Kirchhoff's Second Law is used when calculating the potential difference across a load in an electric circuit and is based on the principle of conservation of energy.

Kirchhoff's Second Law states that the sum of all potential differences across the loads of an electric circuit is equal to the sum of all potential differences supplying the loads.

Example 2.15

Figure 2.35 shows a simple electric circuit consisting of two light bulbs and a 9V battery.

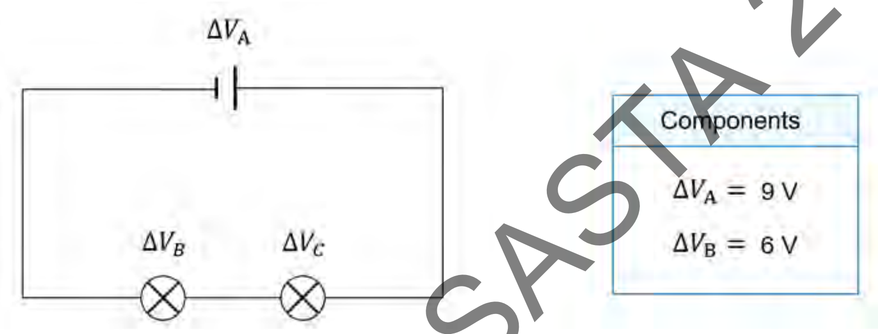


Figure 2.35: Simple electric circuit.

Kirchhoff's Second Law states that the total energy per unit charge supplied by the battery is equal to the total energy per unit charge transferred to the light bulbs in the circuit. The potential difference across the battery is therefore equal to the sum of the potential differences of the light bulbs in the circuit.

$$\frac{\Delta E_{p_A}}{q} = \frac{\Delta E_{p_B}}{q} + \frac{\Delta E_{p_C}}{q}$$

$$\Delta V_A = \Delta V_B + \Delta V_C$$

The potential difference ΔV_C is calculated using Kirchhoff's Second Law.

$$\Delta V_A = \Delta V_B + \Delta V_C$$

$$\Delta V_C = \Delta V_A - \Delta V_B$$

$$\Delta V_C = 9 - 6$$

$$\Delta V_C = 3\ V$$

Components in series

Components and loads in an electric circuit are connected in **series** or **parallel**.

Components or loads are connected in series where charges flow along a single path such that the current is the same through all components. Figure 2.36 shows two resistors connected in series in a simple electric circuit.

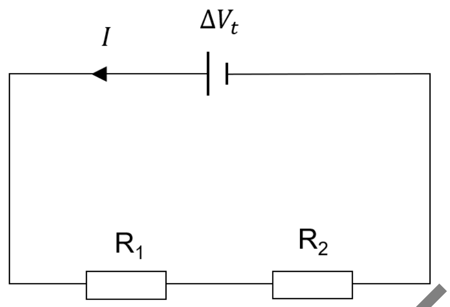


Figure 2.36: Two resistors connected in series in a simple electric circuit.

The current in the circuit is determined by combining Ohm's Law with Kirchhoff's Second Law. Kirchhoff's Second Law states that the sum of the potential differences across the two resistors ($\Delta V_1 + \Delta V_2$) is equal to the potential difference across the battery (ΔV_t) in the circuit. Ohm's law states that the potential difference across each resistor is the product of its current and resistance.

$$\Delta V_t = \Delta V_1 + \Delta V_2$$
$$\Delta V_t = IR_1 + IR_2$$

Current (I) is the same through each resistor in series as charges have only one path to follow. The current in the circuit is calculated by rearranging the formula for Kirchhoff's Second Law.

$$I = \frac{\Delta V_t}{R_1 + R_2}$$

Ohm's Law states that current is equal to the potential difference (ΔV_t) divided by the total resistance (R_t) in the circuit. The total resistance in the circuit is therefore the sum of the series resistors.

$$I = \frac{\Delta V_t}{R_t} = \frac{\Delta V_t}{R_1 + R_2}$$

$$R_t = R_1 + R_2$$

Example 2.16

Figure 2.37 shows a simple electric circuit containing three resistors are connected in series.

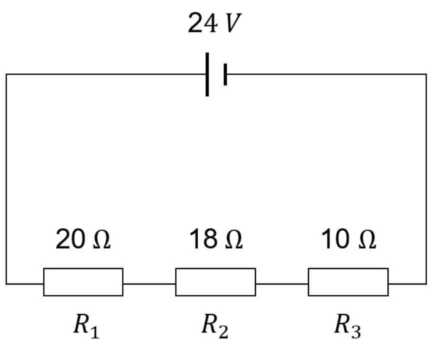


Figure 2.37: Simple electric circuit containing three resistors are connected in series

A potential difference of 24 V is maintained between the two terminals of the power supply.

1. Calculate the total resistance of the three resistors in the circuit.

R_t	=	$R_1 + R_2 + R_3$
R_t	=	$20 + 18 + 10$
R_t	=	$48\ \Omega$

2. Calculate the current in the circuit.

I	=	$\frac{\Delta V_t}{R_t}$
I	=	$\frac{24}{48}$
I	=	0.5 A

3. Calculate the potential difference across each of the three resistors in the circuit.

ΔV_1	=	IR_1
ΔV_1	=	0.5 x 20
ΔV_1	=	10 V

ΔV_2	=	IR_2
ΔV_2	=	0.5 x 18
ΔV_2	=	9 V

ΔV_3	=	IR_3
ΔV_3	=	0.5 x 10
ΔV_3	=	5 V

The potential difference is equal across each parallel component.

Undertake experiments to investigate current, resistance, or potential difference in series and parallel circuits using various circuit elements.

- Solve problems involving $I_t = I_1 + I_2 + \ldots I_n$ and $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2}$ for components in parallel.

Components in parallel are connected along multiple paths such that the potential difference is the same across all components. The current is not necessarily the same across all components as charges flow through multiple paths in the circuit. Figure 2.38 shows two resistors connected in parallel and a power supply in a simple electric circuit.

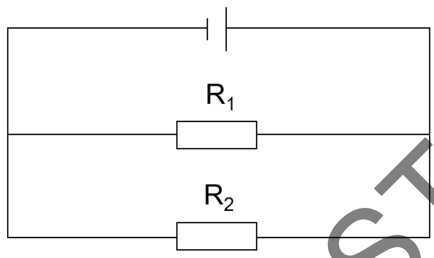
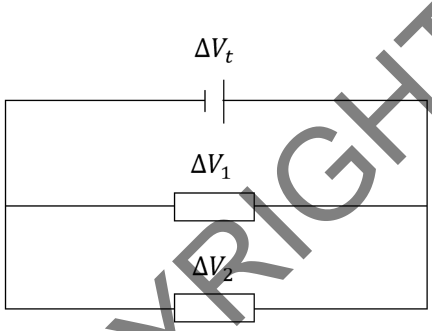


Figure 2.38: Two resistors connected in parallel.

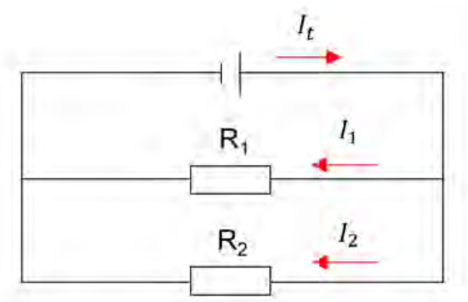
The potential difference is the same across two resistors that are connected in parallel (Figure 2.39).



ΔV_t	=	ΔV_1	=	ΔV_2

Figure 2.39: Potential difference across two resistors in parallel.

Conventional current (I) flows from the positive to the negative terminal of the power supply through the electric circuit. The total current leaving the positive terminal is equal to the total current arriving at the negative terminal (Figure 2.40).



I_t	=	$I_1 + I_2$

Figure 2.40: Current through two resistors in parallel.

Current in parallel components

The current in two parallel components is not always equal in an electric circuit.

Example 2.17

Figure 2.41 shows an electric circuit composed of a 12 V power supply and three resistors connected in parallel.

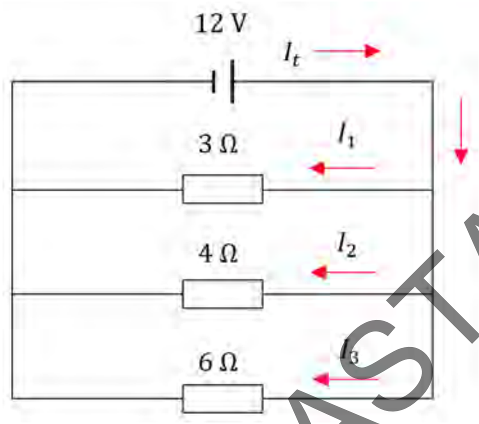


Figure 2.41: Current in three different resistors connected in parallel.

The potential difference across each parallel resistor is 12 V in this example. The current in each resistor is calculated using Ohm's Law.

$$\Delta V_1 = I_1 R_1$$
$$I_1 = \frac{\Delta V_1}{R_1}$$
$$I_1 = \frac{12}{3}$$
$$I_1 = 4\ A$$

$$\Delta V_2 = I_2 R_2$$
$$I_2 = \frac{\Delta V_2}{R_2}$$
$$I_2 = \frac{12}{4}$$
$$I_2 = 3\ A$$

$$\Delta V_3 = I_3 R_3$$
$$I_3 = \frac{\Delta V_3}{R_3}$$
$$I_3 = \frac{12}{6}$$
$$I_3 = 2\ A$$

The calculations reveal that the current in each resistor is different meaning that charge flows at different rates through each of the resistors in parallel. The total current (I_t) in the circuit is calculated using Kirchhoff's First Law as shown below.

$$I_t = I_1 + I_2 + I_3$$
$$I_t = 4 + 3 + 2$$
$$I_t = 9\ A$$

Resistance in parallel components

The total resistance of parallel components is the sum of the reciprocals of each resistor in an electric circuit. The formula for calculating the total resistance (R_t) in a parallel circuit is derived using Kirchhoff's First Law and Ohm's Law.

$$I_t = I_1 + I_2 + \cdots I_n$$

$$\frac{\Delta V_t}{R_t} = \frac{\Delta V_1}{R_1} + \frac{\Delta V_2}{R_2} + \cdots \frac{\Delta V_n}{R_n}$$ (factor out ΔV as ΔV is equal in parallel components)

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

Example 2.18

Figure 2.42 shows an electric circuit composed of three resistors connected in parallel.

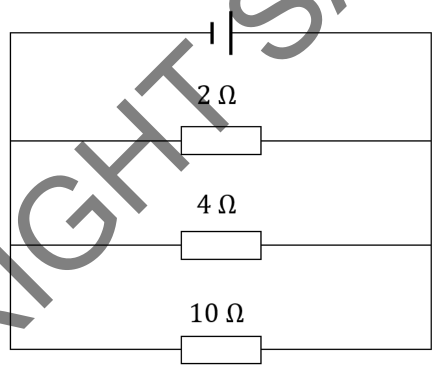


Figure 2.42: Three different resistors connected in parallel.

The total resistance in the circuit is calculated below.

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

$$\frac{1}{R_t} = \frac{1}{2} + \frac{1}{4} + \frac{1}{10}$$

$$\frac{1}{R_t} = 0.85$$

$$R_t = \frac{1}{0.85}$$

$$R_t = 1.18\ \Omega$$

2.4: Electrical power

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

- Solve problems involving $P = \frac{\Delta E}{t}$, $P = VI$ and the use of Ohm's Law.
- Solve problems involving the cost of electrical energy, using kilowatt-hours.

Power (P) is the rate at which energy is transformed and is calculated using the formula below.

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

Symbol	Variable	SI unit
P	Power	W
ΔE	Change in energy	J
t	Time interval	s

The SI unit of measurement of power is the **watt** (W) which is equal to one joule of energy being transformed each second (1 $J.s^{-1}$). The watt is named after Scottish engineer and inventor James Watt (Figure 2.48).

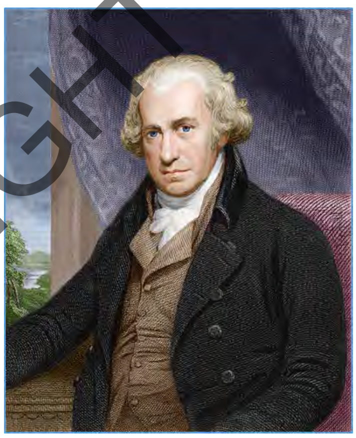


Figure 2.48: James Watt (1736-1819)

Example 2.21

Calculate the power of a microwave that transforms 51 kJ of energy in 30 seconds.

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

$$P = \frac{51 \times 10^3}{30}$$

$$P = 1700 \text{ W}$$

Electrical power

Electrical power is the rate at which electrical energy is transformed by a component or load in an electric circuit and is calculated using the formula below.

Formula	$P = \Delta VI$

Symbol	Variable	SI unit
P	Electrical power	W
ΔV	Potential difference	V
I	Current	A

The two formulae used to calculate electrical power are mathematically equivalent.

$$P = \Delta VI$$
$$P = \frac{\Delta E}{q} \times \frac{q}{t}$$
$$P = \frac{\Delta E}{\cancel{q}} \times \frac{\cancel{q}}{t}$$
$$P = \frac{\Delta E}{t}$$

Electrical power is also calculated using a formula derived using Ohm's Law.

$$P = \Delta VI$$
$$P = IRI$$
$$P = I^2R$$

Example 2.22

A kettle operates at 240 V when plugged into a wall-outlet in the home.

Determine the electrical power when a current of 10 A flows through the kettle.

$$P = \Delta VI$$
$$P = 240 \times 10$$
$$P = 2400 \text{ W}$$

Cost of electrical energy

Property-owners pay an energy-provider for the electrical energy consumed in their homes and businesses. The amount of money paid to the energy-provider is dependent on the total electrical energy used by the consumer and the time of day in which the energy was consumed.

An energy-provider measures the consumption of electrical energy in units of **kilowatt-hours** (kWh). One kilowatt-hour is equal to one kilowatt (kW) of electrical power consumed in one hour (h) and is calculated using the formula below.

Formula	$\Delta E = Pt$

Symbol	Variable	SI unit
ΔE	Electrical energy consumed	kWh
P	Electrical power	kW
t	Time interval	h

An energy-provider charges an amount of money per kilowatt-hour of energy used by a consumer. The cost of electrical power is calculated by finding the product of the energy consumed and the cost per unit of energy consumed.

Example 2.23

A family watches a movie on their 180 W LCD monitor for 3 hours.

1. Calculate the energy used in kilowatt-hours.

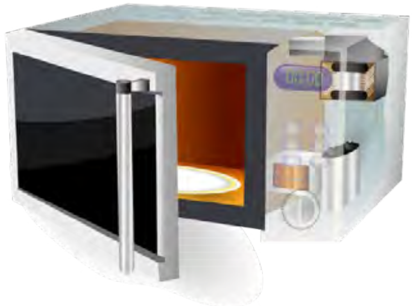
ΔE	=	$P\Delta t$
ΔE	=	0.18 x 3
ΔE	=	0.54 kWh

2. Calculate the cost of operating the monitor for 3 hours if the energy-provider charges 37 cents per kilowatt-hour.

cost	=	$\Delta E \times \frac{\text{cost}}{\Delta E}$
cost	=	0.54 x 0.37
cost	=	\$0.20

Question 61

A microwave oven transforms electrical energy into microwaves that are used to cook food.



(a) The input power of a household microwave is 1600 W.

(1) Calculate the current through the microwave when operating at 240 V.

(2 marks) **KA4**

(2) The output power of the microwave is 1100 W.

Calculate the % efficiency of the microwave.

(2 marks) **KA4**

(b) The microwave is used for two minutes a day.

(1) Show that microwave transforms 0.037 kWh of electrical energy in two minutes.

1 kWh is equal to 3.6×10^6 J.

(3 marks) **KA4**

(2) Calculate the yearly cost of using the microwave if the average cost is 41.5 cents/kWh.

(2 marks) **KA3**

Question 63

Electric light bulbs transform electric potential energy into visible light in the home.

Four bulb types used in residential homes are identified in the diagram below.

BULB TYPE				
LUMENS	STANDARD	HALOGEN	CFL	LED
450	40 W	29 W	9 W	8 W
800	60 W	43 W	14 W	13 W
1100	75 W	53 W	19 W	17 W
1600	100 W	72 W	23 W	20 W
RATED LIFE	1 year	1–3 years	6–10 years	15–25 years

A lumen is the SI unit for luminous flux which is a measure of the total quantity of visible light emitted by a light bulb.

(a) State and explain which bulb type is the most energy efficient.

____

____

____

__________________________________ (2 marks) KA3

(b) The efficiency of a standard 40 W light bulb is 2.2%.

(1) Calculate the useful power output of a standard 40 W light bulb.

(2 marks) KA2

(2) Calculate the number of hours it takes for a standard light bulb to use 1 MJ of energy.

(3 marks) KA2

CHAPTER 6

TOPIC 6: NUCLEAR MODELS AND RADIOACTIVITY

The range of products of nuclear decay, some with long half-lives, means that nuclear waste must be stored for long periods.

- Explain the requirements for the safe storage of nuclear waste.

Nuclear waste is any waste that contains radioactive material. Sources of nuclear waste include mines, processing plants, nuclear power facilities, research facilities and hospitals. Nuclear waste is classified depending on the requirements for safe storage.

Low-level waste (LLW)

Low-level waste (LLW) is nuclear waste containing small quantities of material with short-lived radioactivity. Low-level wastes include paper, clothing, tools, and other small quantities of materials with short-lived radioactivity. Sources of low-level waste include nuclear power facilities, medical schools, private research facilities and hospitals. Low-level waste is stored in steel drums that are encased in lead-lined boxes and containers. The containers are stored below the surface of the Earth in a **shallow land burial**.

High-level waste (HLW)

High-level waste (HLW) is nuclear waste containing large quantities of material with long-lived radioactivity. High-level waste is produced primarily in the reactor core in a nuclear power facility. High-level waste is stored in metal storage containers (Figure 6.18) that are encased in thick concrete and buried deep underground. High-level waste may be transferred to spent fuel pools filled with liquid water to reduce the temperature of the waste material before underground storage.

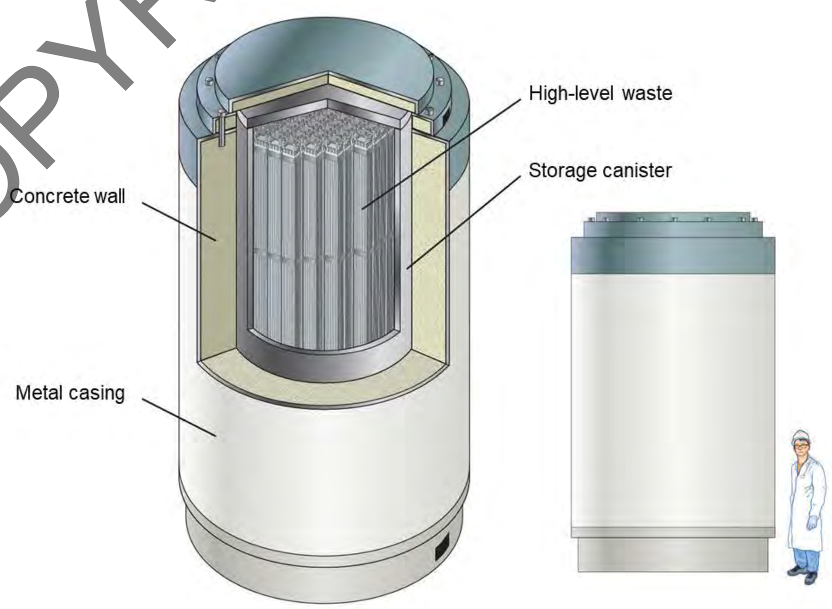


Figure 6.18: Storage container for high-level nuclear waste.

6.: Induced nuclear reactions

Nuclear fission can be induced in some heavy nuclei by the capture of a neutron.

The nucleus splits into two nuclei and several neutrons.

The total mass of the reactants in a fission reaction is greater than that of the products, releasing energy given by $E = \Delta mc^2$, where Δm is the mass of the reactants minus the mass of the products.

- Calculate the energy released per fission reaction, given the relevant masses (in kg).

Nuclear fission is the splitting of a heavy parent nucleus into two lighter daughter nuclei and several neutrons. Nuclear fission can occur spontaneously, or it may be induced in a laboratory or nuclear reactor. The processes of spontaneous and induced nuclear fission are summarised in Figure 6.19.

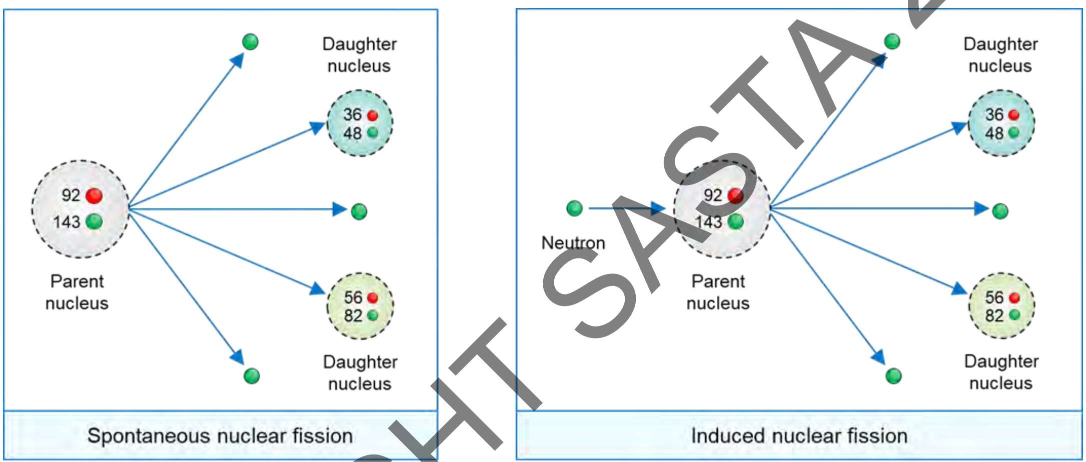


Figure 6.19: Spontaneous and induced nuclear fission.

Induced nuclear fission

Induced nuclear fission occurs when a heavy nucleus is bombarded with neutrons. A neutron is captured by the heavy nucleus which causes it to oscillate and elongate. The average nucleon separation increases as the nucleus elongates which reduces the magnitude of the strong nuclear force between nucleons. The electrostatic force of repulsion dominates, and the nucleus splits (fission) into two daughter nuclei and several neutrons (Figure 6.20).

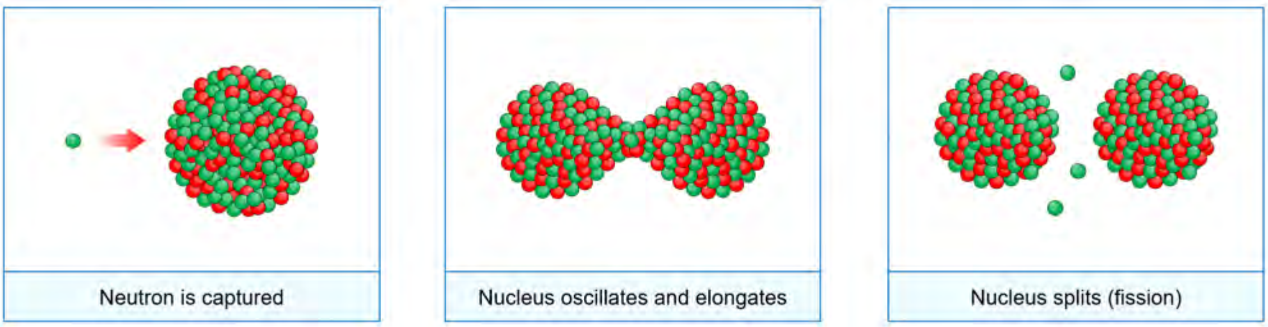


Figure 6.20: Induced nuclear fission.

Nuclear equation

Nuclear equations are used to describe nuclear fission reactions. A nuclear equation shows the parent and daughter nuclei as well as the number of neutrons that are released in a fission reaction. A nuclear equation for the induced nuclear fission of uranium-235 ($^{235}_{92}U$) is shown below.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

The daughter nuclei produced in a nuclear fission reaction are called **fission fragments**. The fission fragments produced of a given isotope are not always the same. The nuclear equations below show the different fission fragments produced in the induced nuclear fission of uranium-235.

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n$$

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2^{1}_{0}n$$

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{101}_{42}Mo + ^{132}_{50}Sn + 3^{1}_{0}n$$

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{137}_{53}I + ^{96}_{39}Y + 3^{1}_{0}n$$

The fission fragments have excess energy and undergo gamma decay following a nuclear fission reaction. The fission fragments also have a high neutron to proton ratio and undergo beta minus decay as soon as they are formed (Figure 6.21). The neutrons emitted in nuclear fission, as well as the gamma rays and electrons emitted in gamma and beta minus decay, carry energy that is transformed into electricity in a nuclear power station.

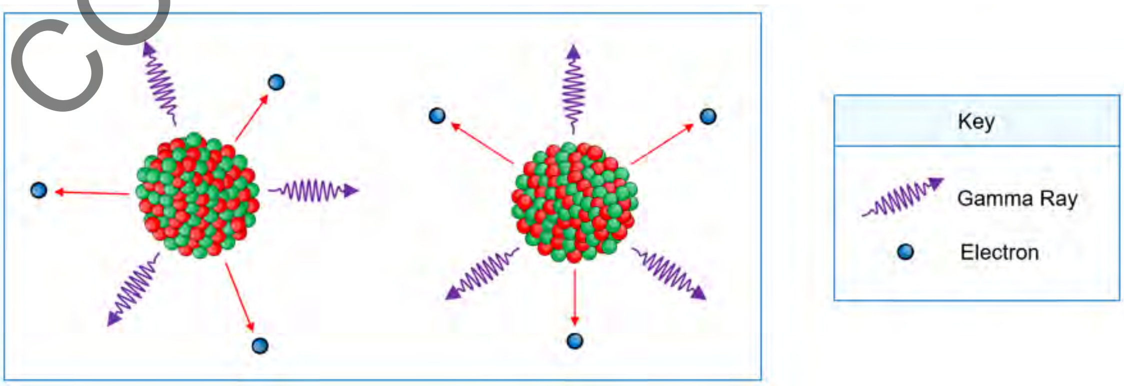


Figure 6.21: Energy released by fission fragments.

Binding energy and mass defect

Work is done in overcoming the strong nuclear force that binds nucleons together in a nucleus. The minimum work done in disassembling a nucleus into its constituent nucleons is called **binding energy** (E) and is calculated using the formula below.

Formula	$E = \Delta mc^2$

Symbol	Variable	SI unit
E	Binding energy	J
Δm	Mass defect	kg
c	Vacuum speed of electromagnetic radiation	$m.s^{-1}$

The binding energy of a nucleus is proportional to the **mass defect** (Δm) which is the difference in mass between the parent nucleus and its constituent nucleons.

Example 6.15

An alpha particle has a mass of 6.644×10^{-27} kg and the mass of its component protons and neutrons is 6.696×10^{-27} kg.

Determine the binding energy of an alpha particle.

$$\Delta m = m_{\text{nucleus}} - m_{\text{nucleons}}$$
$$\Delta m = 6.644 \times 10^{-27} - 6.696 \times 10^{-27}$$
$$\Delta m = 5.2 \times 10^{-29} \text{ kg}$$
$$E = \Delta mc^2$$
$$E = 5.2 \times 10^{-29} \times (3 \times 10^8)^2$$
$$E = 4.68 \times 10^{-12} \text{ J}$$

Energy released in nuclear fission

The energy released (E) in a nuclear fission reaction is equal to the difference in binding energies of the reactants and products and is calculated using $E = \Delta mc^2$ where the mass defect (Δm) is the difference in mass between the reactants and products.

Example 6.16

The nuclear equation below shows the induced nuclear fission of uranium-235.

$$ {}^{1}_{0}n + {}^{235}_{92}\mathrm{U} \rightarrow {}^{138}_{55}\mathrm{Cs} + {}^{96}_{37}\mathrm{Rb} + 2\,{}^{1}_{0}n $$

The masses of all reactants and products are given in the table below:

Reactant	Mass (kg)
${}^{1}_{0}n$	1.675×10^{-27}
${}^{235}_{92}\mathrm{U}$	3.9030×10^{-25}

Product	Mass (kg)
${}^{138}_{55}\mathrm{Cs}$	2.2902×10^{-25}
${}^{96}_{37}\mathrm{Rb}$	1.5930×10^{-25}
${}^{1}_{0}n$	1.675×10^{-27}

Calculate the energy released in the induced nuclear fission reaction.

1. Calculate the combined mass of the reactants.

$$ m_r = m_{{}^{235}_{92}\mathrm{U}} + m_{{}^{1}_{0}n} $$
$$ m_r = (3.9030 \times 10^{-25} + 1.675 \times 10^{-27}) $$
$$ m_r = 3.9198 \times 10^{-25}\,\mathrm{kg} $$

2. Calculate the combined mass of the products.

$$ m_P = m_{{}^{138}_{55}\mathrm{Cs}} + m_{{}^{96}_{37}\mathrm{Rb}} + 2(m_{{}^{1}_{0}n}) $$
$$ m_P = 2.2902 \times 10^{-25} + 1.5930 \times 10^{-25} + 2(1.675 \times 10^{-27}) $$
$$ m_P = 3.9167 \times 10^{-25}\,\mathrm{kg} $$

3. Calculate the mass defect for this nuclear fission reaction.

$$ \Delta m = m_r - m_p $$
$$ \Delta m = (3.9198 \times 10^{-25}) - (3.9167 \times 10^{-25}) $$
$$ \Delta m = 3.05 \times 10^{-28}\ \mathrm{kg} $$

4. Calculate the energy released in this nuclear fission reaction.

$$ E = \Delta mc^2 $$
$$ E = 3.05 \times 10^{-28} \times (3 \times 10^{8})^2 $$
$$ E = 2.75 \times 10^{-11}\ \mathrm{J} $$

On average, more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will induce further fissions, resulting in a chain reaction.

The neutrons emitted as a result of nuclear fission have high speeds.

Uranium-235 undergoes fission with slow neutrons. Hence to induce fission in these nuclei the neutrons must be slowed down.

Many neutrons are absorbed by surrounding nuclei, or escape and cause no further fissions.

- Relate the starting, normal operation, and stopping of a nuclear reactor to the nature of the chain reaction.
- Explain why neutrons have to be slowed down in order to produce fission in uranium-235.

The neutrons released in a nuclear fission reaction are called **fission neutrons**. On average, more than one fission neutron is released when a parent nucleus is split into two daughter nuclei in an induced nuclear fission reaction. Fission neutrons induce a series of fission reactions in surrounding nuclei and this is called a **nuclear chain reaction** (Figure 6.22).

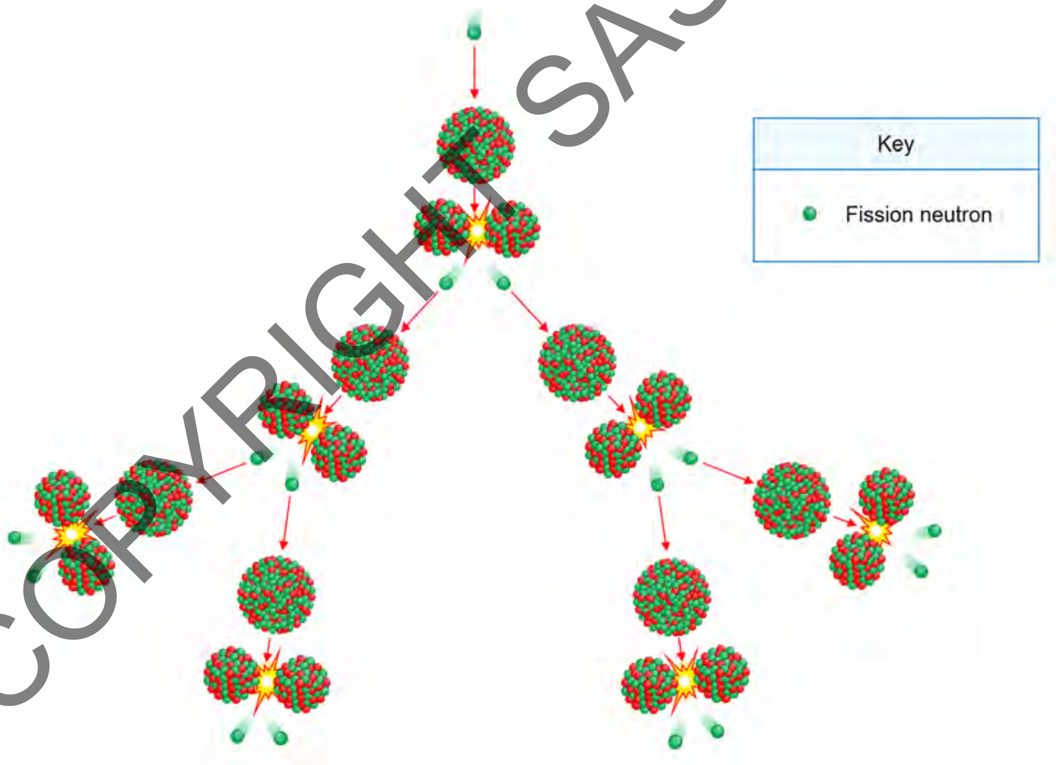


Figure 6.22: Nuclear chain reaction.

Fission neutrons may be absorbed and induce further fission reactions in surrounding nuclei, or they may escape and cause no further fission reactions. A nuclear chain reaction is self-sustaining when one fission neutron from every fission reaction induces a reaction in surrounding nuclei. A material that can sustain a nuclear chain reaction is described as **fissile**, and the mass of fissile material required to achieve a self-sustaining chain reaction is called the **critical mass**.

Nuclear reactor

A **nuclear reactor** is a device used to initiate and control a self-sustaining nuclear chain reaction. The primary function of a nuclear reactor is to generate heat for the production of electricity in a nuclear power station. There are many different types of nuclear reactors including the pressurised water reactor (PWR), boiling water reactor (BWR), and the pressurised heavy-water reactor (PHWR). The most common type of nuclear reactor used in nuclear power stations is the PWR (Figure 6.23).

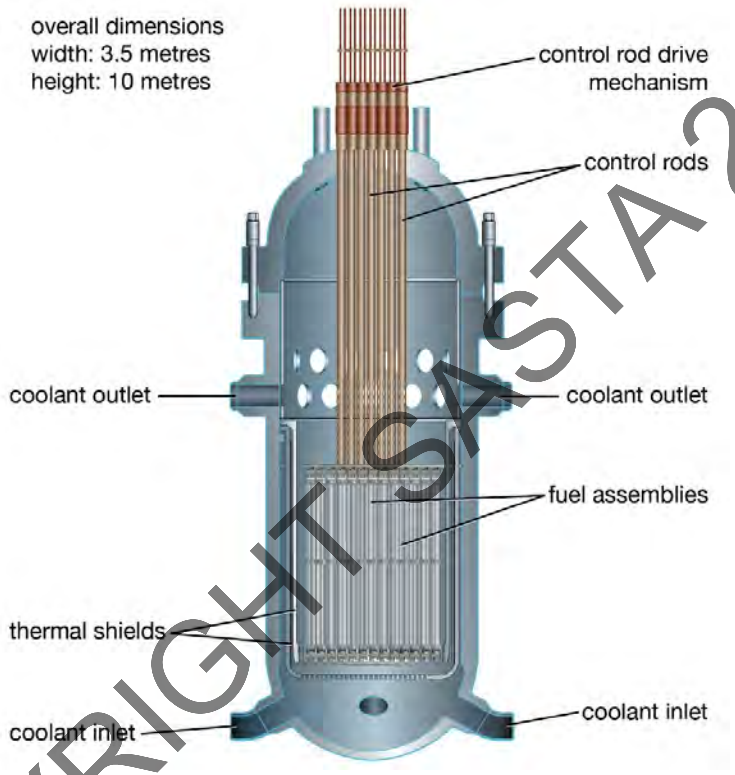


Figure 6.23: Pressurised water reactor (PWR).

Fuel rods

The **fuel rods** in a nuclear reactor contain the critical mass of fissile material such as uranium-235. The fissile material (fuel) is moulded into small pellets that are sealed inside metal cylinders (rods). Fuel rods are assembled into bundles containing 200 rods. A typical reactor contains 150 bundles.

A **start-up neutron source** is used to initiate the nuclear chain reaction inside the fuel rods in a nuclear reactor. A start-up neutron source is a material that emits neutrons (${}^{1}_{0}n$) that can be captured by the fissile isotopes inside the fuel rods. Californium-252 (${}^{252}_{98}\mathrm{Cf}$) is a material that is commonly used as a start-up neutron source. Several neutrons are emitted when californium-252 undergoes spontaneous nuclear fission as shown in the equation below.

$${}^{252}_{98}\mathrm{Cf} \rightarrow {}^{102}_{40}\mathrm{Zr} + {}^{147}_{58}\mathrm{Ce} + 3\,{}^{1}_{0}n$$

Control rods

Energy is released when a nuclear chain reaction occurs in the fuel rods of a nuclear reactor. The power output of a nuclear reactor is controlled using **control rods** that effectively change the rate of the nuclear chain reaction. Control rods are cylindrical rods made from materials that absorb neutrons and reduce the rate of the nuclear chain reaction. The position of the control rods and fuel rods in the **core** of a nuclear reactor is shown in Figure 6.24.

Figure 6.24: Position of control rods and fuel rods in the core of a nuclear reactor.

The rate of the chain reaction is controlled by raising and lowering control rods into the reactor. The effect of raising and lowering the control rods on the power output of a nuclear reactor is summarised in the table below.

Control rods	Response
Lowered	Increases absorption of fission neutrons which reduces the rate of the chain reaction and decreases the power output of the reactor.
Raised	Reduces absorption of fission neutrons which increases the rate of the chain reaction and increases the power output of the reactor.

The power output of the reactor can be reduced to zero in cases of emergency by lowering the control rods all the way into the core of the reactor.

Moderator

Fission neutrons have high kinetic energy and travel at high speeds following a nuclear fission reaction. Some fissile materials, including uranium-235, are unable to capture fast-moving neutrons so the speed must be reduced to sustain the nuclear chain reaction. Fission neutrons are slowed down by a component of the nuclear reactor called the **moderator**.

The moderator is a material that reduces the speed and kinetic energy of fission neutrons in the core of a nuclear reactor. The moderator is positioned around the fuel rods such that fission neutrons pass through the moderator as they propagate between fuel rods in the reactor core (Figure 6.25).

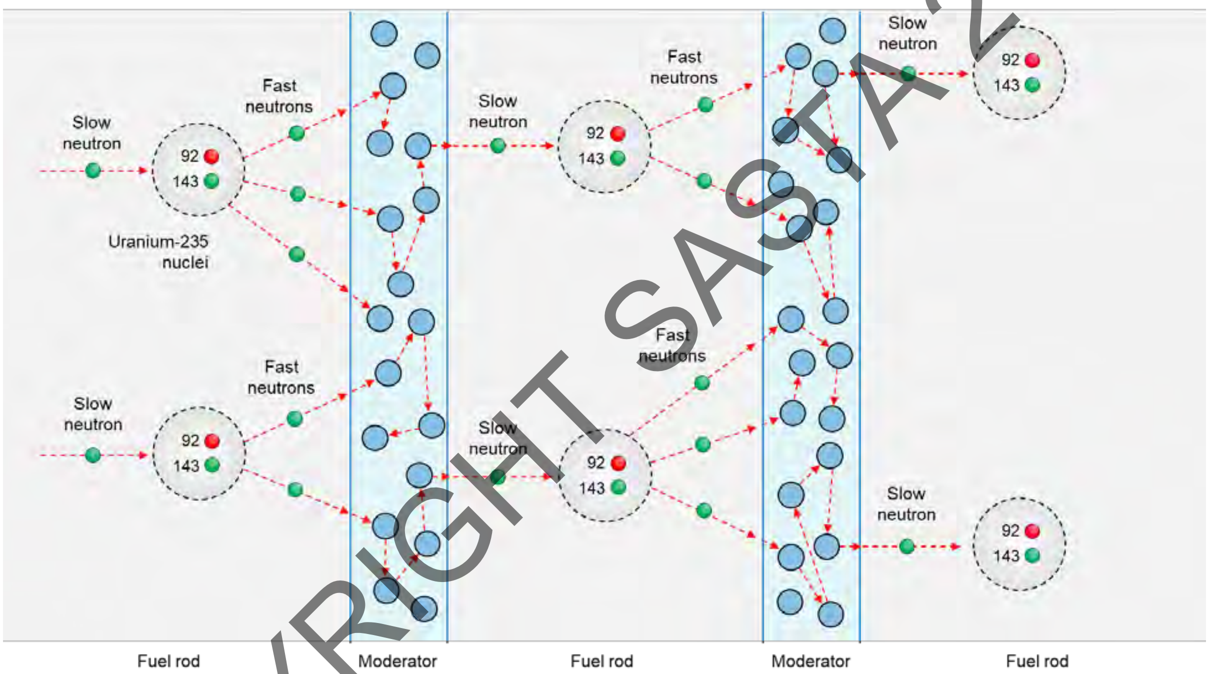


Figure 6.25: Position of a moderator in a nuclear reactor.

Fission neutrons that have been slowed down by the moderator are called **thermal neutrons.** Thermal neutrons are produced when a fast-moving fission neutron collides and transfers energy to the moderator. The most effective moderators have two physical properties:

Physical property	Description
Low neutron absorption	The absorption of neutrons by the moderator would reduce the power output of the reactor.
Similar mass to a neutron	The maximum change in speed occurs when the particles in the moderator have a similar mass to a neutron given that collisions between neutrons and the moderator are elastic.

The most common moderators used in nuclear reactors are water, graphite and heavy water.

Enrichment increases the proportion of $^{235}_{92}U$ in uranium fuel.

- Describe how enrichment enables a chain reaction to proceed.

Uranium-235 is the most widely-used fissile isotope in a nuclear reactor. However, naturally-occurring uranium ore contains a very low concentration of uranium-235 (<1% by mass) which is below the critical mass required to sustain a nuclear chain reaction. After the uranium ore is mined and processed, the resulting material undergoes a process called **enrichment** which is designed to increase the proportion of fissile uranium-235.

Enrichment

The uranium that is mined and processed contains atoms of uranium-235 and uranium-238. The process of enrichment involves separating the uranium isotopes and isolating the uranium-235 atoms to increase the concentration from <1% to between 2 and 4%. Figure 6.26 shows the two techniques used to enrich uranium on a large scale.

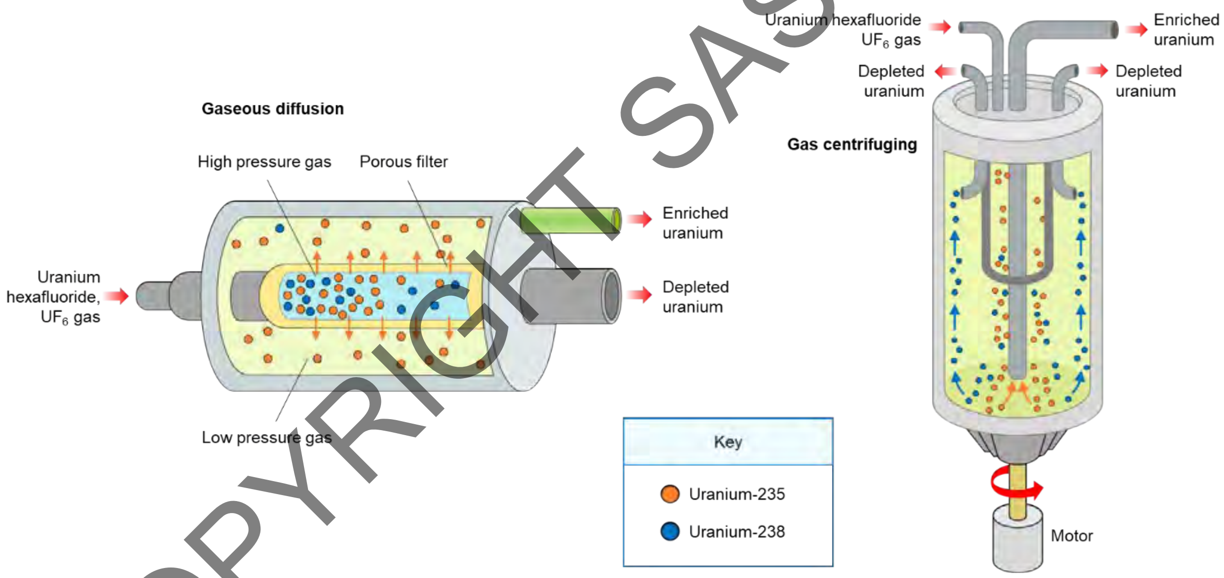


Figure 6.26: Processes used to enrich uranium-235.

In gaseous diffusion, uranium is converted to uranium hexafluoride gas (UF_6), and the gaseous molecules are passed through a porous barrier. The UF_6 molecules containing uranium-235 atoms are lighter and penetrate the barrier more rapidly than the heavier uranium-238 molecules. The uranium-235 gas is removed from the vessel, and the process is repeated thousands of times to obtain the critical mass of uranium-235 required for use in a nuclear reactor.

In gas centrifuging, uranium hexafluoride gas is fed into a high-speed centrifuge that spins at an extremely high rate. The two isotopes have different masses and experience different centripetal forces. The lighter UF_6 molecules containing uranium-235 atoms collect at the centre of the centrifuge and are isolated as an enriched stream.

Energy released during nuclear fission reactions can be harnessed for use in power generation.

- Use a diagram of a reactor to locate and discuss the function of the principal components of a water-moderated fission power reactor.
- Explain the use of nuclear fission in power production.
- Describe some of the risks associated with the use of nuclear energy for power production.

A nuclear power station is a facility designed to transform nuclear energy into electrical energy. The principal components of a nuclear power station are identified in Figure 6.27.

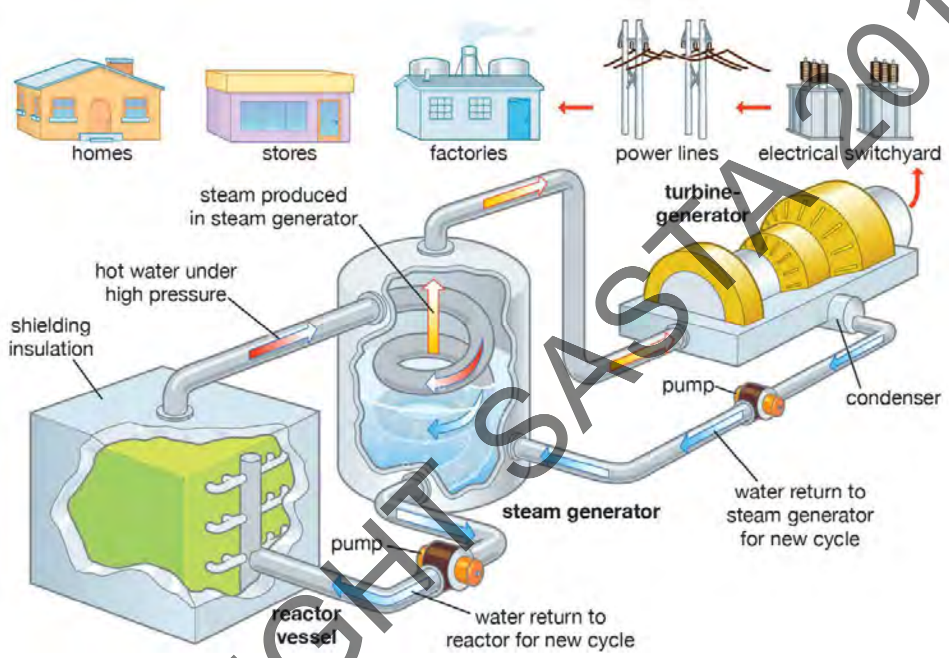


Figure 6.27: Principal components of a nuclear power station.

The process by which nuclear energy is transformed into electrical energy is described below.

1. Heat is released when a nuclear chain reaction occurs inside the fuel rods of the reactor.
2. The heat is transferred to a coolant such as liquid water that flows through the reactor.
3. The heated water is kept under high pressure to prevent boiling as it passes from the reactor to the steam generator.
4. The steam generator contains a large volume of liquid water that is converted to steam as heat is transferred from the pressurised water from the reactor.
5. High-pressure steam is moved to the turbine room where the gas applies a large force on one or more turbines that are each connected to an electric generator.
6. The spinning turbines rotate a loop of wire inside the magnetic field of an electric generator which generates a potential difference that drives the flow of electric current (electricity).
7. Steam from the turbine room is condensed and returned to the steam generator where the cycle is repeated.

Nuclear fusion is the process in which two nuclei combine into a single nucleus.

The energy absorbed or released is given by $E = \Delta mc^2$, where Δm is the difference in mass between the reactants and the products.

- Explain why high temperatures are needed for nuclear fusion to occur.
- Calculate the energy released per fusion reaction, given the relevant masses (in kg).

Nuclear fusion is the process in which two lighter nuclei are fused together forming a single nucleus. The formation of helium-4 (^4_2He) from the nuclear fusion of deuterium (^2_1H) and tritium (^3_1H) nuclei is summarised in Figure 6.28.

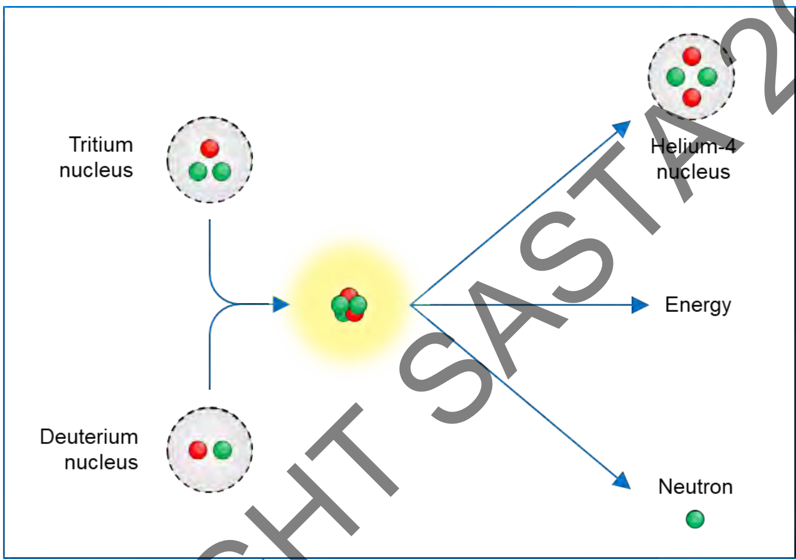


Figure 6.28: Nuclear fusion of deuterium and tritium to form helium-4.

Nuclear fusion reaction

The lighter nuclei that combine in a nuclear fusion reaction are positively charged, and each exerts an electrostatic force of repulsion on the other. For fusion to occur, the lighter nuclei must have sufficient kinetic energy to overcome the electrostatic force of repulsion and get close enough for the strong nuclear force to bind the combining nuclei together into a single nucleus. For this reason, nuclear fusion only occurs at **very high temperatures** such as those present in the core of a star, in a hydrogen bomb, or in a nuclear fusion reactor.

The fusion of lighter nuclei such as hydrogen isotopes occurs at temperatures greater than 10 million degrees celsius whereas the fusion of heavier nuclei such as magnesium ($^{24}_{12}Mg$) and silicon ($^{28}_{14}Si$) occurs at temperatures greater than one billion degrees celsius given the greater number of protons and the greater electrostatic force of repulsion between the combining nuclei.

The energy released (E) in a nuclear fusion reaction is equal to the difference in binding energies of the reactants and products and is calculated using $E = \Delta mc^2$ where the mass defect (Δm) is the difference in mass between the reactants and products.

Example 6.17

The nuclear fusion of deuterium and tritium is described by the nuclear equation below.

$$ {}^{2}_{1}\text{H} + {}^{3}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + {}^{1}_{0}n $$

The masses of the reactants and products are shown below:

Reactant	Mass (kg)
${}^{2}_{1}\text{H}$	3.3436×10^{-27}
${}^{3}_{1}\text{H}$	5.0074×10^{-27}

Product	Mass (kg)
${}^{4}_{2}\text{He}$	6.6447×10^{-27}
${}^{1}_{0}n$	1.675×10^{-27}

1. Calculate the combined mass of the reactants.

$$ m_r = m_{{}^{2}_{1}\text{H}} + m_{{}^{3}_{1}\text{H}} $$
$$ m_r = (3.3436 \times 10^{-27} + 5.0074 \times 10^{-27}) $$
$$ m_r = 8.3510 \times 10^{-27}\,\text{kg} $$

2. Calculate the combined mass of the products.

$$ m_p = m_{{}^{4}_{2}\text{He}} + m_{{}^{1}_{0}n} $$
$$ m_p = 6.6447 \times 10^{-27} + 1.675 \times 10^{-27} $$
$$ m_p = 8.3197 \times 10^{-27}\,\text{kg} $$

3. Calculate the mass defect for this nuclear fusion reaction.

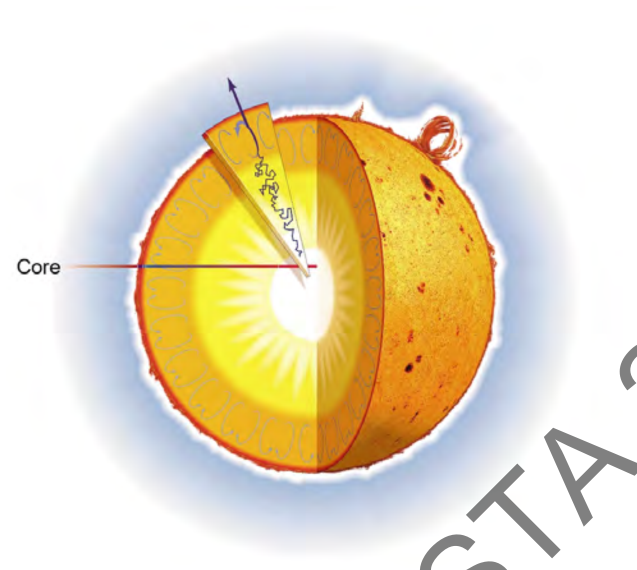
$$ \Delta m = m_r - m_p $$
$$ \Delta m = (8.3510 \times 10^{-27}) - (8.3197 \times 10^{-27}) $$
$$ \Delta m = 3.13 \times 10^{-29}\,\text{kg} $$

4. Calculate the energy released in this nuclear fusion reaction.

$$ E = \Delta mc^2 $$
$$ E = 3.13 \times 10^{-29} \times (3 \times 10^{8})^2 $$
$$ E = 2.82 \times 10^{-12}\,\text{J} $$

Question 161

Nuclear fusion occurs in the core of stars like the sun.



The temperature inside the core of the sun is greater than 15 million degrees celsius.

(a) Explain why nuclear fusion only occurs at high temperatures.

____

____

____

______________________________ (2 marks) KA1

(b) Two protons ($^{1}_{1}H$) undergo a nuclear fusion reaction in the core of the sun to form an unstable isotope called helium-2.

Write a nuclear equation to describe this reaction.

______________________________ (2 marks) KA4

(c) Helium-2 decays radioactively releasing a positron (beta plus decay).

(1) State why helium-2 does not undergo beta minus decay.

____

______________________________ (1 mark) KA2

(2) Write a nuclear equation to describe the radioactive beta plus decay of helium-2 to form a deuterium nucleus ($^{2}_{1}H$).

______________________________ (2 marks) KA4

(d) Deuterium nuclei undergo nuclear fusion in the core of the sun according to the following equation.

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

The masses of all reactants and products are given in the table below:

Reactant	Mass (kg)
$^{2}_{1}H$	3.3436×10^{-27}

Product	Mass (kg)
$^{3}_{1}H$	5.0074×10^{-27}
$^{1}_{1}H$	1.673×10^{-27}

Show that the energy released in one fusion reaction is approximately 6.1×10^{-13} J.

(3 marks) KA4

(e) Five billion years from now the sun will begin fusing helium nuclei as the core of the star collapses and the temperature increases to over 100 million degrees celsius.

Three helium-4 nuclei are fused into a single nucleus of carbon-12 (19.944×10^{-27} kg).

$$3\,^{4}_{2}He \rightarrow ^{12}_{6}C$$

(1) State why the reaction above requires a higher temperature than the fusion of hydrogen nuclei.

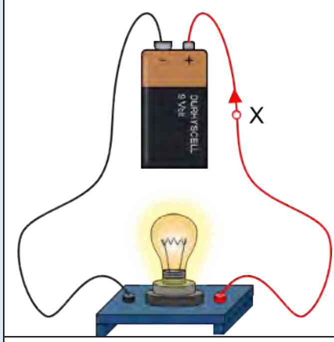
(1 mark) KA2

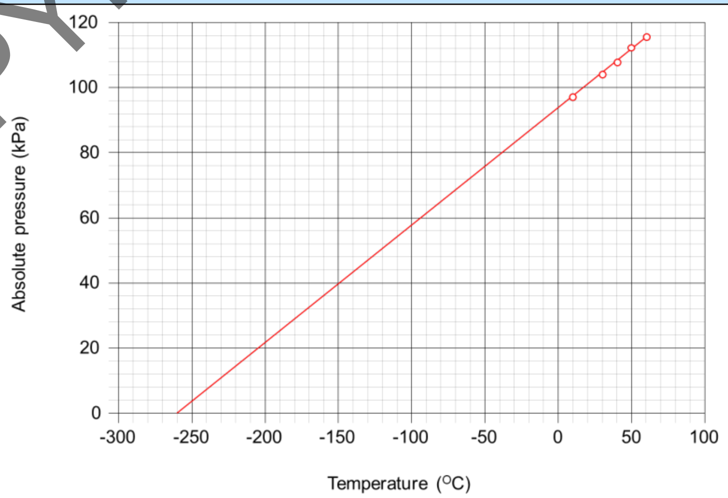
(2) Determine the mass of one helium-4 nucleus if 8.9×10^{-13} J of energy is released in the reaction.

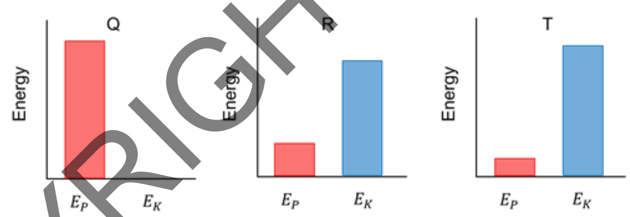
(6 marks) KA4

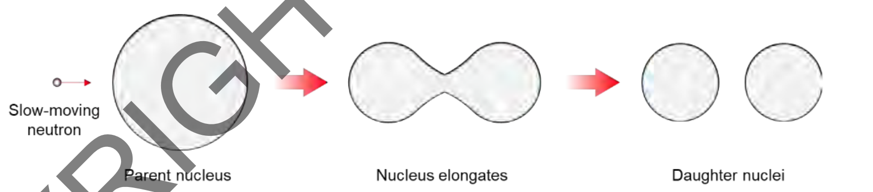
SOLUTIONS TO CHAPTER QUESTIONS AND REVIEW TESTS

Solutions: Chapter 1			
Question	Part	Author's response	Marks
1	(a)	$s = vt$	
		$s = 97.5 \times 10.5$	1
		$s = 1.0 \times 10^3$ m (1023.75)	1
	(b)	$t = \frac{s}{v}$	
		$t = \frac{1.5 \times 10^2}{75}$	1
		$t = 2.0$ s	1
	(c)	$v = \frac{s}{t}$	
		$v = \frac{620}{6}$	1
		$v = 103\ \mathrm{m.s^{-1}}$	1
2	(a)	$a = \frac{\Delta v}{\Delta t}$	
		$a = \frac{(22-0)}{(2.8-0)}$	1
		$a = 7.9\ \mathrm{m.s^{-2}}$ (7.857)	1
	(b) (1)	$\Delta t = \frac{\Delta v}{a}$	
		$\Delta t = \frac{(21-0)}{(6.5)}$	1
		$\Delta t = 3.2$ s (3.23)	1
	(b) (2)	$s = vt$	
		$s = 21 \times 8.5$	1
		$s = 1.8 \times 10^2$ m (178.5)	1
	(c)	Acceleration is any change in the motion of an object.	1
		This includes a decrease in the magnitude of the velocity of the cheetah.	1
	(d)	$t = \frac{s}{v}$	
		$t = \frac{225}{24.3}$	1
		$t = 9.26$ s	1
	(e)	The instantaneous speed of the cheetah is the speed at any instant in time.	1
		The average speed is a measure of the total distance travelled by the cheetah in a given time interval.	1
3	(a)	Displacement of the object is zero.	1
		Describes an object that is not moving.	1
	(b)	The gradient is constant.	1
		Describes an object travelling with constant velocity.	1
	(c)	The gradient is initially positive and constant. The gradient is zero briefly and is then negative and constant.	1
		Velocity is initially positive as the object moves away from the initial position and is then negative as the object returns to the initial position.	1

38	(a)			
			Arrow directed towards the positive terminal of the battery.	1
	(b)		$\Delta V = \frac{\Delta E_p}{q}$	
			$\Delta E_p = \Delta V q$	
			$\Delta E_p = 9 \times 1.6 \times 10^{-19}$	1
			$\Delta E_p = 1.4 \times 10^{-18}$ J	1
	(c)	(1)	$I = \frac{q}{t}$	
			$I = \frac{50}{25}$	1
			$I = 2$ A	1
		(2)	Using a voltmeter.	1
			A voltmeter is connected in parallel with the light bulb as components connected in parallel have the same potential difference.	1
39	(a)		Potential difference refers to the change in electric potential energy of a charge as it is moved between two points in an electric circuit.	1
			The electric potential energy of free electrons changes as they move between the negative and positive terminals of the power supply in the electric circuit.	1
	(b)		The change in electric potential energy of electrons is proportional to the potential difference in the electric circuit ($\Delta E_p \propto \Delta V$).	1
			Increasing the potential difference increases the energy transferred by electrons to the light bulbs and increases the brightness of the light emitted.	1
	(c)	(1)	$I = \frac{q}{t}$	
			$q = It$	
			$q = 0.3 \times 30$	1
			$q = 9$ C	1
		(2)	Using an ammeter.	1
			An ammeter is connected in series with the light bulbs in the circuit because components in series have the same current.	1

Solutions: Chapter 3			
Question	Part	Author's response	Marks
67	(a)	Energy is transferred from the blender blades causing an increase in the average kinetic energy of the molecules in the soup when the device is switched on;	1
		An increase in the average kinetic energy of the molecules results in a proportional increase in the temperature of the soup.	1
	(b)	The vibrational kinetic energy increases causing an increase in the amplitude/magnitude/size of the vibrations/oscillations of the water molecules.	1
		The rotational kinetic energy increases causing an increase in the rotational velocity of the water molecules.	1
		The translational kinetic energy increases causing an increase in the linear velocity of the water molecules as they move in straight lines within the volume of soup.	1
68	(a)	$T_{°C} = (T_{°F} - 32) \times \frac{5}{9}$	
		$T_{°C} = (360 - 32) \times \frac{5}{9}$	1
		$T_{°C} = 182°C$	1
	(b)	$T_{°F} = T_{°C} \times \frac{9}{5} + 32$	
		$T_{°F} = 25 \times \frac{9}{5} + 32$	1
		$T_{°F} = 77°F$	1
69	(a)	$T_K = T_{°C} + 273.15$	
		$T_K = 440 + 273.15$	1
		$T_K = 713.15\ K$	1
	(b)	$T_{°C} = T_K - 273.15$	
		$T_{°C} = 4 - 273.15$	1
		$T_{°C} = -269.15°C$	1
70	(a)		
		Data plotted correctly/ line of best fit extrapolated to x-intercept of the graph.	1+1
	(b)	The temperature at which the air molecules are motionless and exert zero pressure on the walls of the hollow copper sphere.	1
		This temperature is known as absolute zero.	1

	(c)	$P = \frac{W}{t}$	
		$P = \frac{4468.8}{2.6}$	1
		$P = 1.7 \times 10^3$ W (1718.77)	1
	(d)	$E_k = \Delta E_p = 4468.8$ J	
		$E_k = \frac{1}{2}mv^2$	
		$v = \sqrt{\frac{2E_k}{m}}$	
		$v = \sqrt{\frac{2 \times 4468.8}{190}}$	1
		$v = 6.9$ m.s^{-1}	1
105	(a)	$\Delta E_p = mg\Delta h$	
		$\Delta E_p = m \times 9.8 \times (65 - 25)$	
		$\Delta E_p = 392$m	1
		$\Delta E_k = \Delta E_p$	
		392m $= \frac{1}{2}mv^2$ (cancel out mass, m)	1
		$392 = \frac{1}{2}v^2$	
		$v = \sqrt{2 \times 392}$	
		$v = 28$ m.s^{-1}	1
	(b)		
		Q: Cart is not moving so E_k is zero.	1
		E_p is at a maximum.	1
		R: Cart has more kinetic energy than it does at S.	1
		E_p is less than it is at S.	1
		T: Kinetic energy is greater than Q, R and S.	1
		E_p is at its lowest but is not zero.	1
106	(a)	$E_k = \frac{1}{2}mv^2$	
		$E_k = \frac{1}{2}(74) \times (55)^2$	1
		$E_k = 1.1 \times 10^5$ J (111 925)	1
	(b)	$\Delta E_p = mg\Delta h$	
		$\Delta E_p = 74 \times 9.8 \times (0 - 175)$	1
		$\Delta E_p = -1.3 \times 10^5$ J (126 910)	1

Question	Part	Sub-part	Answer	Marks
157	(a)		$A = 146, Z = 35$	1+1
	(b)		$\Delta m = m_{reactants} - m_{products}$ $\Delta m = (1.675 \times 10^{-27} + 3.9030 \times 10^{-25}) - (2.4227 \times 10^{-25} + 1.4433 \times 10^{-25} + (3 \times 1.675 \times 10^{-27}))$ $\Delta m = 3.5 \times 10^{-28}$ kg $E = \Delta mc^2$ $E = 3.5 \times 10^{-28} \times (3 \times 10^8)^2$ $E = 3.2 \times 10^{-11}$ J	 1 1 1
	(c)	(1)	$P_t = \frac{\text{Useful output power}}{\text{efficiency}}$ $P_t = \frac{12}{0.25}$ $P_t = 48$ MW	 1
		(2)	$P_t = \frac{\Delta E}{\Delta t}$ $\Delta E = P_t \Delta t$ $\Delta E = 48 \times 10^6 \times (24 \times 60 \times 60)$ $\Delta E = 4.2 \times 10^{12}$ J Reactions $= \frac{\text{Total energy released}}{\text{energy released in one reaction}}$ Reactions $= \frac{4.2 \times 10^{12}}{3.15 \times 10^{-11}}$ Reactions $= 1.3 \times 10^{23}$ reactions One U-235 nucleus undergoes fission per reaction, so total number of uranium nuclei that are fissioned in 24 hours is 1.3×10^{23}.	 1 1 1 1
158	(a)			1
			A slow-moving neutron is captured by a heavy, unstable nucleus such as uranium-235 which causes the nucleus to oscillate and elongate. The nucleon separation increases as the nucleus elongates which decreases the magnitude of the strong nuclear force in the nucleus. The electrostatic force of repulsion between protons dominates, and the nucleus splits (fission).	1 1 1
	(b)		Protons have a positive charge and are repelled strongly by the parent nucleus.	1
	(c)	(1)	$N:Z = \frac{N}{Z}$ $N:Z = \frac{141}{56}$ $N:Z = 1:2.5$	 1
		(2)	Beta minus decay Barium-141 is neutron-rich/has a high neutron to proton ratio.	1 1

Equations Sheet

Symbols of quantities used in this book.

s	distance	E	energy	L_f	latent heat of fusion
$\vec{s}$	displacement	ΔV	potential difference	L_v	latent heat of vapourisation
t	time	I	current	E_k	kinetic energy
v	speed	q	charge	E_p	potential energy
$\vec{v}$	velocity	R	resistance	$\vec{p}$	momentum
$\vec{a}$	acceleration	ρ	resistivity	f	frequency
m	mass	P	power	λ	wavelength
$\vec{F}$	force	Q	quantity of heat	T	period
W	work	c	specific heat capacity	n	refractive index
$\vec{J}$	impulse	ΔT	temperature difference	μ	mass per unit length

Physical constants used in Stage 1 Physics.

g	acceleration due to gravity near Earth's surface.	magnitude	$9.8\ \text{m.s}^{-2}$
e	charge on an electron	magnitude	-1.6×10^{-19} C
m_e	mass of an electron	magnitude	9.11×10^{-31} kg
m_p	mass of a proton	magnitude	1.673×10^{-27} kg
m_n	mass of a neutron	magnitude	1.675×10^{-27} kg
c	speed of light in a vacuum	magnitude	$3 \times 10^{8}\ \text{m.s}^{-1}$

Equations used in Stage 1 Physics.

Topic 1: Linear Motion and Forces

$v = \frac{s}{t}$ $\quad a = \frac{v - v_0}{\Delta t}$ $\quad v^2 - v_0^2 = 2as$ $\quad v = v_0 + at$

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

Topic 2: Electric Circuits

$\Delta V = \frac{W}{q}$ $\quad I = \frac{q}{\Delta t}$ $\quad \rho = \frac{RA}{L}$ $\quad \Delta V = IR$

For resistors in series: $R_t = R_1 + R_2 + \cdots R_n$

For resistors in parallel: $\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}$

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

Topic 3: Heat

$Q = mc\Delta T$ $\quad Q = mL_f$ $\quad Q = mL_v$ $\quad \Delta L = \alpha L_0 \Delta T$

$\Delta V = \beta V_0 \Delta T$

Topic 4: Energy and Momentum

$W = Fs$ $\quad E_k = \frac{1}{2}mv^2$ $\quad E_p = mgh$ $\quad P = \frac{W}{t}$

$P = Fv$ $\quad p = mv$ $\quad F = \frac{\Delta p}{\Delta t}$ $\quad J = F\Delta t$

Topic 5: Waves

$v = f\lambda$ $\quad f = \frac{1}{T}$ $\quad v = \sqrt{\frac{T}{\mu}}$ $\quad f_0 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$

$n_1 sin\theta_i = n_2 sin\theta_r$ $\quad \lambda = \frac{\lambda_0}{n}$ $\quad n = \frac{c}{v}$

Topic 6: Nuclear Models and Radioactivity

$E = \Delta mc^2$

Table of prefixes

Prefix	Symbol	Value
pico	p	10^{-12}
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}

Significant figures

Answers are given to the least number of significant figures provided in the question.

1. Integers (1-9) are significant.
2. Zeros between integers are significant.
3. Trailing zeros to the right of the decimal are significant
4. Leading zeros are not significant.