IB Physics DP

5. Electricity & Magnetism

YOUR NOTES

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5.1 Electric Fields

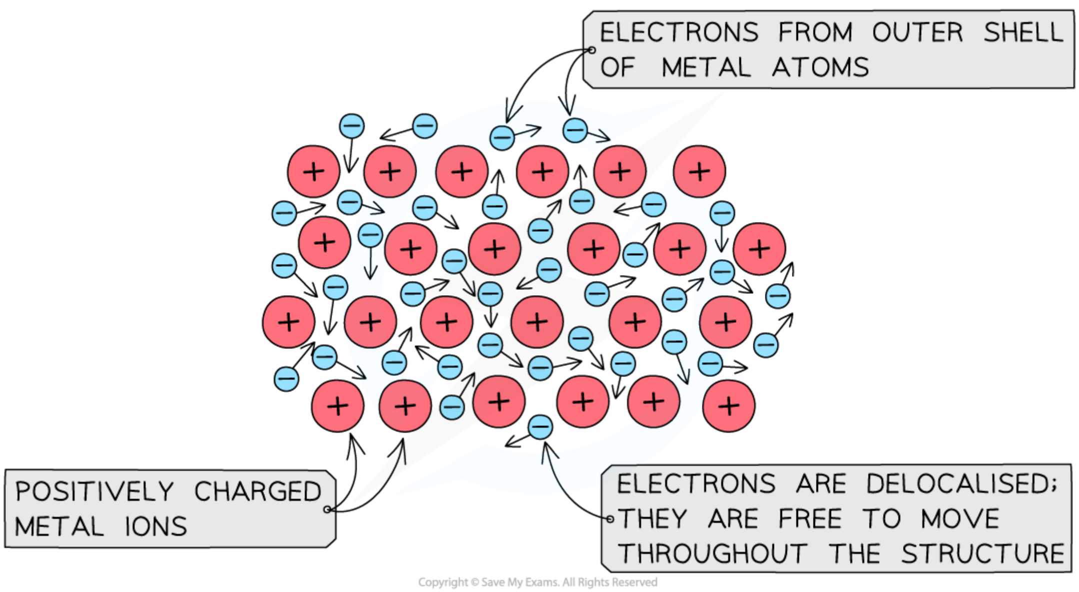
5.1.1 Charge & Current

Charge

- Charge is measured in **coulombs** (**C**). One coulomb is defined as:

The charge carried by an electric current of one ampere in one second

- Charge is a scalar quantity
  - **Electrons** have a **negative charge**
  - **Protons** have a **positive charge**
- Like charges **repel** each other and **attract** opposite ones
- In **neutral** (i.e. **uncharged**) atoms and objects the number of electrons and the number of protons are equal
- The **movement of electrons** determines the charge of an atom or object
- In **charged** atoms or objects there is a net amount of either positive or negative charge
  - An object that **gains electrons** has an overall negative charge
  - An object that **loses electrons** has an overall positive charge
- In **conductors**, some electrons are free to move between atoms



Delocalised electrons in the outer shell of the atoms in a conductor can move between atoms. When a neutral atom loses electrons it becomes a positive ion

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Electric Current

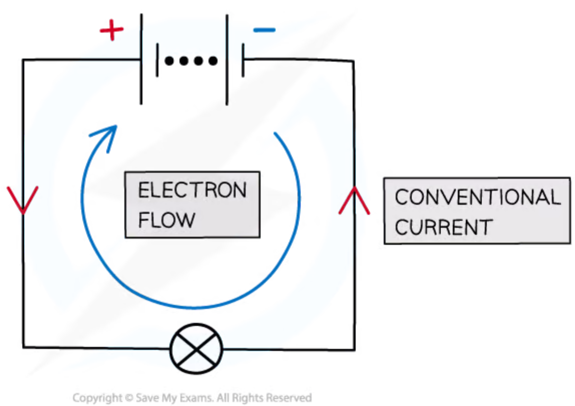
- The **electric current** through a conductive material is defined as follows:

The rate of flow of electric charge past a cross-section of material

- Current is measured in **amperes** (**A**)
  - The ampere is a **fundamental unit** of the SI system
- Current is calculated as follows:

$$I = \frac{\Delta q}{\Delta t}$$

- Where:
  - I = current in amperes (A)
  - Δq = net charge flowing past a cross-section of material in coulombs (C)
  - Δt = time interval in seconds (s)
- The conventional **direction** of current is **from positive to negative**
  - Electrons flow opposite to the conventional direction of current



By definition, conventional current always goes from positive to negative (even through electrons go the other way)

Worked Example

A charge of 20 μC flows through a given section of a conductor in 60 ms.

Calculate the electric current.

Step 1: Write down the known quantities

- Δq = 20 μC = 20 × 10^{-6} C
- Δt = 60 ms = 60 × 10^{-3} s

Note the conversions:

- The amount of charge must be converted from micro coulombs (μC) into coulombs (C)
- The time must be converted from milliseconds (ms) into seconds (s)

Step 2: Write down the equation for the electric current *I*

$$I = \frac{\Delta q}{\Delta t}$$

Step 3: Substitute the numbers into the equation

$$I = \frac{20 \times 10^{-6}}{60 \times 10^{-3}}$$

$$I = 3.3 \times 10^{-4} \text{ A}$$

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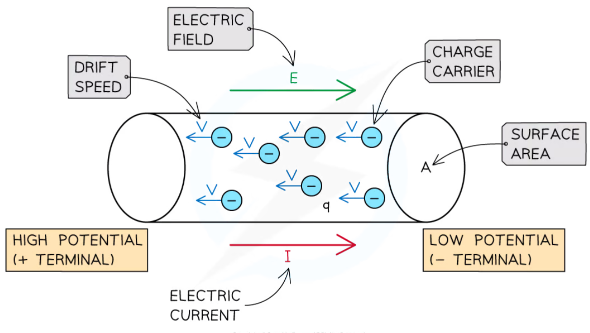
5.1.2 Drift Speed

Drift Speed

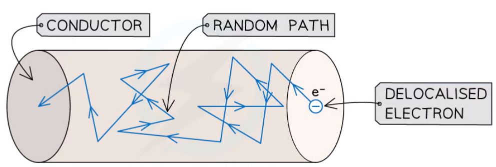
- In conductors, only negatively charged (delocalised) electrons are allowed to move between atoms
    - In general, an electric current can arise from the flow of either positive or negative particles
- Charged particles moving through a material or through vacuum are known as **charge carriers**



Charge carriers drift towards the positive terminal of the conductor. Conventional current flows in the opposite direction

Movement in a Conductor

- Delocalised electrons are the charge carriers in a conductor
    - These electrons normally move **randomly** through the conductor



Random path of a delocalised electron through a length of conductor

- If a **potential difference** is applied between two points in the conductor, an **electric field** is created
- As a consequence:
    - An **electric force** will act on the charge carriers
    - The charge carriers will **drift** along the conductor
    - A steady average current will flow through the conductor

Electric Current & Drift Speed

- The average speed at which the charge carriers move through a conductor is known as the **drift speed**
- The value of the drift speed is usually very small
    - For most everyday situations, $v \sim 10^{-4}$ m s^{-1}

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- The electric current arising from the movement of a given number of charge carriers through a conductor is calculated as follows:

$$I = nAvq$$

- Where:
  - n = number of charge carriers per unit volume, i.e. **charge density** (m^{-3})
  - A = cross-sectional area of the conductor (m^2)
  - v = average drift speed of the charge carriers ($m\ s^{-1}$)
  - q = charge of the charge carriers (C)

Worked Example

A number N of charge carriers, each with a charge q, moves through a conductor of length L and cross-sectional area A. Show that the electric current flowing through the conductor is given by:

$$I = nAvq$$

Where n is the number of charge carriers per unit volume and v is their drift speed.

Step 1: Write down the equation for electric current

$$I = \frac{\Delta q}{\Delta t}$$

Step 2: Write down the expression for the total charge *Δq* and substitute it into the above equation

- The total charge is equal to the number of charge carriers times the charge of each carrier

$$\Delta q = Nq$$

- Substituting this into the current equation:

$$I = \frac{Nq}{\Delta t}$$

Step 3: Write down the number of charge carriers in terms of charge density *n*, and substitute it into the above equation

- The charge density is equal to the number of charges per unit volume

$$n = \frac{N}{V}$$

$$N = nV$$

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- Substituting this into the current equation:

$$I = \frac{nVq}{\Delta t}$$

Step 4: Write down the volume of the conductor in terms of cross-sectional area and length, and substitute it into the above equation

- The volume of the cylindrical section of the conductor is equal to the cross-sectional area times the length

$$V = AL$$

- Substituting this into the current equation:

$$I = \frac{nALq}{\Delta t}$$

Step 5: Recognise average speed into the above equation

- Average speed *v* is total distance *L* over total time *Δt*

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

- Substituting this into the current equation

$$I = nAvq$$

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5.1.3 Potential Difference & DC

Potential Difference

- Potential difference is a measure of the electrical potential energy transferred from an electron as it moves between two points in a conductor

Potential difference is work done per unit charge

- It is also known as **voltage**
- Potential difference (pd) is calculated as follows:

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

- Where:
  - V = potential difference in **volts** (**V**)
  - W = work done in joules (J)
  - q = charge in coulombs (C)
- From the above equation, one volt is equal to one joule per unit coulomb
  - $1\ V = 1\ J\ C^{-1}$

The Electronvolt

- The energy values associated to electrons and other microscopic particles are very small when expressed in SI units
- For this reason, it is often more convenient to use another unit for energy - the **electronvolt** (**eV**)
- The electronvolt is defined as follows:

The amount of energy needed to move an electron through a potential difference of one volt

Worked Example

Determine the value of 1 eV in joules (J).

Step 1: Recall the definition of electronvolt

- One electronvolt is the work W associated to an electron of charge e moving through a potential difference V = 1V

$$W = eV$$

Step 2: Look up the charge e of the electron in the data booklet

- $e = 1.6 \times 10^{-19}$ C

Step 3: Substitute this and the value of the voltage into the above equation for *W*

$$W = (1.6 \times 10^{-19}\ C) \times 1\ V$$

$$W = 1.6 \times 10^{-19} \text{ J}$$

One electronvolt is equal to 1.6×10^{-19} joules

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Direct Current

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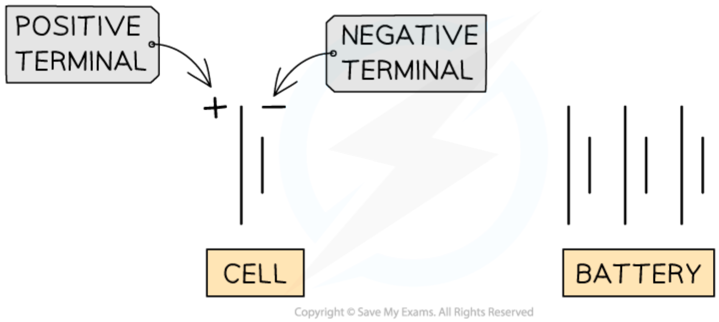
- The potential difference in a circuit is provided by **cells** or **batteries**
  - Each cell has a **positive terminal** (high potential location) and a **negative terminal** (low potential location)
  - A battery is a collection of cells arranged positive terminal to negative terminal



A cell and a battery made of three cells

- When a cell or a battery is connected to a loop of **copper wire**, a **circuit** is formed
- The battery is the source of the potential difference *V* needed for the electrons to flow
- Electrons gain electrical potential energy as they move through the battery
- They then leave the battery and move through the wire
  - A little amount of their energy is transferred to the metal atoms of the wire
  - The flow of electrons is from the negative terminal to the positive one

- **Direct current** (**dc**) flows through the circuit in **one direction**
  - The direction of conventional current is **from the positive terminal to the negative one**
  - This is opposite to the electrons flow

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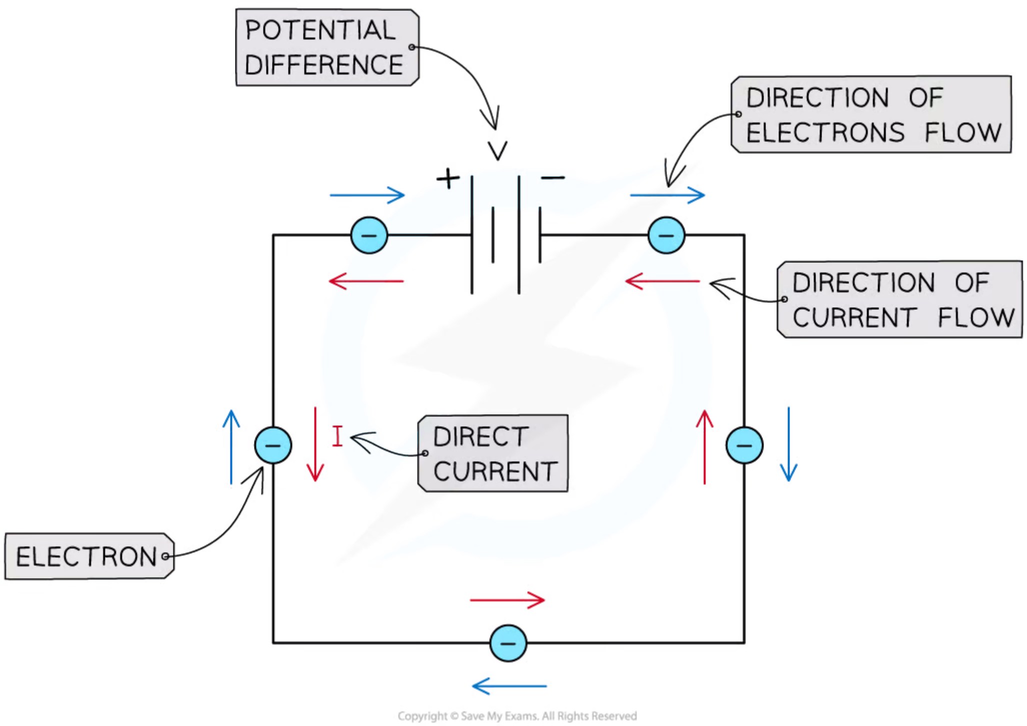

Direct current flows from the positive to the negative terminal of the battery in a circuit. Electrons flow in the opposite direction

Alternating Current

- Alternating current (**ac**) is used instead of dc in high voltage devices (i.e. those typically used in homes and industries)
- Alternating current flows one way around the circuit and then reverses its flow
- ac direction usually changes every 0.01 s

5.1.4 Electric Fields

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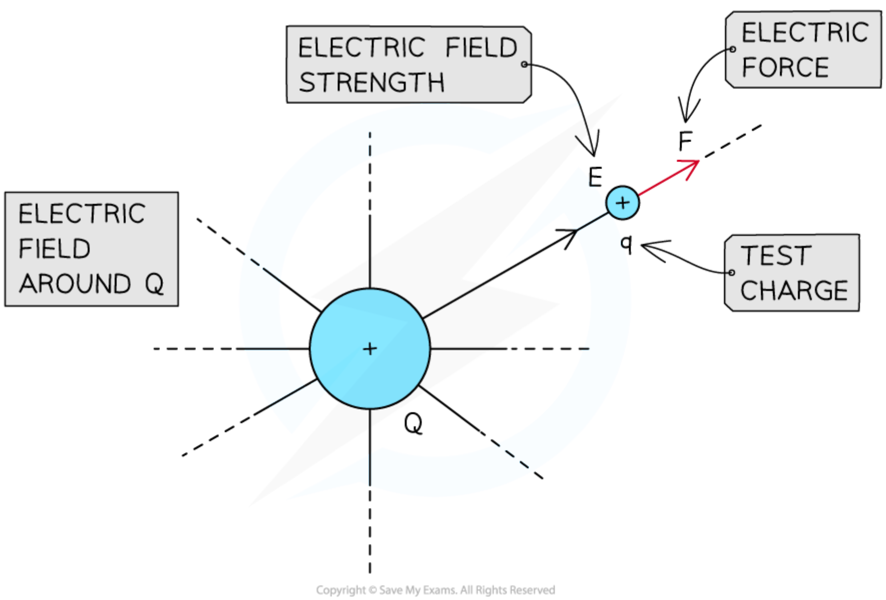
Electric Fields

- An **electric field** is a region of space in which an electric charge "feels" a force
  - It is a vector field
  - The direction of the electric field is the same as the direction of the electric force

Electric Field Strength

- The electric field strength is a measure of the strength of the electric field

The electric field strength is defined as the magnitude of the electric force per unit charge experienced by a small positive test charge placed at that point



The strength of the electric field generated by charge Q is measured by placing a test charge q in the field

- The equation to calculate the electric field strength at a given point in space is:

$$E = \frac{F}{q}$$

- Where:
  - E = electric field strength in newtons per coulomb **N C^{-1}**
  - F = electric force in newtons (N)
  - q = electric charge in coulombs (C)

Representing Electric Fields

- **Electric field lines** are used to visualise electric fields
- Arrows along the lines indicate the direction of the field

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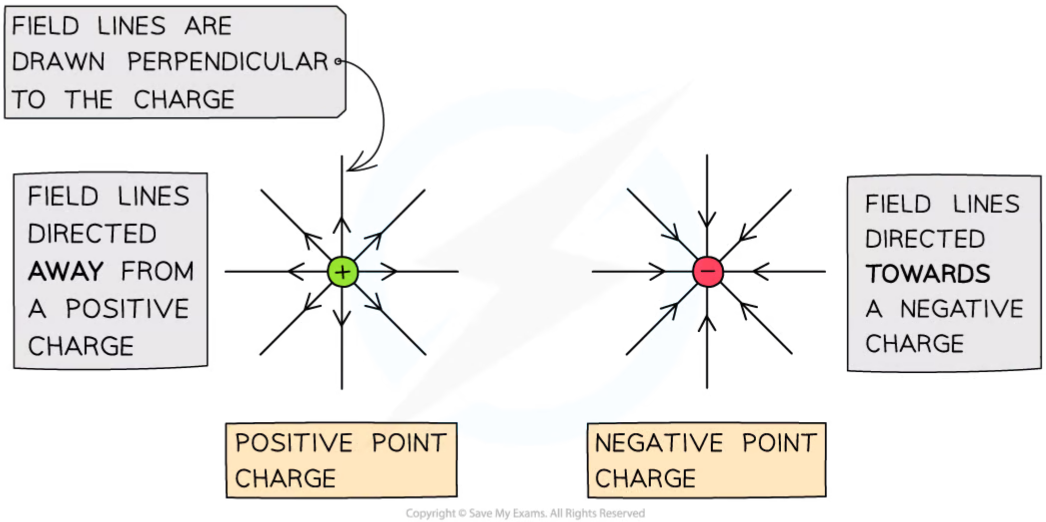
- The arrows always point away from the positive charge and towards negative the charge

- Around a **point charge** or a charged sphere, the electric field lines are directly radially inwards or outwards:
    - If the charge is **positive** (+), the field lines are radially **outwards**
    - If the charge is **negative** (–), the field lines are radially **inwards**

- This shares many similarities to radial gravitational field lines around a point mass
    - The difference being that the gravitational force is always attractive, whilst the electric force can be either attractive or repulsive



Electric field lines around isolated positive and negative point charges

- The strength of the electric field is proportional to the number of lines per unit cross-sectional area
    - A stronger electric field is represented by arrows that are closer together

- The field lines between opposite charges are connected, showing attraction
- The field lines between like repelling charges never connect

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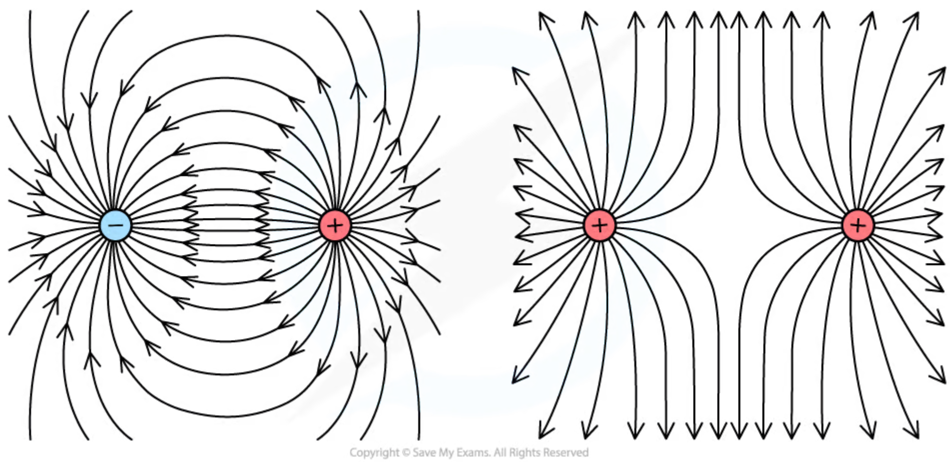
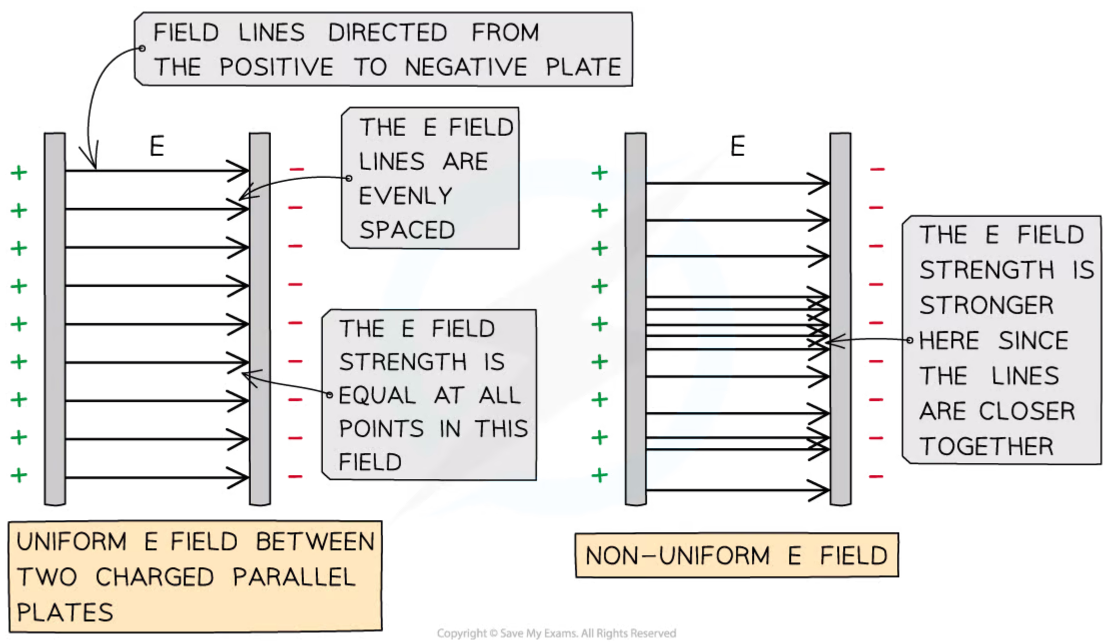


Electric field lines showing attraction between a positive and a negative charge, and repulsion between two positive charges

Uniform and Non-Uniform Electric Fields

- A **uniform** electric field is a field of force in which the strength of the electric force is the same throughout
  - It is represented by **parallel** and **equally spaced** field lines
- Whenever the spacing between the field lines changes, the electric field is non-uniform



Uniform and non-uniform electric fields between two parallel plates

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Worked Example

A charged particle is in an electric field with electric field strength 3.5×10^4 N C^{-1}, where it experiences a force of 0.3 N. Calculate the charge of the particle.

Step 1: Write down the known quantities

- $E = 3.5 \times 10^4$ N C^{-1}
- $F = 0.3$ N

Step 2: Write down the equation for the electric field strength

$$E = \frac{F}{q}$$

Step 3: Rearrange the above equation to calculate the charge *q*

$$q = \frac{F}{E}$$

Step 4: Substitute the numbers into the above equation

$$q = \frac{0.3}{3.5 \times 10^4}$$

$$q = 8.6 \times 10^{-6} \text{ C}$$

Exam Tip

When drawing field lines, make sure they never cross. The electric field can only have one value at any given point.

5.1.5 Coulomb's Law

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Coulomb's Law

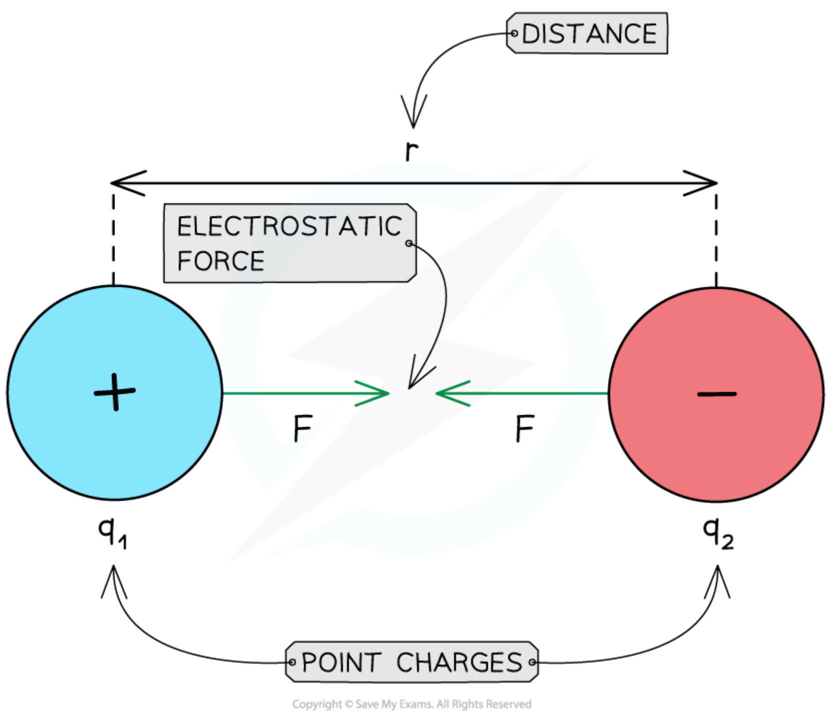
- Any charged particle generates an electric field
  - This field exerts a force on any other charged particle within range
- The electrostatic force between two charges is defined by **Coulomb's Law**, which states that:

  The attractive or repulsive electrostatic force between two point charges is directly proportional to the product of the charges and inversely proportional to the square of their separation

- According to Coulomb's law, the electrostatic force between two point charges is calculated as follows:

$$F = k\frac{q_1 q_2}{r^2}$$

- Where:
  - F = electrostatic force (N)
  - q_1, q_2 = magnitudes of the charges (C)
  - r = distance between the centres of the two charges (m)
  - k = **Coulomb constant** (N m^2 C^{-2})



Attractive electrostatic force between two opposite charges

- Coulomb's constant is given by:

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$$k = \frac{1}{4\pi\varepsilon_0}$$

- The value of k depends on the material between the charges
  - In a **vacuum**, $k = 8.99 \times 10^9$ N m^2 C^{-2}
- ε_0 is the **permittivity of free space**
  - $\varepsilon_0 = 8.85 \times 10^{-12}$ C^2 N^{-1} m^{-2} and refers to charges in a vacuum
  - The value of the permittivity of air is taken to be the same as ε_0
  - Any other material has a higher permittivity $\varepsilon > \varepsilon_0$
  - ε is a measure of the resistance offered by a material in creating an electric field within it

Repulsive & Attractive Forces

- For **like charges**:
  - The product q_1q_2 is positive
  - F is **positive**
  - The charges **repel** each other
- For **opposite charges**:
  - The product q_1q_2 is negative
  - F is **negative**
  - The charges **attract** each other

Worked Example

An alpha particle is situated 2.0 mm away from a gold nucleus in a vacuum.Assuming them to be point charges, calculate the magnitude of the electrostatic force acting on each of the charges.

- Atomic number of helium = 2
- Atomic number of gold = 79

Step 1: Write down the known quantities

- Distance, r = 2.0 mm = 2.0×10^{-3} m
- Elementary charge, e = 1.60×10^{-19} C (from the data booklet)

Note that you must convert the distance from millimetres (mm) into metres (m)

Step 2: Calculate the charges of the alpha particle and gold nucleus

- The elementary charge e (when taken to be positive) is the charge of a proton
- An alpha particle (helium nucleus) has 2 protons
  - So its charge is:

$$q_1 = 2 \times (1.60 \times 10^{-19}) = 3.2 \times 10^{-19} \text{ C}$$

- A gold nucleus has 79 protons
  - So its charge is:

$$q_2 = 79 \times (1.60 \times 10^{-19}) = 1.264 \times 10^{-17} \text{ C}$$

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Step 3: Write down the equation to calculate the electrostatic force

$$F = k\frac{q_1 q_2}{r^2}$$

Step 4: Substitute the numbers into the equation

$$F = (8.99 \times 10^9) \times \frac{(3.2 \times 10^{-19}) \times (1.264 \times 10^{-17})}{(2.0 \times 10^{-3})^2}$$

$$F = 9.1 \times 10^{-21}\ \text{N}$$

Exam Tip

You do not need to memorise the numerical value of the Coulomb's constant k or that of the permittivity of free space ε_0. They will both be given in the data booklet.

Unless specified in the question, you should assume that charges are located in a vacuum.

You should note that Coulomb's law can only be applied to charged spheres whose size is much smaller than their separation. Only in this case, the point charge approximation is valid. You must remember that the separation r must be taken from the centres of the spheres.

You cannot use Coulomb's law to calculate the electrostatic force between charges distributed on irregularly-shaped objects.

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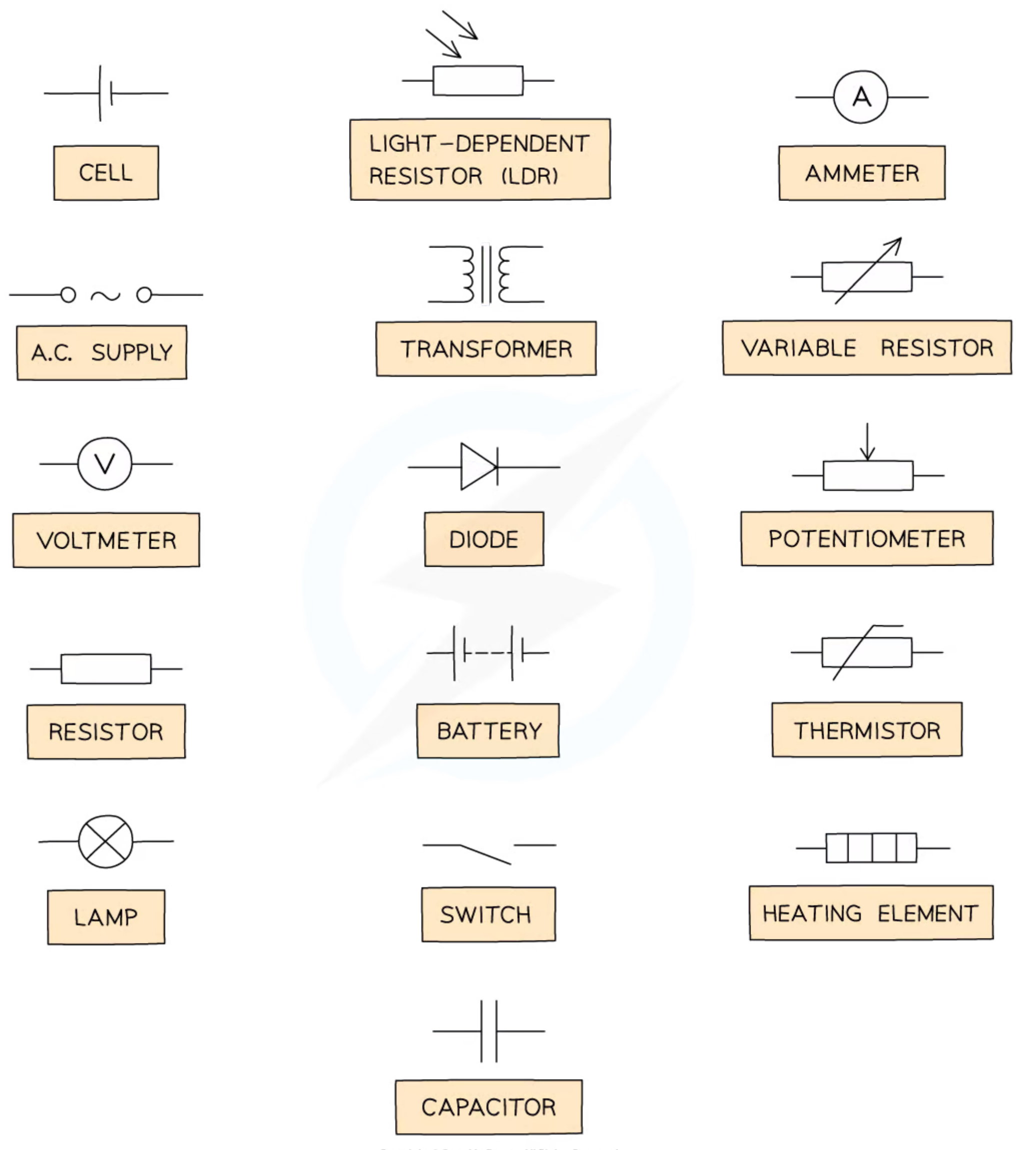
5.2 Heating Effect of Electric Currents

5.2.1 Circuits

Circuit Diagrams

- The diagram below shows the various circuit symbols that could be used in circuit diagrams



Common circuit symbols

Functions of Most Common Components

- **Switch:** it turns the circuit on (closed), or off (open)
- **Fixed resistor:** it limits the flow of current

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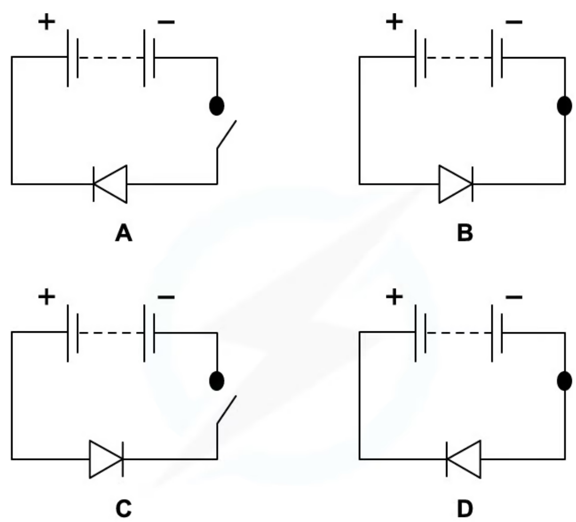
- As electrons flow through a resistor, they transform electrical potential energy into other forms of energy (i.e. thermal energy)

- **Variable resistor:** a resistor with a slider that can be used to change its resistance
  - As the resistance of the variable resistor increases, the current in the circuit decreases and vice versa
- **Thermistor:** a resistor whose resistance depends on its temperature
  - As temperature increases, the resistance of a thermistor decreases and vice versa
- **Light-dependent resistor (LDR):** a resistor whose resistance depends on the light intensity
  - As light intensity increases, the resistance of a LDR decreases and vice versa
- **Diode:** it allows current to flow in one direction only
  - It is often use for rectification - i.e. conversion of AC into DC
- **Light-emitting diode (LED):** it emits light when a current passes through it
- **Light bulb**: a resistor that transforms electric potential energy into such large thermal energy that energy is dissipated as light emitted to the surroundings
- **Ammeter:** it measures the current in the circuit
- **Voltmeter:** it measures the potential difference of an electrical component

Worked Example

Which circuit diagram correctly represents a circuit with current flowing through?



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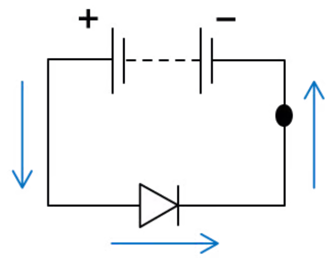
ANSWER: B

THIS IS SEEN IN CIRCUIT B



- For a circuit to be connected, the switch must be closed
  - This is either circuit **B** or **D**
- The other circuit symbol is a diode
  - Diodes only allow current to flow in one direction
- Since current flow is from positive to negative, a forward-biased diode must point in this direction in order for the current to flow
  - This is seen in circuit **B**

Exam Tip

The standard circuit symbols are given in the data booklet, so you do not need to memorise them. However, you must be able to identify them and draw them correctly.

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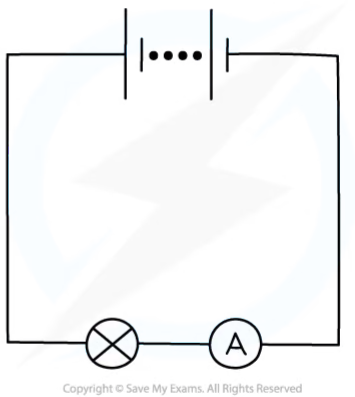
Ammeters & Voltmeters

Measuring Current

- Electric current is measured using an **ammeter**
- Ammeters should always be connected in **series** within a circuit

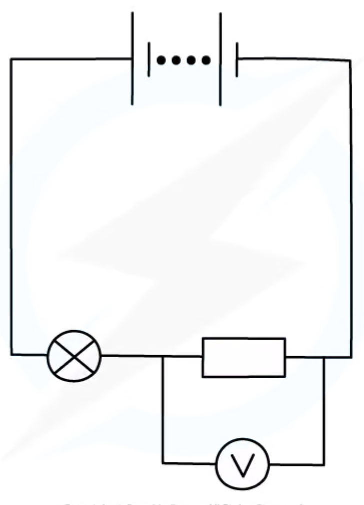


To measure the current flowing through a light bulb, an ammeter must be connected in series with it

- An ideal ammeter should have zero resistance
  - This way, it will not take any energy from the electrons flowing through it
  - Otherwise it would alter the value of the current it is trying to measure

Measuring Potential Difference

- Potential difference (or voltage) is measured using a **voltmeter**
- A voltmeter is always set up **in parallel** to the component whose voltage is being measured
  - This means that the voltmeter must be hooked across the terminals of the component



To measure the potential difference of a fixed resistor, a voltmeter must be connected in parallel to it

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- When electrons flow through a component in the circuit (e.g. a resistor):
  - They transfer some of their electrical potential energy to it
  - The component transforms this electrical potential energy into some other form of energy (e.g. thermal)
- Measuring the potential difference across a component means comparing the value of the electric potential energy of the electrons before they enter the component to when they leave it

5.2.2 Resistance & Resistors

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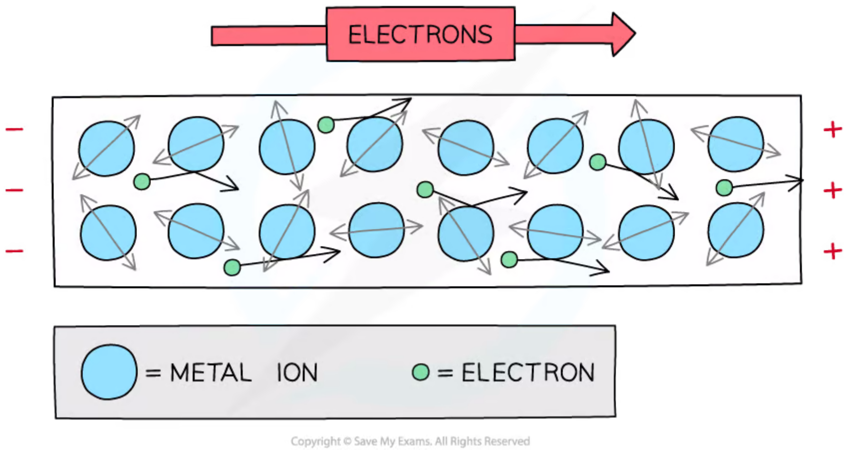
Resistance

- As electrons move through the metal wire of a circuit (or any other component), they transfer some of their electrical potential energy to the positive ions of the metal



Free electrons collide with metal ions which resist their flow

- This energy results in an increase in the kinetic energy of the lattice
- Which means a higher internal energy of the metal
- The macroscopic result of this transfer is the **heating up** of the wire
- Some metals heat up more than others
  - The higher the heating, the higher the **resistance**
  - Wires are often made from **copper** because copper has a low electrical resistance

- The resistance ***R*** of a component is defined as:

  The ratio of the potential difference across the component to the current flowing through it

- It is calculated as follows:

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

- Where:
  - V = potential difference in volts (V)
  - I = electric current in amperes (A)
  - R = resistance in **ohms** **(Ω)**

- This means that the higher the resistance of a component, the lower the current flowing through it and vice versa
- In terms of SI base units: 1 Ω = 1 kg m^2 s^{-3} A^{-2}

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Worked Example

A charge of 5.0 C passes through a resistor at a constant rate in 30 s. The potential difference across the resistor is 2.0 V.

Calculate the resistance R of the resistor.

Step 1: Write down the known quantities

- Charge, Δq = 5.0 C
- Time, Δt = 30 s
- Potential difference, V = 2.0 V

Step 2: Write down the equation for the resistance *R*

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

Step 3: Calculate the current *I* from the charge and time

$$I = \frac{\Delta q}{\Delta t}$$

Step 4: Substitute the numbers into the above equation

$$I = \frac{5.0}{30}$$

I = 0.17 A

Step 5: Substitute this value of the current into the equation for the resistance given in Step 2

$$R = \frac{2.0}{0.17}$$

R = 12 Ω

Resistors in Series & Parallel

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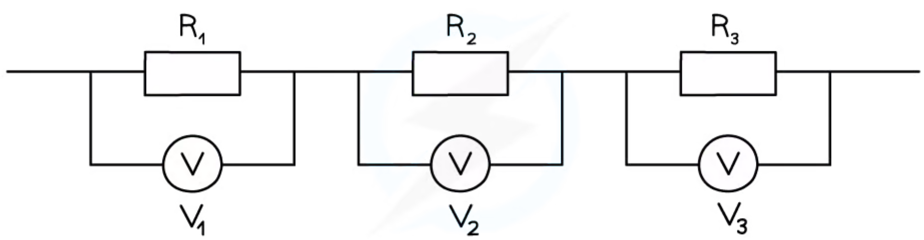
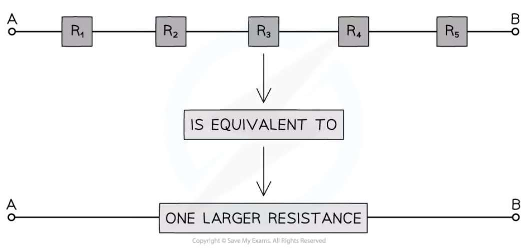
Resistors in Series

- When two or more components are connected **in series**:



The combined resistance of the components is equal to the sum of individual resistances

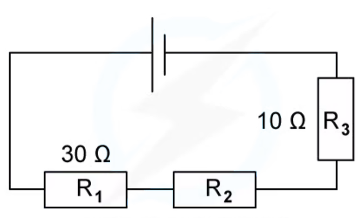
- This means as more resistors are added, their combined resistance increases and is, therefore, more than the resistance of the individual components



Connecting more resistors in series increases the overall resistance

Worked Example

The combined resistance R in the following series circuit is 60 Ω. What is the resistance value of R_2?



A. 100 Ω **B.** 30 Ω **C.** 20 Ω **D.** 40 Ω

Step 1: Write down the known quantities

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- Total resistance, $R = 60\ \Omega$
- Resistance of first resistor, $R_1 = 30\ \Omega$
- Resistance of third resistor, $R_3 = 10\ \Omega$

Step 2: Write down the equation for the combined resistance of resistors in series

$$R = R_1 + R_2 + R_3$$

Step 3: Rearrange the above equation to calculate the resistance R_2 of the second resistor

$$R_2 = R - R_1 - R_3$$

Step 4: Substitute the numbers into the above equation

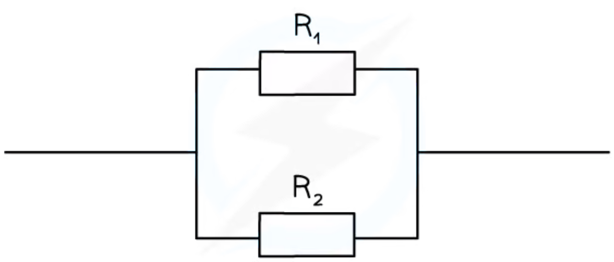
$$R_2 = (60 - 30 - 10)\ \Omega$$

$$R_2 = 20\ \Omega$$

ANSWER: C

Resistors in Parallel

- When two or more components are connected in parallel:



The reciprocal of the combined resistance is the sum of the reciprocals of the individual resistances

COMBINED RESISTANCE IN PARALLEL $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \ldots$

- This means as more resistors are added, their combined resistance decreases and is, therefore, less than the resistance of the individual components

YOUR NOTES
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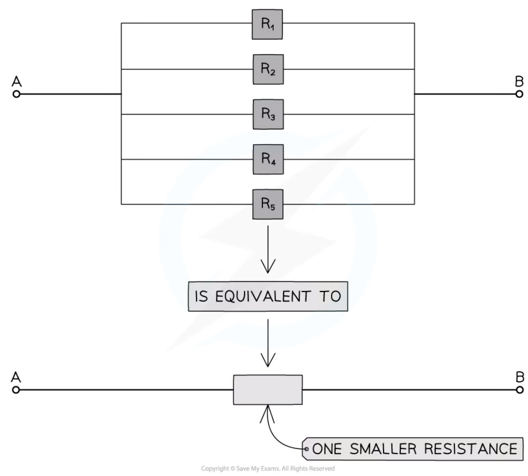
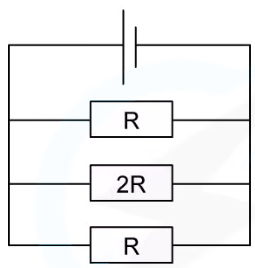


Connecting more resistors in parallel decreases the overall resistance

Worked Example

The circuit below shows 3 resistors connected in parallel.



Which value gives the combined resistance of all the resistors in this circuit?

A. $\frac{5R}{2}$ **B.** $\frac{2}{5R}$ **C.** $\frac{5}{2R}$ **D.** $\frac{2R}{5}$

Step 1: Write down the known quantities

- Resistance of first resistor, $R_1 = R$
- Resistance of second resistor, $R_2 = 2R$
- Resistance of third resistor, $R_3 = R$

Step 2: Write down the equation for the reciprocal of the combined resistance ($1/R_{TOT}$) of resistors in parallel

$$\frac{1}{R_{TOT}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Step 3: Substitute the given quantities into the above equation

$$\frac{1}{R_{TOT}} = \frac{1}{R} + \frac{1}{2R} + \frac{1}{R}$$

YOUR NOTES
⬇

$$\frac{1}{R_{TOT}} = \frac{5}{2R}$$

Step 4: Take the reciprocal of the second equation above to get the combined resistance R_{TOT}

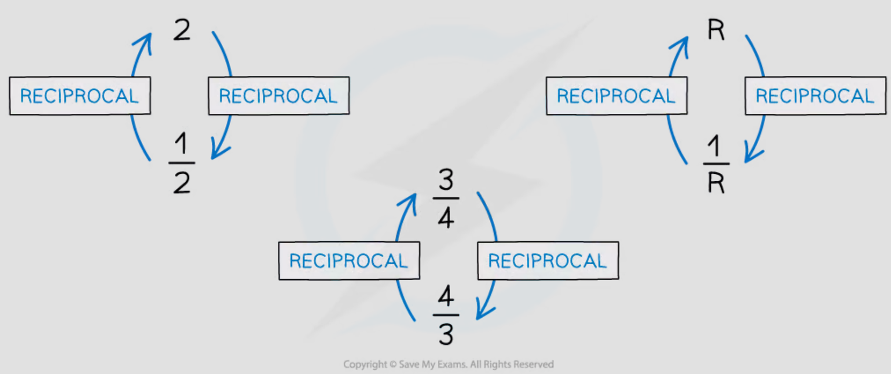
$$R_{TOT} = \frac{2R}{5}$$

ANSWER: D

Exam Tip

The most common mistake in questions about parallel resistors is to forget to find the reciprocal of R_T (i.e. $1/R_T$) instead of R_T. Here is a maths tip to rejig your memory on reciprocals:

- The reciprocal of a value is 1 / value
- For example, the reciprocal of a whole number such as 2 equals ½
  - Conversely, the reciprocal of ½ is 2
- If the number is already a fraction, the numerator and denominator are 'flipped' round



The reciprocal of a number is 1 ÷ number

- In the case of the resistance R, this becomes $1/R$
- To get the value of R from $1/R$, you must calculate 1 ÷ your answer
- You can also use the reciprocal button on your calculator (labelled either x^{-1} or $1/x$, depending on your calculator)

YOUR NOTES
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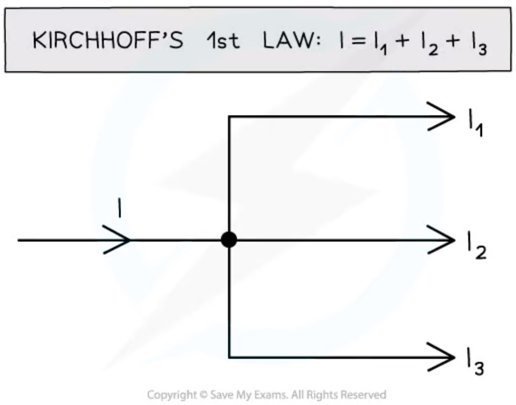
Kirchhoff's Circuit Laws

Kirchhoff's First Law

- Kirchhoff's first law states that:

    The sum of the currents entering a junction always equals the sum of the currents out of the junction

- A **junction** is a point where at least three circuit paths meet



The current I into the junction is equal to the sum of the currents I_1, I_2 and I_3 out of the junction

- Kirchhoff's first law is a consequence of **conservation of charge**
    - The charge is the same on both sides of the junction
- Kirchhoff's first law is often written as follows:

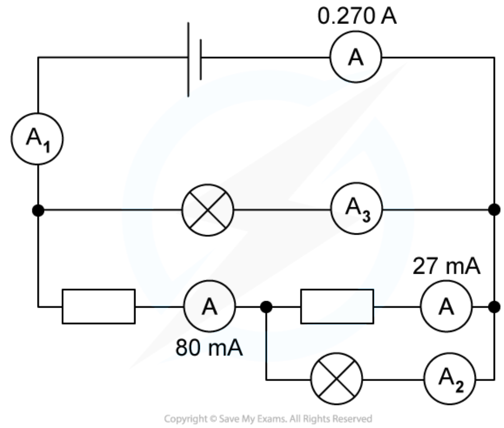
$$\sum I = 0$$

- Where:
    - $\sum I$ = net current entering and leaving the junction
    - The current entering a junction is defined as positive
    - The current leaving a junction is defined as negative

YOUR NOTES
⬇

Worked Example

For the circuit below, state the readings of ammeters A_1, A_2 and A_3.



Step 1: Ammeter A_1 is in series with ammeter A

- The current reading of ammeter A_1 is the same as that of ammeter A

$$A_1 = 0.270 \text{ A}$$

Step 2: From Kirchhoff's first law, the total current entering the junction must be equal to the total current leaving the junction

- The current from ammeter A_1 enters a junction and splits into two branches
- One branch has a current of 80 mA = 0.080 A
- The current in the other branch is the reading of ammeter A_3

$$0.270 \text{ A} = 0.080 \text{ A} + A_3$$

$$A_3 = (0.270 - 0.080) \text{ A} = 0.19 \text{ A}$$

Step 3: Apply Kirchhoff's law to the other junction of the circuit

- The 0.080 A current enters a junction and splits into two branches
- One branch has a current of 27 mA = 0.027 A
- The current in the other branch is the reading of ammeter A_2

$$0.080 \text{ A} = 0.027 \text{ A} + A_2$$

$$A_2 = (0.080 - 0.027) \text{ A} = 0.053 \text{ A}$$

The current readings of the three ammeters are:

- $A_1 = 0.270 \text{ A} = 270 \text{ mA}$
- $A_2 = 0.053 \text{ A} = 53 \text{ mA}$
- $A_3 = 0.19 \text{ A} = 190 \text{ mA}$

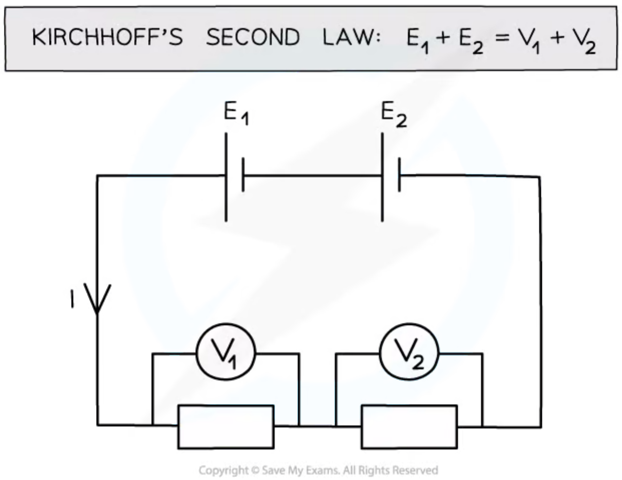
Kirchhoff's Second Law

- Kirchhoff's second law states that:

YOUR NOTES
⬇

The net potential difference in a closed loop is equal to zero

- This is a consequence of **conservation of energy**
  - The electric potential energy carried by the electrons as they flow through a circuit must be equal to the overall thermal energy transferred to the different components



The sum of the electric potential energies E_1 and E_2 provided by the two cells must be equal to the sum of the potential differences across the two fixed resistors

- Kirchhoff's second law is often written as follows:

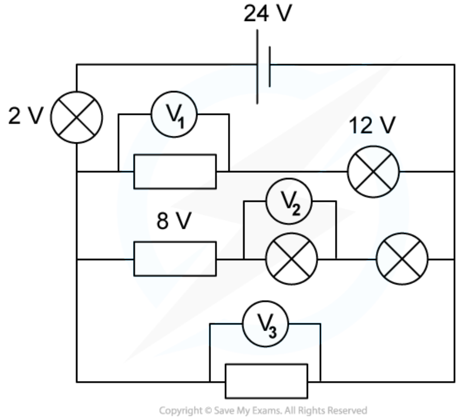
$$\Sigma V = 0$$

- Where:
  - ΣV = net potential difference in a closed loop
  - The potential difference entering a cell is defined as positive
  - The potential difference entering a resistor (or another circuit component offering resistance) is defined as negative

YOUR NOTES
↓

Worked Example

For the circuit below, state the readings of the voltmeters V_1, V_2 and V_3. All the lamps and resistors have the same resistance.



Step 1: Kirchhoff's second law states that the sum of all potential differences in the first loop is equal to zero

- The potential difference provided by the cell is positive and equal to 24 V
- The potential difference across the first light bulb is negative and equal to 2V
- The potential difference across the second light bulb is negative and equal to 12 V

$$V_1 = (24 - 2 - 12)\text{ V} = 10\text{ V}$$

Step 2: Apply Kirchhoff's second law to the second loop of the circuit

- The potential difference across the fixed resistor is negative and equal to 8 V
- The potential difference across each light bulb is negative and equal in value to the reading of V_2 (since they have the same resistance)
- All these negative potential differences must be summed to:
  - The positive potential difference provided by the cell (24 V)
  - The negative potential difference across the light bulb connected in series with the cell (2 V)

$$2V_2 = (24 - 2 - 8)\text{ V} = 14\text{ V}$$

$$V_2 = 7\text{ V}$$

Step 3: Apply Kirchhoff's second law to the third loop of the circuit

- The reading of V_3 is equal to the sum of:
  - The positive potential difference provided by the cell (24 V)
  - The negative potential difference across the light bulb connected in series with the cell (2 V)

$$V_3 = (24 - 2)\text{ V} = 22\text{ V}$$

The potential difference readings of the three voltmeters are:

- $V_1 = 10$ V
- $V_2 = 7$ V
- $V_3 = 22$ V

YOUR NOTES

Exam Tip

Kirchhoff's first and second laws are given in the data booklet, so you do not need to memorise them. However, you need to apply them to both simpler and more complex circuits.

5.2.4 I-V Characteristics

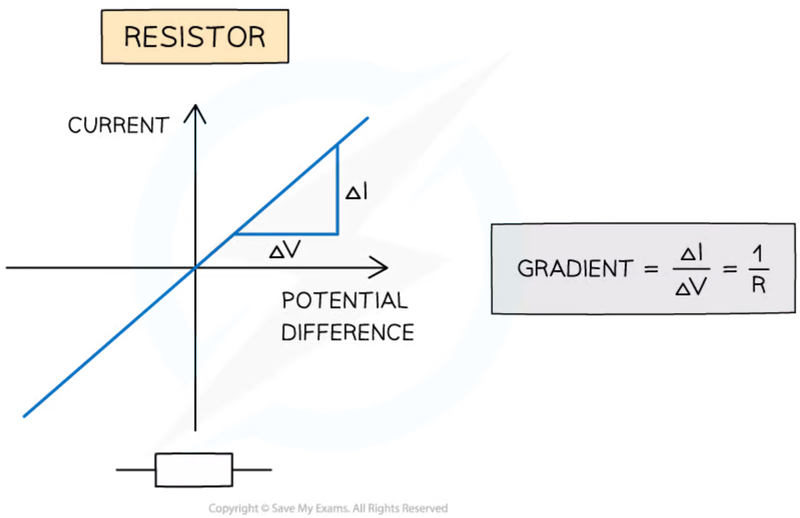
YOUR NOTES

Ohm's Law

- Ohm's law states that:

  For a conductor at a constant temperature, the current through it is proportional to the potential difference across it

- An electrical component obeys Ohm's law if its graph of current against potential difference is a **straight line** through the origin
  - A **fixed resistor** obeys Ohm's law - i.e. it is an **ohmic** component
  - A **filament lamp** does **not** obey Ohm's law - it is a **non-ohmic** component



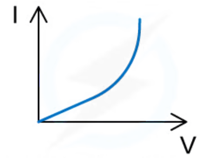
The current-voltage graph for a fixed resistor is a straight line through the origin. The fixed resistor is an ohmic component

- The resistance of an ohmic component can be calculated from the gradient of its current-voltage graph
  - Since resistance is $R = V/I$
  - $\boldsymbol{R = 1/gradient}$

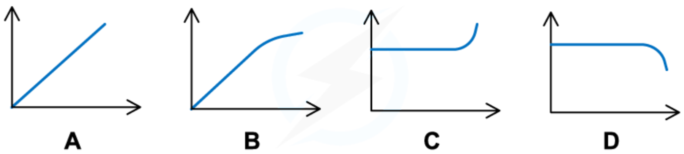
YOUR NOTES
⬇

Worked Example

The current flowing through a component varies with the potential difference *V* across it as shown.



Which graph best represents how the resistance *R* varies with *V*?



ANSWER: D

Step 1: Write down the equation for the resistance *R*

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

Step 2: Link the resistance to the gradient of the graph

- *Gradient = I/V*

$$R = 1/gradient$$

Step 3: Identify the gradient of different sections of the graph and use it to deduce what happens to the resistance

- The first straight section of the graph has a constant gradient
  - So the resistance remains constant
- The second section is curved and the steepness of the line increases, so the gradient increases
  - So the resistance decreases

Step 4: Identify the correct graph out of the four proposed

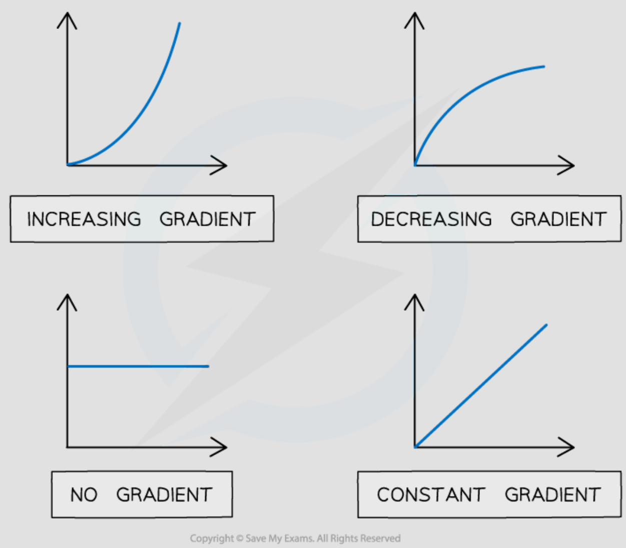
- Constant resistance is indicated by a straight horizontal line
  - So either C or D are correct
- Decreasing resistance is indicated by a line curving downwards
  - So only D is correct

YOUR NOTES
⬇

Exam Tip

When solving problems about Ohm's law you will often deal with graphs. You need to be confident identifying and calculating their gradients.

- In maths, the gradient is the **slope** of the graph (i.e. rise/run)
- The graphs below show a summary of how the slope of the graph represents the gradient



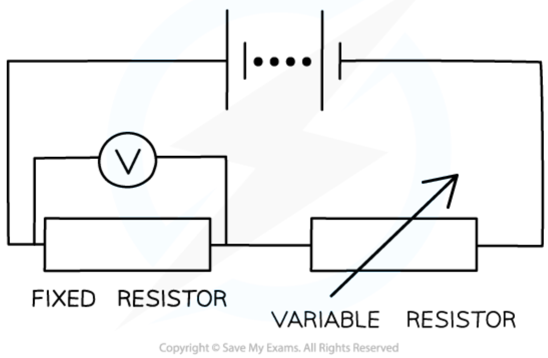
I-V Characteristics

YOUR NOTES
⬇

- The *I*-*V* characteristics of a circuit component is a graph of the current flowing through the component plotted against the voltage across it

Obtaining *I*-*V* Characteristics Experimentally

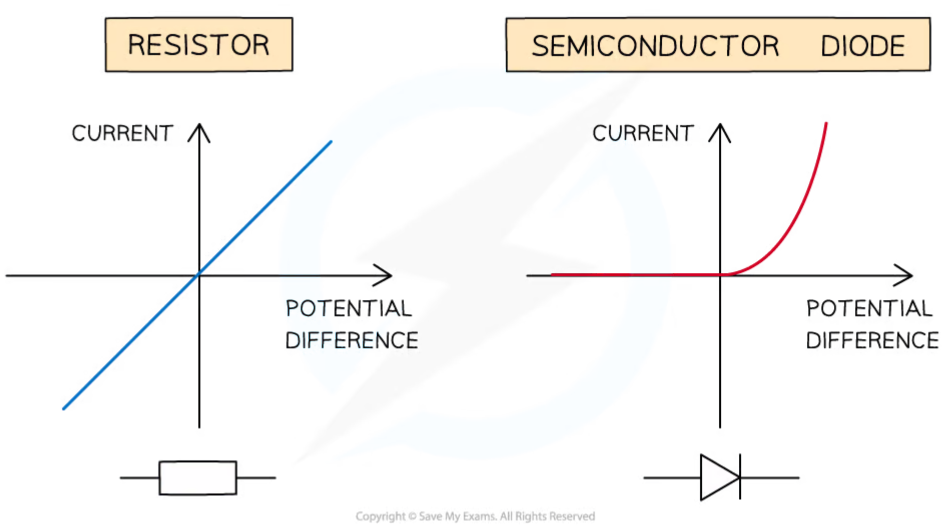
- The relation between potential difference across an electrical component (e.g. a fixed resistor) and current can be investigated through a circuit such as the one below



Circuit for plotting graphs of current against voltage. The component being investigated here is a fixed resistor

- By adjusting the resistance on the variable resistor:
  - The current in the circuit will change
  - For each value of the current *I*, the potential difference *V* can be recorded
- A graph of current against potential difference can be plotted

I-*V* Graphs of Some Circuit Components



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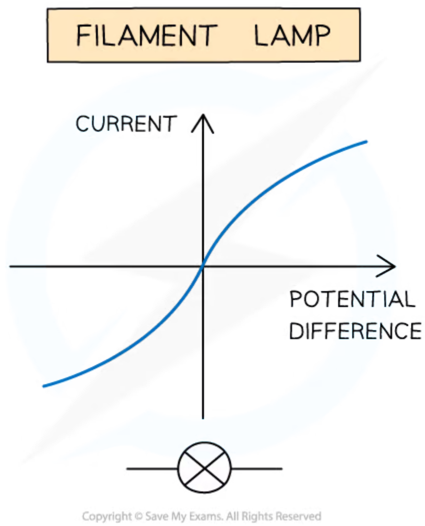

I–V characteristics for an ohmic conductor (e.g. resistor), semiconductor diode and filament lamp

Ohmic Conductor

- Current is directly proportional to potential difference
- The *I-V* graph is a **straight line** through the origin

Semiconductor Diode

- When the current is in the direction of the arrowhead symbol, the diode is said to be **forward biased**
  - There is a sharp increase in current
  - This is shown on the right side of the graph
- When the diode is switched around, it does not conduct and it is said to be **reverse biased**
  - The current through the diode is zero
  - This is shown on the left side of the graph
- The diode is a **non-ohmic** component
  - Its *I-V* graph is not a straight line through the origin

Filament Lamp

- For **very small voltages**, the filament lamp behaves as an **ohmic** component
  - The middle section of the graph (around zero voltage) is straight and passes through the origin
- As voltage increases:
  - More current flows through the filament lamp and the temperature of the filament in the lamp increases
  - The higher the temperature of the filament, the higher its resistance
  - Since resistance opposes current, the **current flows** through the filament **at a slower rate**
  - This is shown by the curved section of the graph

- For slightly **higher voltages**, the filament lamp is **non-ohmic**
  - The *I*-*V* graph is a curve with decreasing gradient

YOUR NOTES ↓

Exam Tip

Make sure you're confident in drawing the *I*–*V* characteristics for different components, as you may be asked to sketch these from memory or to identify those given in exam questions

5.2.5 Resistivity

YOUR NOTES
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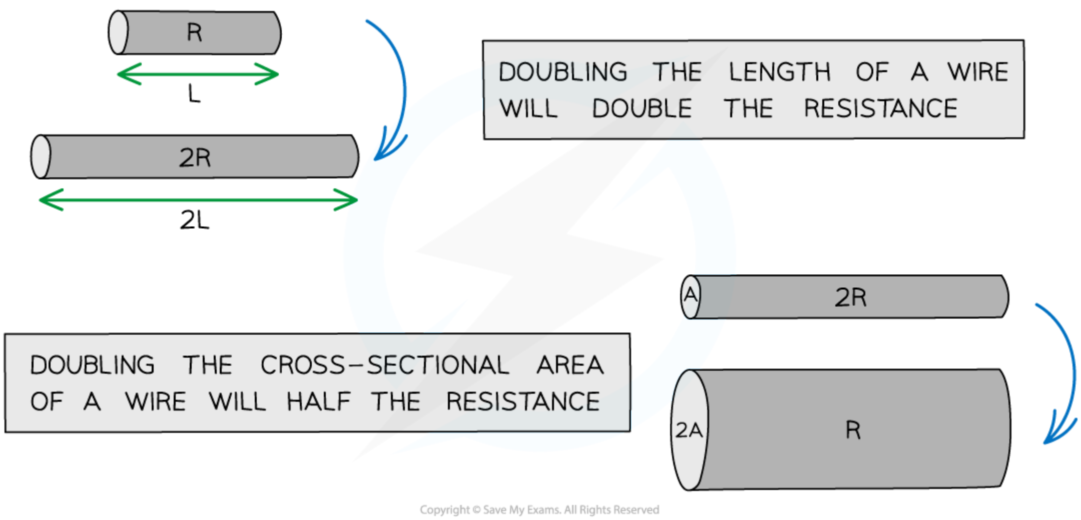
Resistivity

Resistance, Length and Cross-Sectional Area

- The **resistance** of a sample depends on:
  - The material it is made of
  - The length of the sample
  - The cross-sectional area of the sample

- The resistance of a conductor (e.g. a wire) is:
  - **Directly proportional** to its **length**
  - **Inversely proportional** to its **cross-sectional area**



How the length and width of a wire affect its resistance

Defining Resistivity

- This leads to the definition of a new quantity, called **resistivity**
- Resistivity is a property describing the extent to which a material opposes the flow of electric current through it
- It is defined as follows:

The resistivity of a material is equal to the resistance per unit length of a material with unit cross-sectional area

- The equation for the resistivity is:

$$\rho = \frac{RA}{L}$$

- Where:
  - ρ = resistivity in ohm-metres (Ω m)
  - R = resistance in ohms (Ω)
  - A = cross sectional area of material in square metres (m^2)

YOUR NOTES
↓

- L = length of material in meres (m)

Resistivity of Conductors and Insulators

- Resistivity is dependent on **temperature**
  - In **conductors**, the resistivity **increases** with increasing temperature
  - In **insulators**, the resistivity **decreases** with increasing temperature
- Since $\rho \propto R$, when a wire or the filament inside a lamp heat up, their resistance increases

Resistivity of some materials at room temperature

	Material	Resistivity ρ/Ωm
Metals	Copper	1.7×10^{-8}
	Gold	2.4×10^{-8}
	Aluminium	2.6×10^{-8}
Semiconductors	Germanium	0.6
	Silicon	2.3×10^{3}
Insulators	Glass	10^{12}
	Sulfur	10^{15}

- Conductors have the lowest values of resistivity
- Wires are made from copper because of its relatively low resistivity at room temperature
- Insulators have such a high resistivity that virtually no current will flow through them

YOUR NOTES
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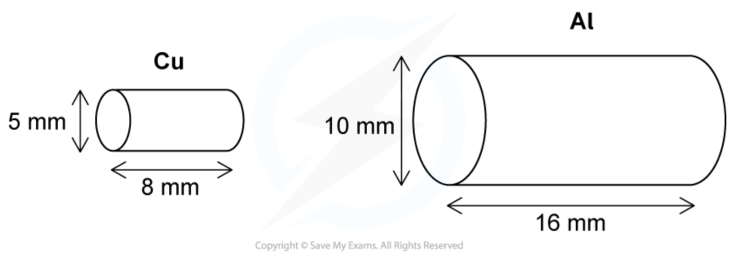
Worked Example

Two electrically-conducting cylinders made from copper and aluminium respectively.

Their dimensions are shown below.



Copper resistivity = 1.7×10^{-8} Ω m

Aluminium resistivity = 2.6×10^{-8} Ω mDetermine which cylinder is a better conductor.

Step 1: Write down the known quantities

- Copper (Cu):
  - Diameter, d_{Cu} = 5 mm = 5×10^{-3} m
  - Length, L_{Cu} = 8 mm = 8×10^{-3} m
  - Resistivity, $\rho_{Cu} = 1.7 \times 10^{-8}$ Ω m
- Aluminium (Al):
  - Diameter, d_{Al} = 10 mm = 10×10^{-3} m
  - Length, L_{Al} = 16 mm = 16×10^{-3} m
  - Resistivity, $\rho_{Al} = 2.6 \times 10^{-8}$ Ω m

Step 2: A conductor is better if it has a lower resistance

Step 3: Write down the equation for resistivity

$$\rho = \frac{RA}{L}$$

Step 4: Rearrange the above equation to calculate the resistance *R*

$$R = \frac{\rho L}{A}$$

Step 5: Substitute the numbers into the above equation to calculate the resistance of copper R_{Cu} and the resistance of aluminium R_{Al}

- The cross-sectional area *A* is calculated from the diameter *d* as follows:
  - $A = \pi(d/2)^2$

$$R_{Cu} = \frac{\left(1.7 \times 10^{-8}\right) \times \left(8 \times 10^{-3}\right)}{\pi\left(2.5 \times 10^{-3}\right)^2}$$

$$R_{Al} = \frac{(2.6 \times 10^{-8}) \times (16 \times 10^{-3})}{\pi(5.0 \times 10^{-3})^2}$$

YOUR NOTES

Step 6: Compare the two values of the resistance

- The cylinder with the lower resistance is the better conductor

$$R_{Cu} = 6.9 \times 10^{-6}\,\Omega$$

$$R_{Al} = 5.3 \times 10^{-6}\,\Omega$$

$$R_{Al} < R_{Cu}$$

The aluminium cylinder is the better conductor.

Exam Tip

You won't need to memorise the value of the resistivity of any material, these will be given in the exam question. The equation for resistivity is given in the data booklet.Remember, if the cross-sectional area is a circle (e.g. in a wire), it is proportional to the diameter squared. This means if the diameter doubles, the area quadruples causing the resistance to drop by a quarter.

YOUR NOTES
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Investigating Resistivity

Aims of the Experiment

- The aim of the experiment is to determine the resistivity of a 2 metre constantan wire

Variables:

- Independent variable = Length, *L*, of the wire (m)
- Dependent variable = The current, *I*, through the wire (A)
- Control variables:
  - Voltage through the wire
  - The material the wire is made from

Equipment List

Equipment	Purpose
Ammeter	To determine the current through the wire
Voltmeter	To determine the voltage across the wire
2.0 m of constantan wire (22–36 swg)	To calculate its resistivity
Flying lead	A wire with a crocodile clip at one end to allow connection at any point along the test wire
Metre ruler	To measure the length of the wire
Micrometer	To measure the diameter of the wire
Power supply	To provide the voltage through the wire

- Resolution of measuring equipment:
  - Metre ruler = 1 mm
  - Micrometer screw gauge = 0.01 mm
  - Voltmeter = 0.1 V
  - Ammeter = 0.01 A

Method

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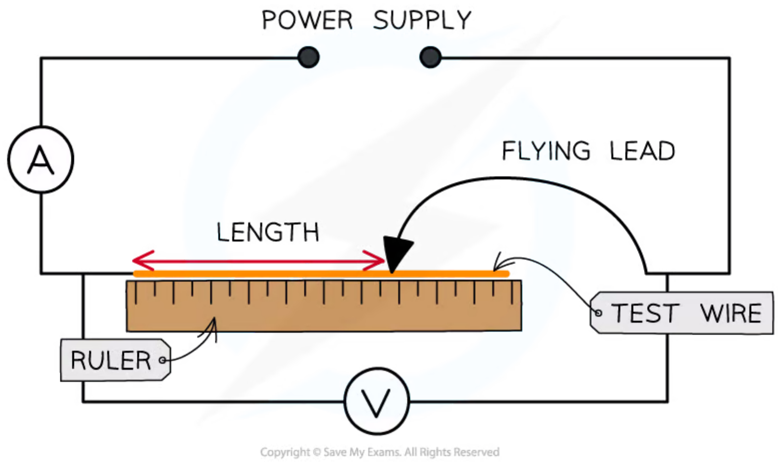


1. Measure the diameter of the constantan wire using a micrometer. The measurement should be taken between 5–10 times randomly along the wire. Calculate the mean diameter from these values
2. Set up the equipment so the wire is taped or clamped to the ruler with one end of the circuit attached to the wire where the ruler reads 0. The ammeter is connected in series and the voltmeter in parallel to the wire
3. Attach the flying lead to the test wire at 0.25 m and set the power supply at a voltage of 6.0 V. Check that this is the voltage through the wire on the voltmeter
4. Read and record the current from the ammeter, then switch off the current immediately after the reading (the short wire will get very hot)
5. Vary the distance between the fixed end of the wire and the flying lead in 0.25 m intervals (0.25 m, 0.50 m, 0.75 etc.) until the full length of the 2.0 m wire. The original length and the intervals can be changed (e.g. start at 0.1 m and increase in 0.1 m intervals), as long as there are 8–10 readings
6. Record the current for each length at least 3 times and calculate an average current, *I*
7. For each length, calculate the average resistance of the length of the wire using the equation

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

where *V* is the voltage and *I* is the average current through the wire for that length

- An example of a table of results might look like this:

YOUR NOTES ↓

LENGTH OF WIRE L/m	CURRENT I_1/A	CURRENT I_2/A	CURRENT I_3/A	AVERAGE CURRENT I/A	RESISTANCE R/Ω
0.25					
0.50					
0.75					
1.00					
1.25					
1.50					
1.75					
2.00					

Analysis of Results

- The resistivity, ρ, of the wire is equal to

$$\rho = \frac{RA}{L}$$

- Where:
  - ρ = resistivity (Ω m)
  - R = resistance (Ω)
  - A = cross-sectional area of the wire (m^2)
  - L = length of wire (m)

- Rearranging for the resistance, R:

$$R = \frac{\rho L}{A}$$

- Comparing this to the equation of a straight line: y = mx
  - y = R
  - x = L
  - Gradient = ρ / A

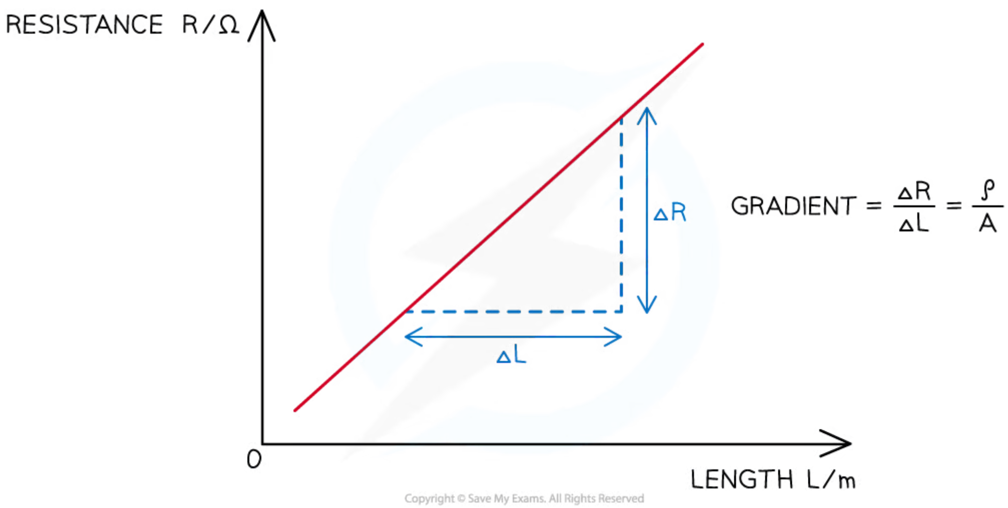
- The resistivity can therefore be calculated from the gradient of the resistance against length graph, multiplied by the cross-sectional area of the wire

1. Calculate the cross-sectional area, A, of the wire

$$\text{Cross-sectional area } A = \frac{\pi d^2}{4}$$

2. Plot a graph of the length of the wire, L, against the average resistance of the wire, R3. Draw a line of best fit and calculate the gradient of this graph4. Calculate the resistivity ρ by multiplying the gradient by the cross-sectional area A

$$\rho = \text{gradient} \times A$$



Evaluating the Experiment

Systematic Errors:

- The end of the wire that is attached to the circuit (not the flying lead) must start at 0 on the ruler
  - Otherwise, this could cause a zero error in your measurements of the length

Random Errors:

- Only allow small currents to flow through the wire
  - The resistivity of a material depends on its temperature. The current flowing through the wire will cause its temperature to increase and affect its resistance and resistivity. Therefore the temperature is kept constant and low by small currents
- The current should be switched off between readings so its temperature doesn't change its resistance
- Make at least 5–10 measurements of the diameter of the wire with the micrometer screw gauge and calculate an average diameter to reduce random errors in the reading

Safety Considerations

- When there is a high current, and a thin wire, the wire will become very hot. Make sure never to touch the wire directly when the circuit is switched on
- Switch off the power supply right away if you smell burning
- Make sure there are no liquids close to the equipment, as this could damage the electrical equipment

YOUR NOTES
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Worked Example

A student wants to find the resistivity of a constantan wire. They set up the experiment by attaching one end of the wire to a circuit with a 6.0 V battery and the other with a flying lead and measure the length with a ruler. Attaching the flying lead onto the wire at different lengths, they obtain the following table of results.

Length of wire L / m	Current I_1 / A	Current I_2 / A	Current I_3 / A	Average Current I / A	Resistance R / Ω
0.25	1.34	1.34	1.35		
0.50	0.85	0.85	0.83		
0.75	0.51	0.51	0.50		
1.00	0.35	0.36	0.35		
1.25	0.30	0.31	0.31		
1.50	0.27	0.27	0.27		
1.75	0.23	0.21	0.21		
2.00	0.18	0.17	0.18		

The following additional data for the wire is:

										Average diameter / mm
0.19	0.19	0.20	0.19	0.18	0.19	0.20	0.18	0.20	0.19	0.19

Calculate the resistivity of the wire

Step 1: Complete the average current and resistance columns in the table

The resistance is calculated using the equation

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

Length of wire L / m	Current I_1 /A	Current I_2 /A	Current I_3 /A	Average Current I /A	Resistance R / Ω
0.25	1.34	1.34	1.35	1.34	4.48
0.50	0.85	0.85	0.83	0.84	7.14
0.75	0.51	0.51	0.50	0.51	11.76
1.00	0.35	0.36	0.35	0.35	17.14
1.25	0.30	0.31	0.31	0.31	19.35
1.50	0.27	0.27	0.27	0.27	22.22
1.75	0.23	0.21	0.21	0.22	27.27
2.00	0.18	0.17	0.18	0.18	33.33

Step 2: Calculate the cross-sectional area of the wire from the diameter

- The average diameter is 0.191 mm = 0.191×10^{-3} m
- The cross-sectional area is equal to

$$A = \frac{\pi\left(0.191 \times 10^{-3}\right)^2}{4} = 2.87 \times 10^{-8}\ m^2$$

Step 3: Plot a graph of the length L against the resistance R

YOUR NOTES
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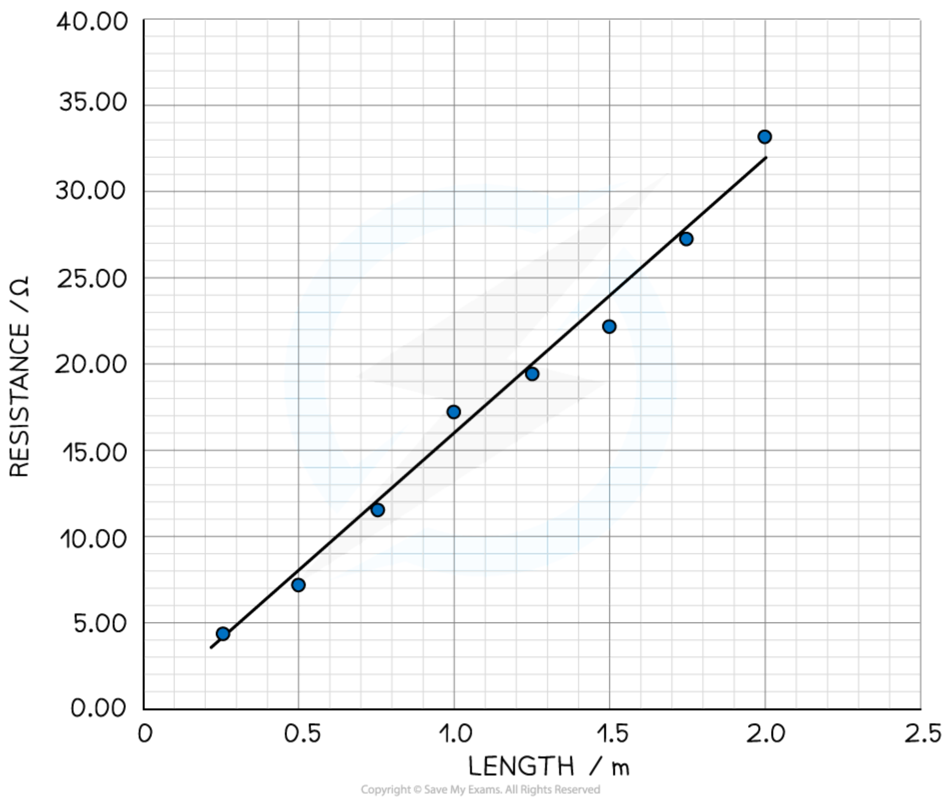

YOUR NOTES
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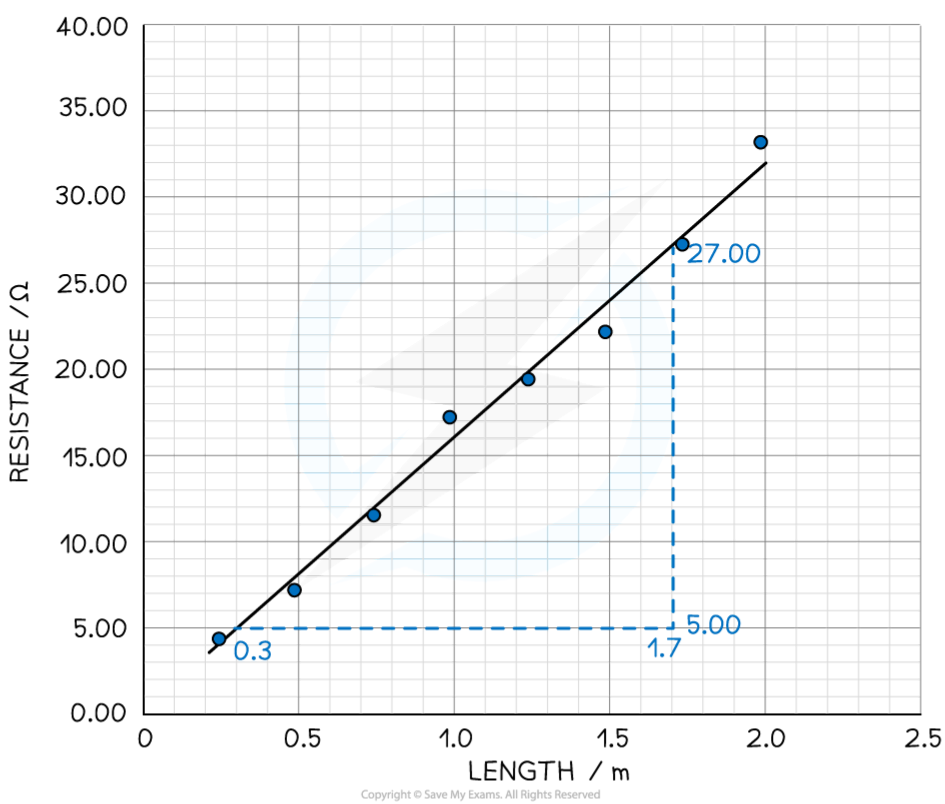
Step 4: Calculate the gradient of the graph



$$\frac{\Delta R}{\Delta L} = \frac{\rho}{A} = \frac{27.00\text{-}5.00}{1.7\text{-}0.3} = \frac{110}{7}$$

Step 5: Calculate the resistivity of the wire

$$\rho = \text{gradient} \times A = \frac{110}{7} \times (2.87 \times 10^{-8}) = 4.51 \times 10^{-7}\ \Omega\text{m}$$

YOUR NOTES
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5.2.7 Series & Parallel Circuits

YOUR NOTES
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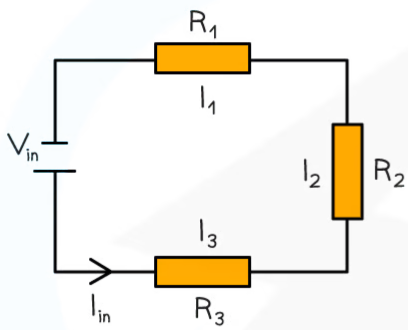
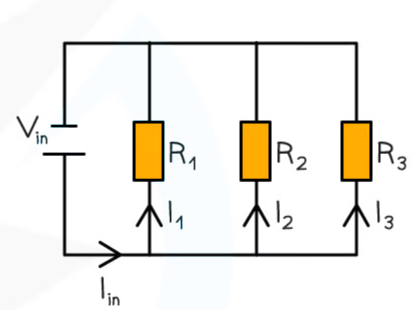
Series & Parallel Circuits

- The following statements for series and parallel circuits are a consequence of Kirchhoff's first and second law
- In a **series** circuit:
  - The current is the same at any point
  - The potential difference is split across all components depending on their resistance
- In a **parallel** circuit:
  - The total current is equal to the sum of the currents in each parallel branch of the circuit
  - The potential difference across each loop is the same

Series and Parallel Circuit Rules

- The table below summarises the rules for calculating current, potential difference (i.e. voltage) and resistance within series and parallel circuits

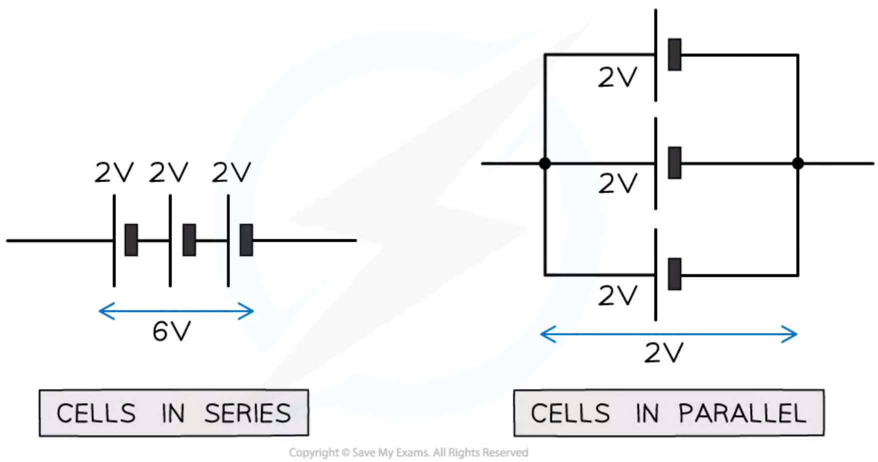
	Series	Parallel
Circuit		
Voltage	$V_{in} = V_1 + V_2 + V_3$	$V_{in} = V_1 = V_2 = V_3$
Current	$I_{in} = I_1 = I_2 = I_3$	$I_{in} = I_1 + I_2 + I_3$
Resistance	$R_{total} = R_1 + R_2 + R_3$	$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

Advantages of Parallel Circuits

- Parallel circuits are incredibly useful for home wiring systems
  - A single power source supplies all lights and appliances with the same potential difference
  - If one light breaks, current can still flow through the rest of the lights and appliances

Series and Parallel Cells

- Cells can also be connected in series or parallel
  - If the cells are connected in **series**, the total potential difference between the ends of the chain of cells is the sum of the potential difference across each cell
  - If the cells are connected in **parallel**, the total potential difference across the arrangement is the same as for one cell



YOUR NOTES

5.2.8 Heating Effect of Current

YOUR NOTES

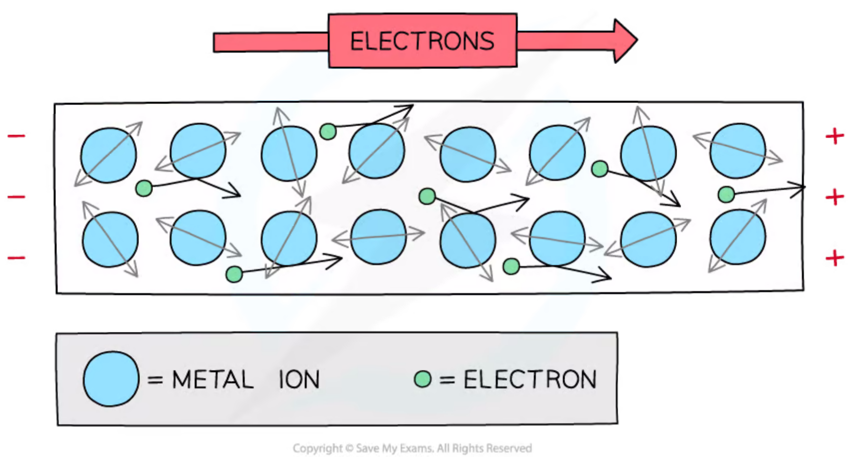
Heating Effect of Current

- When electricity passes through a component, such as a resistor, some of the electrical energy is turned into heat, therefore, increasing its temperature
  - The heat that is produced will dissipate (spread out) into the environment via thermal conduction, convection and radiation

- When electricity passes through a component, there is energy transferred to **heat**
- This is due to **collisions** between:
  - **Electrons** flowing in the conductor, and
  - The **lattice of atoms** within the metal conductor

- Electricity, in metals, is caused by a **flow of electrons**
  - This is called the **current**

- Metals are made up of a **lattice** of ions
- As the electrons pass through the metal lattice they **collide** with ions
  - The ions **resist** the flow of the electrons



As electrons flow through the metal, they collide with ions, making them vibrate more

- When the electrons collide, they lose some energy by giving it to the ions, which start to vibrate **more**
  - As a result of this, the metal **heats up**

- This is used to an advantage to generate heat for appliances such as electric hobs

YOUR NOTES
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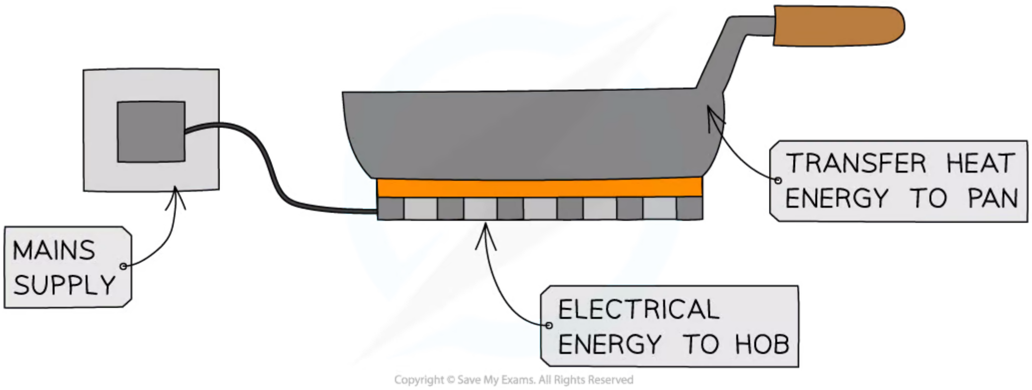

The heating effect of current can be used for many applications such as electric hobs

Power Dissipation

YOUR NOTES
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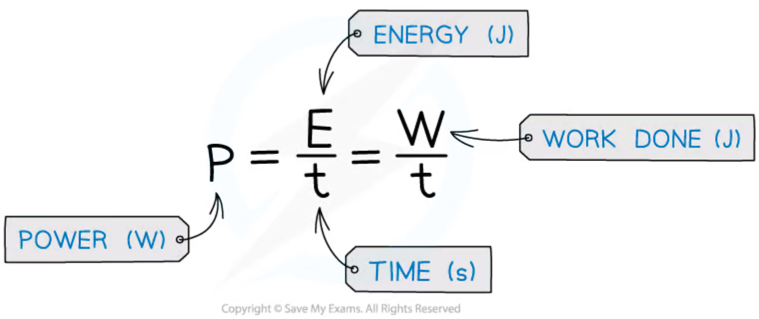
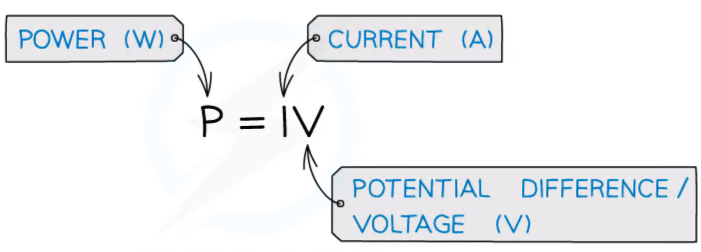
- When an electrical current does work against electrical resistance:
  - Electrical energy is **dissipated as thermal energy** in the surroundings
  - The heat that is produced will dissipate via thermal conduction, convection and radiation
- The amount of heat produced depends on two factors:
  - **Current:** The greater the current, the more heat that is produced
  - **Resistance:** The higher the resistance, the more heat that is produced (for a given current)
- Note that reducing the resistance can cause the current to increase
  - This could actually **increase** the amount of heat produced
- In mechanics, power *P* is defined as the **rate of doing work**
  - The potential difference is the **work done per unit charge**
  - Current is the **rate of flow of charge**
- Therefore, the electrical power is defined as the **rate of change of work done**:



- The work done is the energy transferred so the power is the **energy transferred per second** in an electrical component
- The power dissipated (produced) by an electrical device can also be written as



- Using Ohm's Law $\boldsymbol{V = IR}$ to rearrange for either *V* or *I* and substituting into the power equation, means power can be written in terms of resistance *R*

YOUR NOTES
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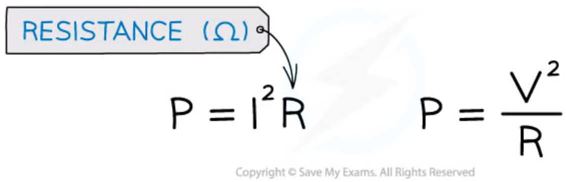


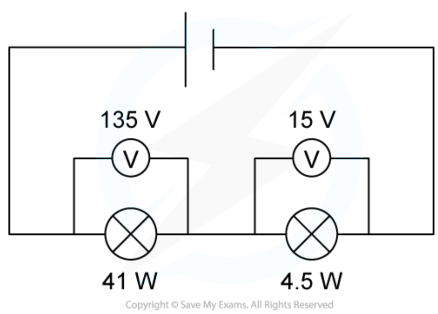
- This means for a given resistor if the current or voltage **doubles** the power will be **four** times as great.
  - Which equation to use will depend on whether the value of current or voltage has been given in the question
- Rearranging the energy and power equation, the energy can be written as:

$$E = VIt$$

- Where:
  - E = energy transferred (J)
  - V = voltage (V)
  - I = current (A)
  - t = time (s)

Worked Example

Two lamps are connected in series to a 150 V power supply.



Which statement most accurately describes what happens?**A.** Both lamps light normally

B. The 15 V lamp blows

C. Only the 41 W lamp lights
D. Both lamps light at less than their normal brightness

ANSWER: A

YOUR NOTES
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STEP 1	CALCULATE CURRENT NEEDED FOR BOTH LAMPS TO OPERATE $P = IV$
STEP 2	REARRANGE FOR I $I = \frac{P}{V}$
STEP 3	FOR THE 41 W LAMP: $I = \frac{41\ W}{135\ V} = 0.3\ A$ FOR THE 4.5 W LAMP: $I = \frac{4.5\ W}{15\ V} = 0.3\ A$
STEP 4	FOR BOTH TO OPERATE AT THEIR NORMAL BRIGHTNESS, A CURRENT OF 0.3 A IS REQUIRED. SINCE THE LAMPS ARE CONNECTED IN SERIES, THE SAME CURRENT WOULD FLOW THROUGH BOTH.
STEP 5	THE LAMPS WILL LIGHT AT THEIR NORMAL BRIGHTNESS – OPTION A

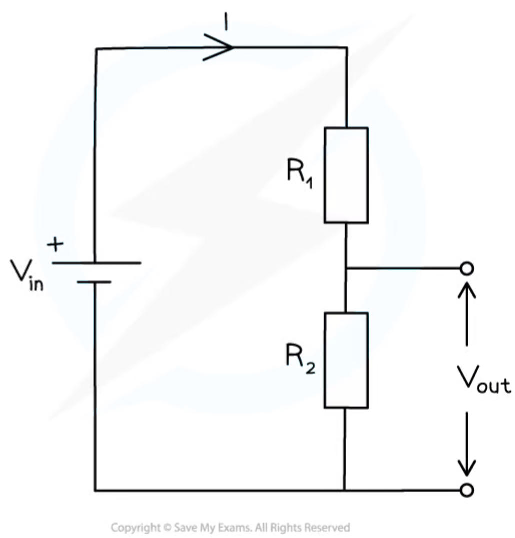
5.2.9 Potential Divider Circuits

YOUR NOTES

Potential Divider Circuits

- When two resistors are connected in series, through Kirchhoff's Second Law, the potential difference across the power source is divided between them
- Potential dividers are circuits that can produce an output voltage as a **fraction** of its input voltage
- The main purposes of a potential divider are:
  - To provide a **variable** potential difference
  - To enable a **specific** potential difference to be chosen
  - To **split** the potential difference of a power source between two or more components
- Potential dividers have a wide range of applications in devices requiring features such as volume control and sensory circuits
  - This can be achieved using components such as LDRs and thermistors
- Potential divider circuits are based on the **ratio** of voltage between components
- This is equal to the ratio of the resistances of the resistors in the diagram below, giving the following equation:

POTENTIAL DIVIDER EQUATION: $V_{out} = \frac{R_2}{R_1 + R_2} V_{in}$



Potential divider diagram and equation

- The input voltage V_{in} is applied to the top and bottom of the series resistors
- The output voltage V_{out} is measured from the centre to the bottom of resistor R_2
- The potential difference *V* across each resistor depends upon its resistance *R*:
  - The resistor with the **largest resistance** will have a **greater potential difference** than the other one from *V* = *IR*

YOUR NOTES
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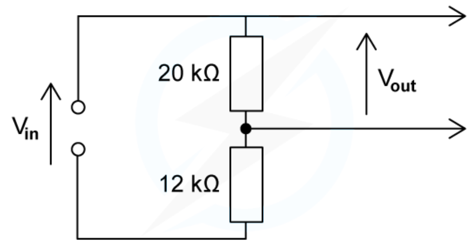
- If the resistance of one of the resistors is increased, it will get a greater share of the potential difference, whilst the other resistor will get a smaller share

- In potential divider circuits, the p.d across a component is proportional to its resistance from *V* = *IR*

Worked Example

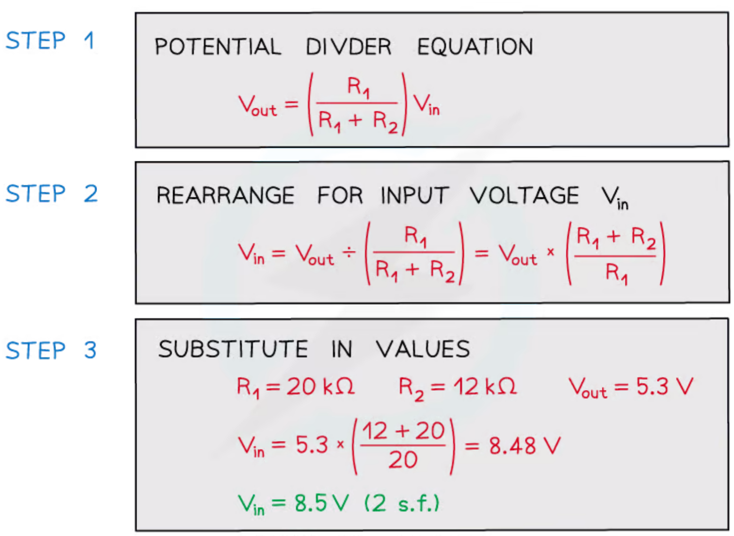
The circuit is designed to light up a lamp when the input voltage exceed a preset value.

It does this by comparing V_{out} with a fixed reference voltage of 5.3 V.



V_{out} is equal to 5.3

Calculate the input voltage V_{in}.



Exam Tip

Always make sure the correct resistance is in the numerator of the potential divider equation. This will be the resistance of the component you want to find the output voltage of.

5.3 Electric Cells

5.3.1 Primary & Secondary Cells

YOUR NOTES
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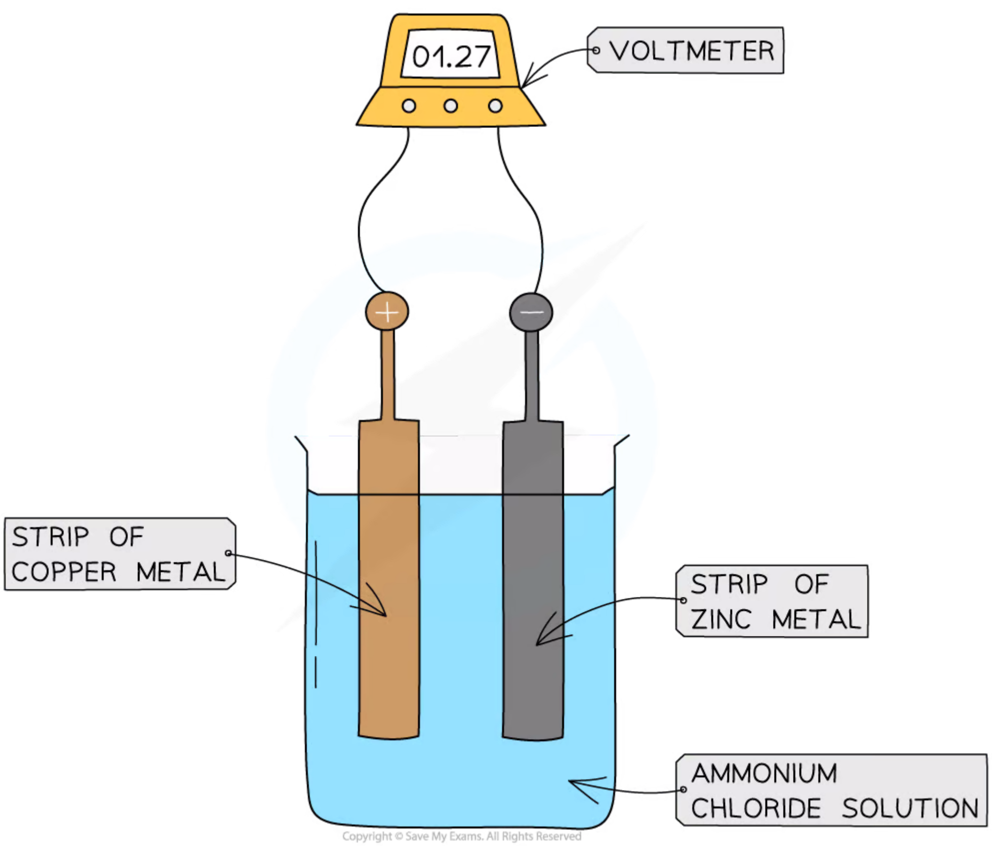
Primary & Secondary Cells

Simple Cells

- A simple cell is a source of electrical **energy**
- The simplest design consists of two electrodes made from metals of **different reactivity** immersed in an electrolyte and connected to an external voltmeter by wire, creating a complete circuit
- A common example is zinc and copper
- Zinc is the more reactive metal and forms ions more easily, readily **releasing electrons**
- The electrons give the more **reactive electrode** a **negative** charge and sets up a **charge difference** between the electrodes
- The electrons then flow around the circuit to the copper electrode which is now the more **positive** electrode
- The **difference** in the ability of the electrodes to release electrons causes a voltage to be produced
- The greater the difference in the metals **reactivity** then the greater the **voltage** produced
- The electrolyte used also affects the voltage as different ions react with the electrodes in different ways



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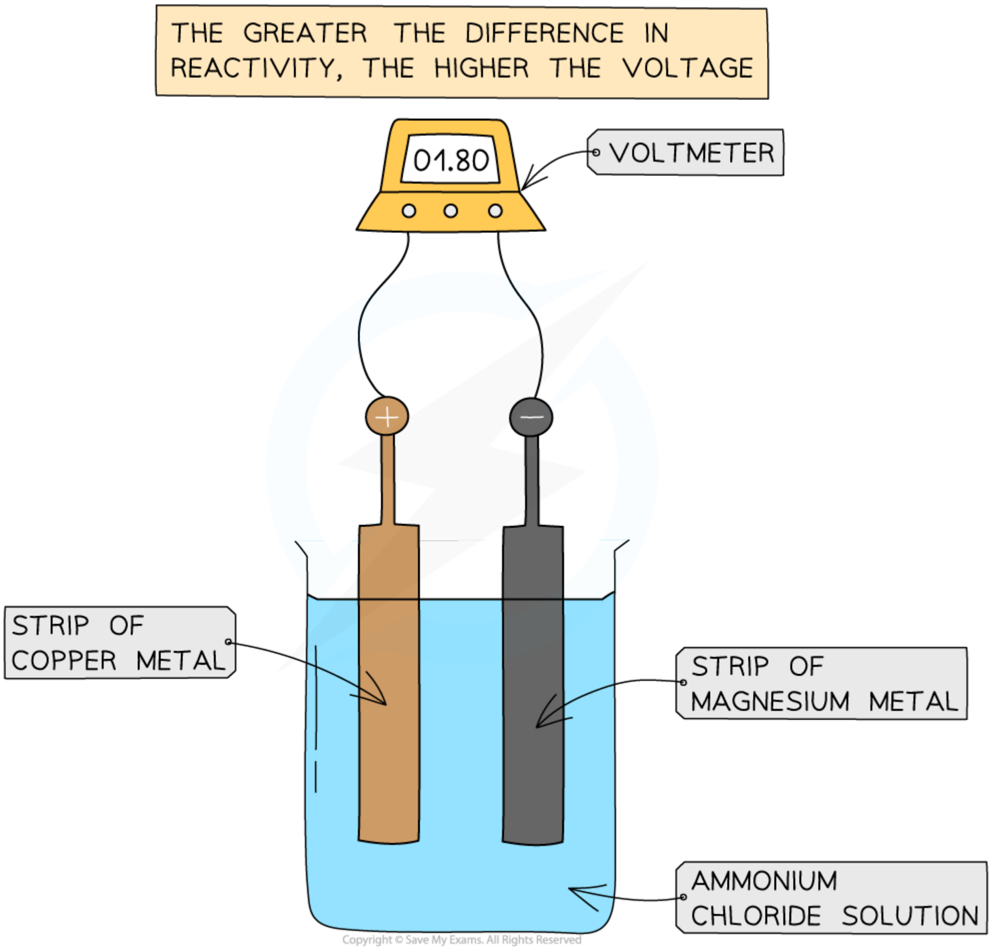

Simple cell made with Cu and Mg. These metals are further apart on the reactivity series than Cu and Zn and produce a greater voltage

Batteries

- Electrochemical cells include the familiar **batteries** used in everyday appliances and cars
- Batteries work by connecting two or more cells in **series**, which combine to give a larger overall voltage
- Over time the electrodes **degrade** as the reactions that occur there are **irreversible**
- Cells produce a voltage only until one of the reactants is used up and when this occurs the battery dies or goes flat
- The products formed cannot be reverted back into reactants as the reaction is irreversible and the battery must be replaced
- This happens in **non-rechargeable** batteries such as **alkaline** batteries
- In rechargeable batteries the reactions are **reversed** by connecting the cells to an external electrical supply
- This reverses the chemical reactions taking place allowing the cycle to be repeated

Primary Cells

YOUR NOTES
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- Cells that are **non-rechargeable** are known as **primary cells**
  - Primary cells include AA batteries (known as dry-cells) common in many small devices
- Primary cells are by definition only able to be **used once** as the chemicals within them are used up
- During normal operation of a primary cell, the electrons flow **from** the **negative** plate to the **positive** plate of the cell

Secondary Cells

- Cells that are **rechargeable** are known as **secondary cells**
  - Secondary cells include:
    - Lithium-ion batteries used in laptops and other larger modern devices
    - Lead-acid batteries such as those used in cars and other motor vehicles
- Secondary cells can be **used many times** as they are attached to a charger and the **chemical reaction** is **reversed** allowing the cells to store energy for use once again
- When **recharging** a secondary cell, the electrons are forced from the **positive** plate to the **negative** plate by an external current

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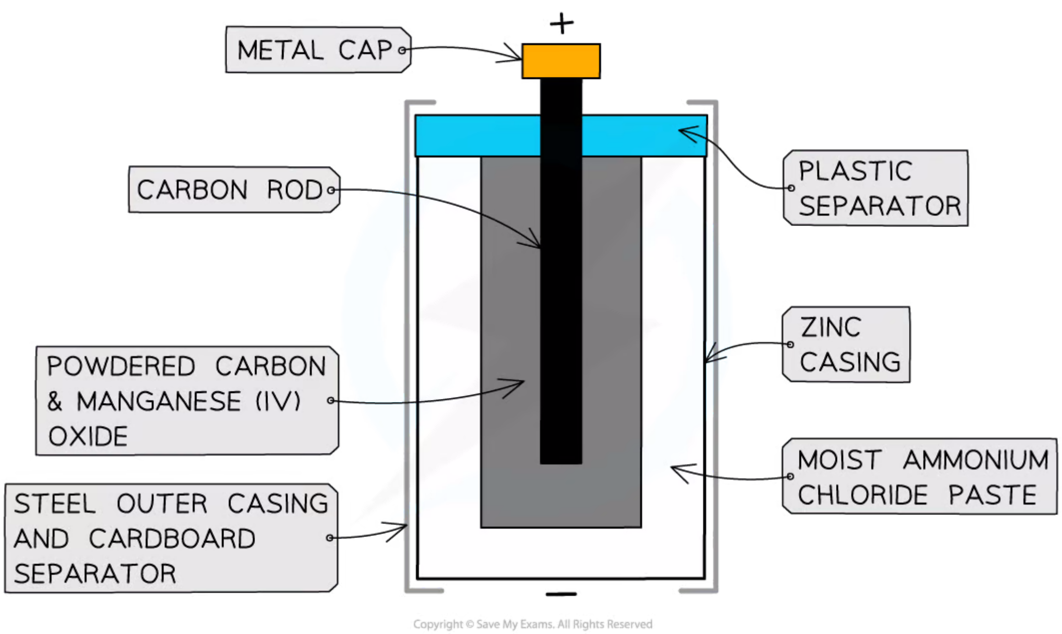
Investigating Electric Cells

Zinc-carbon cells

- Zinc-carbon cells are the most common type of **primary cells**, consisting of
  - a zinc casing which acts as the **negative electrode**
  - a paste of ammonium chloride which acts as an **electrolyte** as well as the **positive electrode**
  - a carbon rod which acts as an **electron carrier** in the cell



The zinc-carbon cell

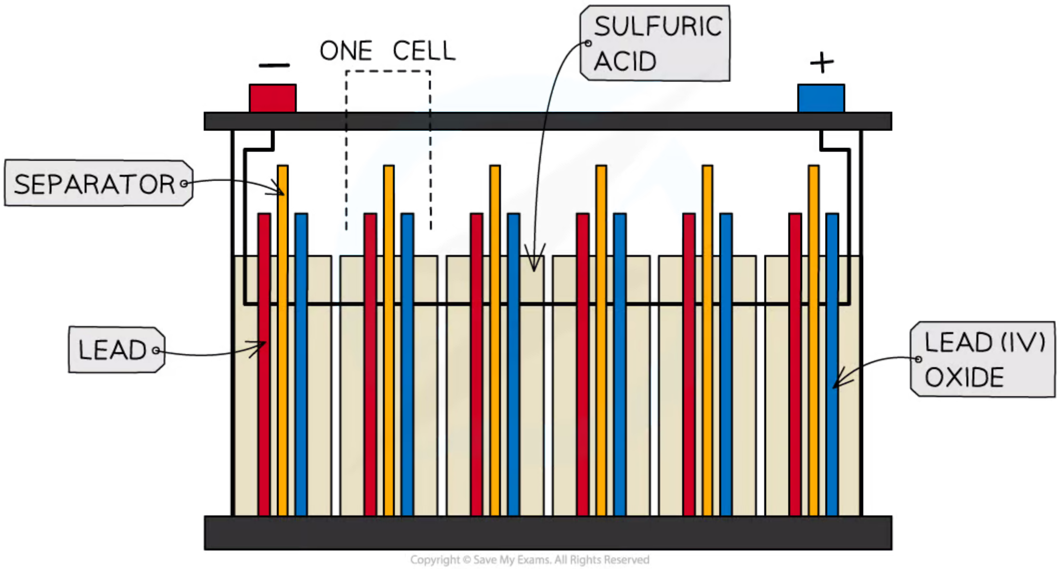
- These cells are the commonly found AA and AAA and other similar battery types
- As the cell discharges, the zinc casing eventually wears away and the corrosive contents of the electrolyte paste can **leak out**, which is an obvious **disadvantage** of zinc-carbon cells
- The cell provides a **small current** and is relatively **cheap** compared to other cells
- Extra-long **life cells** have similar chemistry, but supply a **higher current** and use **zinc chloride** in the paste; they are suitable for torches, radios, and clocks
- Another variation on the cell uses an **alkaline paste** in the electrolyte and they have a much **longer** operating **life** but are noticeably **more expensive** than regular zinc-carbon cells

Secondary Cells

Lead-acid batteries

- Lead-acid batteries consist of **six cells** joined together **in series**
- The cells use **lead** metal as the **negative electrode** and **lead(IV) oxide** as the **positive electrode**
- The electrolyte is sulfuric acid

YOUR NOTES



A lead-acid battery

- When the car is in motion, the generator provides a push of electrons that reverses the reaction and regenerates lead and lead(IV) oxide
- Lead-acid batteries are designed to produce a **high current** for a short period of time, hence their use in powering a starter motor in car engines
- The disadvantage of lead-acid batteries is that:
  - They are very **heavy**
  - They contain **toxic** materials: lead and lead(IV) oxide
  - The sulfuric acid electrolyte is very **corrosive**
- This presents challenges of disposal when lead-acid batteries come to the end of their useful life

Lithium Cells

- Lithium ion cells power the laptop or mobile device you are probably reading this on
- The Noble Prize for Chemistry in 2019 was awarded to John B. Goodenough, M. Stanley Whittingham and Akira Yoshino for their work on lithium ion cells that have **revolutionized** portable electronics
- Lithium is used because it has a very **low density** and relatively **high electrode potential**
- The cell consists of:
  - a positive lithium cobalt oxide electrode
  - a negative carbon electrode
  - a porous polymer membrane electrolyte
- The polymer electrolyte cannot leak since it is not a liquid or paste, which presents advantages over other types of cells

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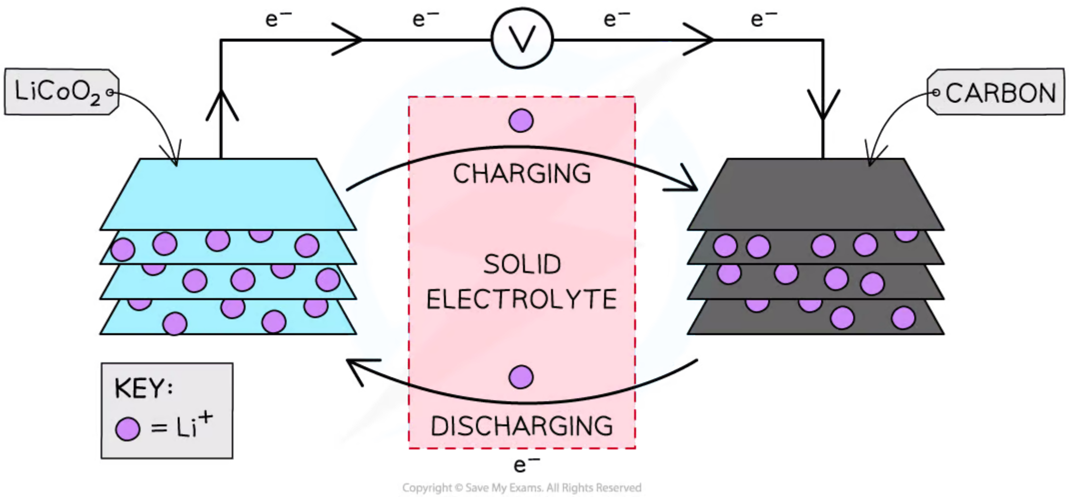

Lithium ion cell

- The cell consists of a sandwich of different layers of **lithium cobalt oxide** and **carbon**
- When the cell is charged and discharged the lithium ions flow between the negative and the positive through the solid electrolyte
- The half-cell reactions on discharge are:

$Li(s) \rightarrow Li^+(s) + e^-$ $\quad$ $E = -3\ V$

$Li^+(s) + CoO_2(s) + e^- \rightarrow Li^+(CoO_2)^-(s)$ $\quad$ $E = +1\ V$

- The cell generates an emf of between 3.5 V and 4.0 V and the overall reaction is

$Li(s) + CoO_2(s) \rightarrow Li^+(CoO_2)^-(s)$ $\quad$ $E_{cell} \sim +3.5$

- NiCad cells have a **problem** called the **memory effect** in which they gradually begin to **lose their charge after repeated charge cycles** when the cell is not fully discharged. The cells appear to 'remember' their lower state of charge
- Lithium-ion cells **do not have this problem** so can be topped up without any loss of charge
- Some of the problems with lithium ion cells:
  - A **global shortage of lithium** is likely to make lithium ion cells unsustainable as the current demand for lithium exceeds the supply
  - If cells are not recycled but thrown away in landfills, then a huge amount of lithium becomes **lost** to future generations
  - Reports of lithium ion cell fires have raised concern about the safety of these batteries in electronic devices; it is a reminder to us that **lithium** is a **very reactive element** in Group 1 of the periodic table, which is why it has a high electrode potential

5.3.3 Terminal Potential Difference

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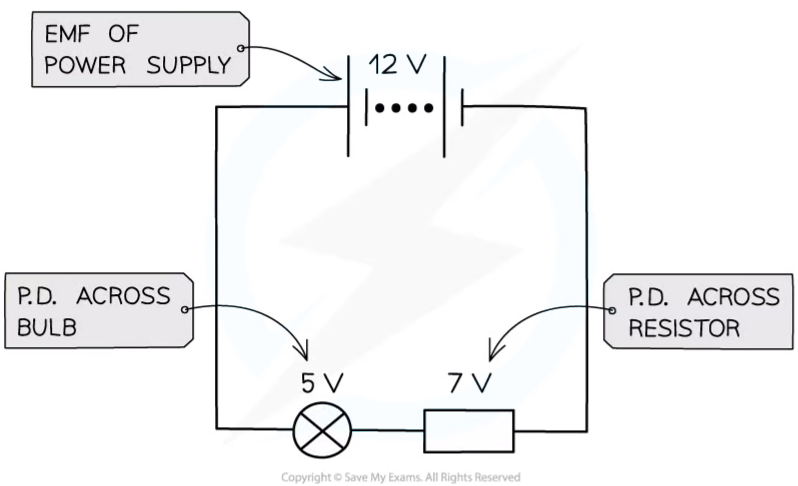
Terminal Potential Difference

Defining Potential Difference

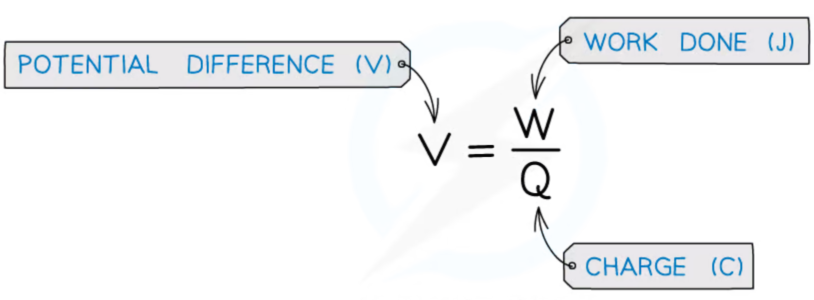
- A cell makes one end of the circuit positive and the other negative. This sets up a **potential difference *V*** across the circuit
- The potential difference across a component in a circuit is defined as the **energy transferred per unit charge flowing from one point to another**
- The energy transfer is from electrical energy into other forms
- Potential difference is measured in **volts (V)**. This is the same as a **Joule per coulomb (J C^{-1})**
    - If a bulb has a voltage of 3 V, every coulomb of charge passing through the bulb will transfer 3 J of energy
- The potential difference of a power supply connected in series is always shared between all the components in the circuit



The potential difference is the voltage across each component in a circuit

Calculating Potential Difference

- The potential difference is defined as the **energy transferred per unit charge**
- Another measure of energy transfer is work done
- Therefore, potential difference can also be defined as the **work done per unit charge**



$$V = \frac{W}{Q}$$

Potential difference is the work done per unit charge

YOUR NOTES
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Terminal Potential Differnce & Lost Volts

- The **terminal potential difference (p.d)** is the potential difference across the terminals of a cell
  - If there was no internal resistance, the terminal p.d would be equal to the e.m.f
- It is defined as:

$$V = IR$$

- Where:
  - V = terminal p.d (V)
  - I = current (A)
  - R = load resistance (Ω)
- If a cell has internal resistance r, the terminal p.d is always **lower** than the e.m.f
- If you have a load resistor R across the cell's terminals, then the terminal p.d V **is equal to** the p.d across the load resistor
- In a closed circuit, current flows through a cell and a potential difference develops **across the internal resistance**
- Since resistance opposes current, this reduces the energy per unit charge (voltage) available to the rest of the external circuit
- This difference is called the 'lost volts'
  - **Lost volts** is usually represented by little v
  - It is defined as the voltage **lost** in the cell due to internal resistance
  - So, from conservation of energy, we can say:

$$v = \text{e.m.f} - \text{terminal p.d}$$

$$\mathbf{v = \varepsilon - V = \mathit{Ir}} \text{ (Ohm's law)}$$

- Where:
  - v = lost volts (V)
  - I = current (A)
  - r = internal resistance of the battery (Ω)
  - ε = e.m.f (V)
  - V = terminal p.d (V)
- Therefore, lost volts is the **difference** between the e.m.f and the terminal p.d

Discharging a Cell

- When a cell is discharging, it will **not discharge** a **constant amount** of voltage
- Instead, an **initial high amount** that **slowly decreases** over time is discharged **ending** in a **rapid decrease**
  - This means that cells make a **distinctive discharge curve** with a drop, plateau and final rapid drop

YOUR NOTES
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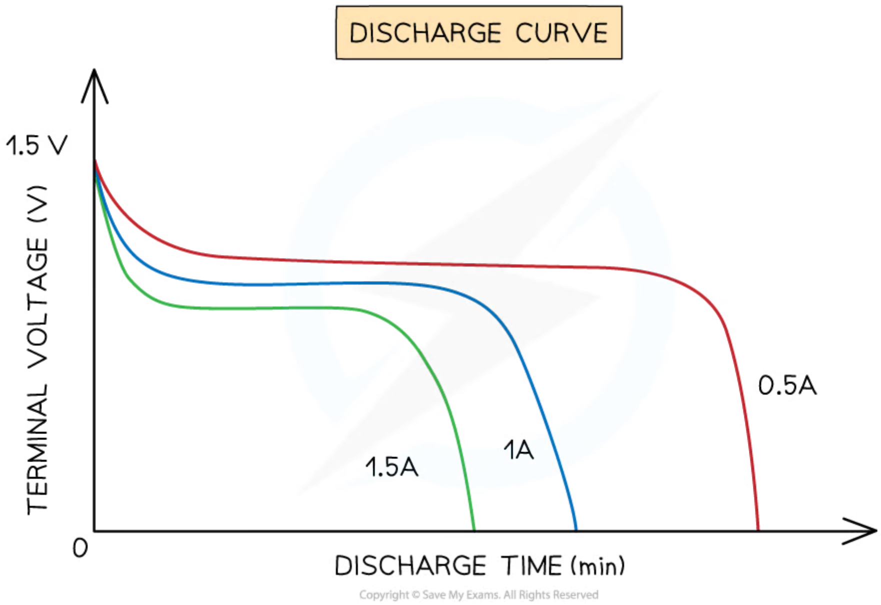


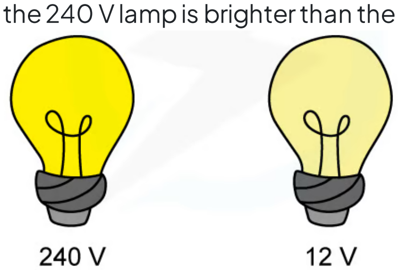
Typical discharge curves for a 1.5 V terminal cell showing discharge for a 0.5A, 1A and 1.5A drawing current

The Capacity of a Cell

- The **capacity** of a cell is the **amount of charge** that it contains and is **able to discharge**
- This is measured in Ampere hours (***A hr***)
- When a cell has a certain capacity the amount of **current drawn** from this cell will impact the amount of **time** that it can **run** for
    - In the image above three different drawing currents are shown for the same 1.5 V cells
- The relationship between current drawn and hours of cell lifetime is a simple **linear relationship**
- As an example: A 100 A.hr capacity battery is able to provide 100 hours of 1A current
- However, the same battery when fully charged can give 50 hours of charge for a 2A current or 25 hours for a 4A current

Worked Example

A lamp is connected to a 240 V mains supply and another to a 12 V car battery.Both lamps have the same current, yet 240 V lamp glows more brightly. Explain in terms of energy transfer why the 240 V lamp is brighter than the 12 V lamp.



YOUR NOTES
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ANSWER:

- Both lamps have the same current, which means charge flows at the same rate in both
- The 240 V lamp has 20 times more voltage than the 12 V lamp
- Voltage is the energy transferred (work done) per unit charge
- This means the energy transferred to each coulomb of charge in the 240 V lamp is 20 times greater than for the 12 V lamp
- This makes the 240 V lamp shine much brighter than the 12 V lamp

Exam Tip

- Think of potential difference as being the **energy per coulomb** of charge transferred between two points in a circuit
- If the exam question states 'a battery of negligible internal resistance', this assumes that e.m.f of the battery is equal to its voltage. Internal resistance calculations will not be needed here.
  - If the battery in the circuit diagram includes internal resistance, then the e.m.f equations must be used.

5.3.4 Electromotive Force & Internal Resistance

YOUR NOTES
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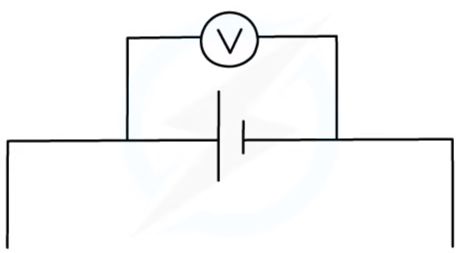
Electromotive Force

- When charge passes through a power supply such as a battery, it **gains** electrical energy
- The **electromotive force (e.m.f)** is the amount of **chemical** energy converted to **electrical** energy per **coulomb** of charge **(C)** when charge passes through a power supply
- e.m.f is measured in **Volts (V)**

$$\text{E.M.F.} = \frac{\text{ENERGY TRANSFORMED FROM OTHER FORMS TO ELECTRICAL}}{\text{CHARGE}}$$

Definition of e.m.f with regards to energy transfer

- e.m.f is also the potential difference across the cell when no current is flowing
- e.m.f can be measured by connecting a high-resistance voltmeter around the terminals of the cell in an open circuit



e.m.f is measured using a voltmeter connected in parallel with the cell

EMF & Potential Difference

- The difference between **potential difference** and **e.m.f** is the type of energy transfer per unit charge

$$\text{P.D.} = \frac{\text{ENERGY TRANSFORMED FROM ELECTRICAL TO OTHER FORMS}}{\text{CHARGE}}$$

Definition of potential difference with regards to energy transfer

- When charge passes through a resistor, for example, its electrical energy is converted to heat in the resistor
  - The resistor, therefore, has a **potential difference** across it

- Potential difference describes the loss of energy from charges; ie. when **electrical energy** is **transferred** to other forms of energy in a component
- e.m.f. describes the **transfer of energy** from the **power supply** to **electrical charges** within the circuit

YOUR NOTES

Exam Tip

Although voltage and potential difference are the same thing, make sure not to confuse them with e.m.f, which is slightly different!

YOUR NOTES
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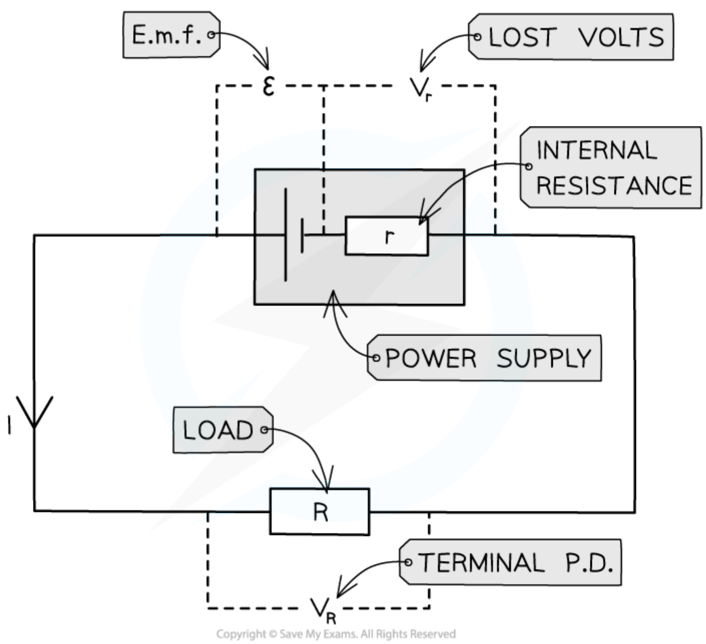
Internal Resistance

- All power supplies have some resistance between their terminals
  - This is called **internal resistance** (r)
- This internal resistance causes the charge circulating to dissipate some electrical energy from the power supply itself
  - This is why the cell becomes warm after a period of time
- The internal resistance therefore causes **loss of voltage** or energy loss in a power supply
- A cell can be thought of as a source of e.m.f with an internal resistance connected in series. This is shown in the circuit diagram below:



Circuit showing the e.m.f and internal resistance of a power supply

- Where:
  - Resistor R is the 'load resistor'
  - r is the internal resistance
  - ε is the e.m.f
  - V_r is the lost volts
  - V_R is the p.d across the load resistor, which is the same as the terminal p.d
- The e.m.f is the sum of these potential differences, giving the equation below

YOUR NOTES
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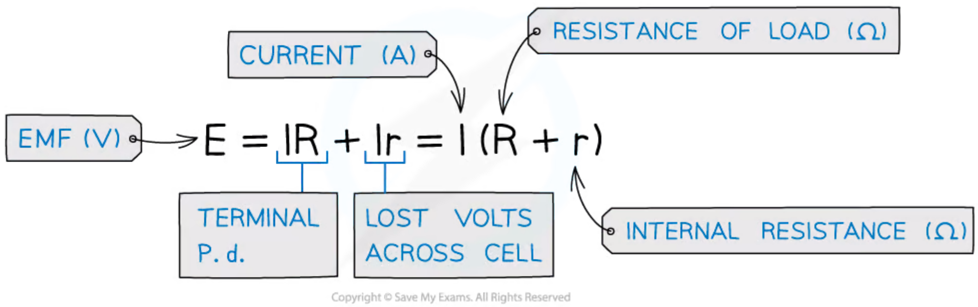
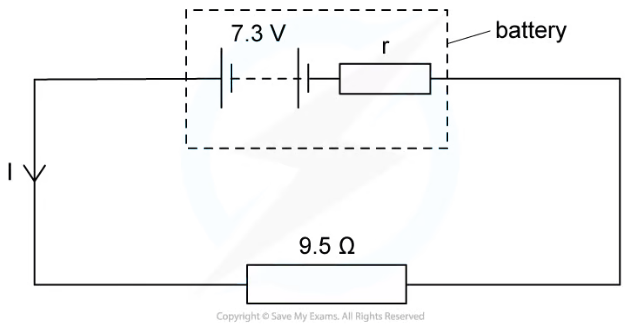


e.m.f equation

- e.m.f is therefore the total, or maximum, voltage available to the circuit

Worked Example

A battery of e.m.f 7.3 V and internal resistance r of 0.3 Ω is connected in series with a resistor of resistance 9.5 Ω.



Determine:

a) The current in the circuit

b) Lost volts from the battery

YOUR NOTES

a.)

STEP 1 — USING THE e.m.f EQUATION TO DETERMINE THE CURRENT I

$$E = I(R + r)$$

STEP 2 — REARRANGE FOR I

$$I = \frac{E}{(R + r)}$$

STEP 3 — SUBSTITUTE IN THE VALUES

$$I = \frac{7.3}{(9.5 + 0.3)} = 0.745... = 0.7\ A \quad (2\ s.f.)$$

b.)

STEP 1 — THE LOST VOLTS IS THE VOLTAGE LOST DUE TO INTERNAL RESISTANCE

$$LOST\ VOLTS = I \times r$$

STEP 2 — SUBSTITUTE IN THE VALUES

$$LOST\ VOLTS = 0.7 \times 0.3 = 0.21 = 0.2 \quad (2\ s.f.)$$

Determining Internal Resistance

Aims of the Experiment

The overall aim of the experiment is to investigate the relationship between e.m.f and internal resistance by measuring the variation of current and voltage using a variable resistor

Variables

- Independent variable = voltage, *V* (V) & current, *I* (A)
- Dependent variable = resistance, *R* (Ω)
- Control variables:
  - E.m.f of the cell
  - Internal resistance of the cell

Equipment List

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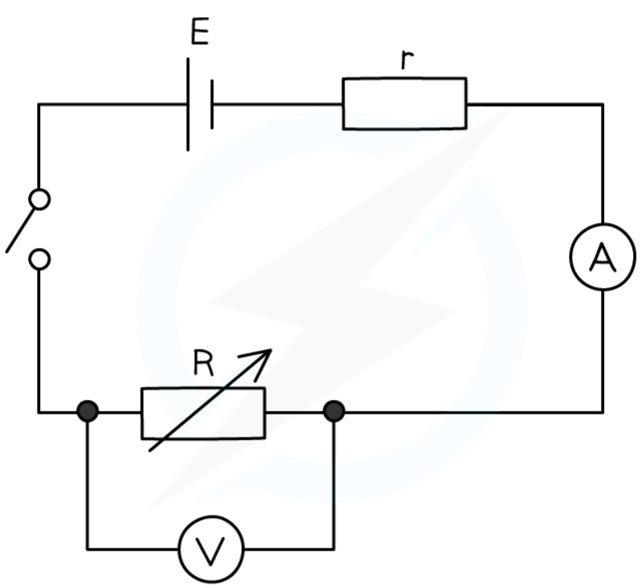
Apparatus	Purpose
1.5 V Cell	To provide an e.m.f. to the circuit
Resistor	Unknown resistance – to act as internal resistance
100Ω Variable Resistor	To change the values of current and voltage in the circuit
Voltmeter	0–2 V range – to measure voltage
Ammeter	0–200 mA range – to measure current
Wires	At least 6 leads – to make electrical connections
Switch	To open between readings to not run down the battery

- Resolution of measuring equipment:
  - Voltmeter = 1 mV
  - Ammeter = 0.1 mA

Method



1. The cell and the resistor, labelled *r*, should be connected in series and considered to be a single cell
2. With the switch open, record the reading *V* on the voltmeter

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3. Set the variable resistor to its maximum value, close the switch and record *V* and the reading *I* on the ammeter - make sure to open the switch between readings
4. Vary the resistance of the variable resistor up to a minimum of 8–10 readings and record values for *V* and *I* for each resistance. Ensure to take readings for the whole range of the variable resistor

- An example of a suitable table might look like this:

RESISTANCE OF VARIABLE RESISTOR · VOLTMETER READING · AMMETER READING

	1st READING		2nd READING		3rd READING		MEAN	
R / Ω	V / V	I / mA	V / V	I / mA	V / V	I / mA	V / V	I / mA
0								
10								
20								
30								
40								
50								
60								
70								
80								
90								
100								

Analysing the Results

- The relationship between e.m.f. and internal resistance is given by

$$\varepsilon = I(R + r)$$

- Where:
  - ε = electromotive force (V)
  - I = current (A)
  - R = resistance of the load in the circuit (Ω)
  - r = internal resistance of the cell (Ω)

- This can be simplified into the form:

$$\varepsilon = IR + Ir = V + Ir$$

- Rearranging this equation for *V*:

$$V = -rI + \varepsilon$$

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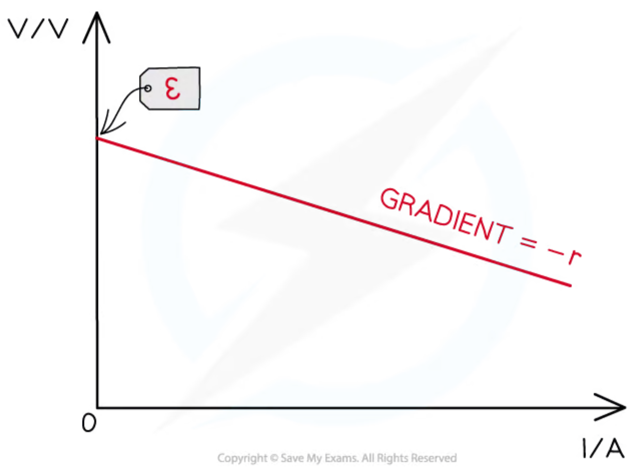
- Comparing this to the equation of a straight line: y = mx + c
  - y = V (V)
  - x = I (A)
  - Gradient = $-r$ (Ω)
  - Y-intercept = ε (V)

1. Plot a graph of V against I and draw a line of best fit
2. Measure the gradient of the graph and compare it with the manufacturer's value of the resistor
3. The y-intercept will be the e.m.f and the gradient will be the negative internal resistance:



Evaluating the Experiment

Systematic Errors:

- Only close the switch for as long as it takes to take each pair of readings
  - This will prevent the internal resistance of the battery or cell from changing during the experiment

Random Errors:

- Only use fairly new cells otherwise the e.m.f. and internal resistance of run-down batteries can vary during the experiment
- Wait for the reading on the voltmeter and ammeter to stabilise (stop fluctuating) before recording the values
- Take multiple repeat readings (at least 3) for each voltage and current and calculate a mean to reduce random errors

Safety Considerations

- This is a very safe experiment, however, electrical components can get hot when used for a long period
- Switch off the power supply right away if burning is smelled
- Make sure there are no liquids close to the equipment, as this could damage the electrical equipment

YOUR NOTES
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Worked Example

In an experiment, a student uses a variable resistor as an external load. The current flowing through the circuit is measured with a suitable milliammeter and the potential difference across the variable resistor is measured with a voltmeter for a range of resistance values. The data collected was as follows:

V / V	I / mA
1.60	0.0
1.30	13.1
1.14	20.0
0.96	28.2
0.80	35.2
0.65	41.5
0.49	48.8
0.38	53.4
0.23	60.3
0.10	66.0

Plot a graph of these results and determine the e.m.f. and the internal resistance directly from the graph.

Step 1: Plot the data on a graph of *V* against *I* and draw a line of best fit

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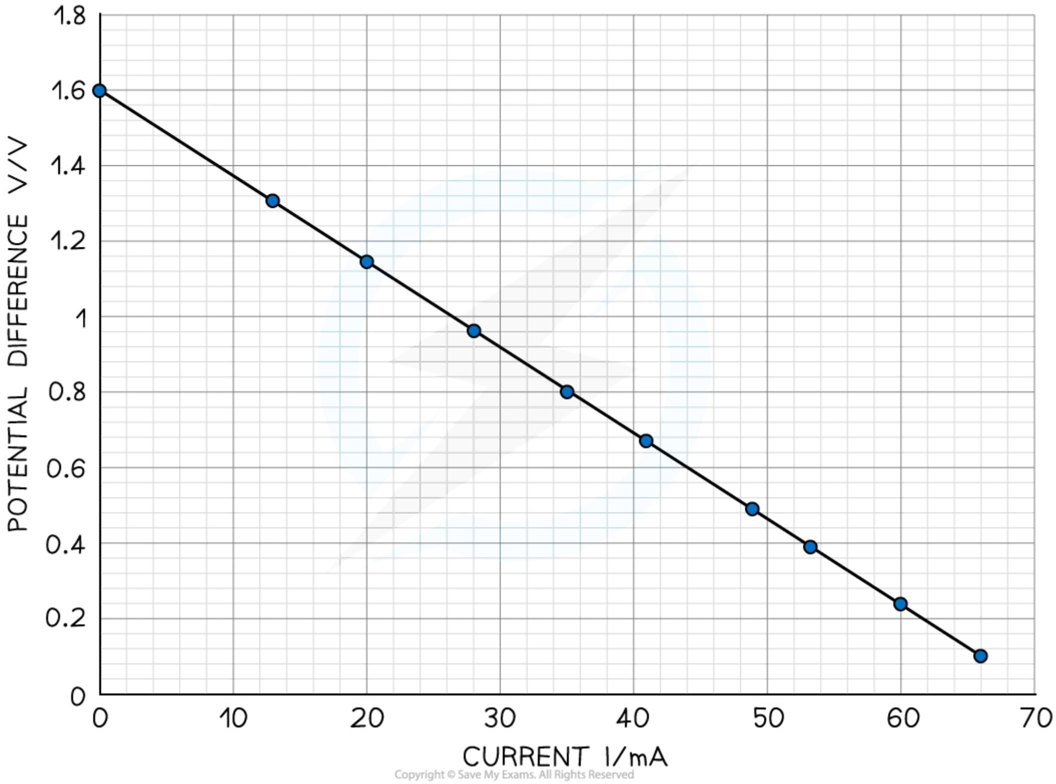
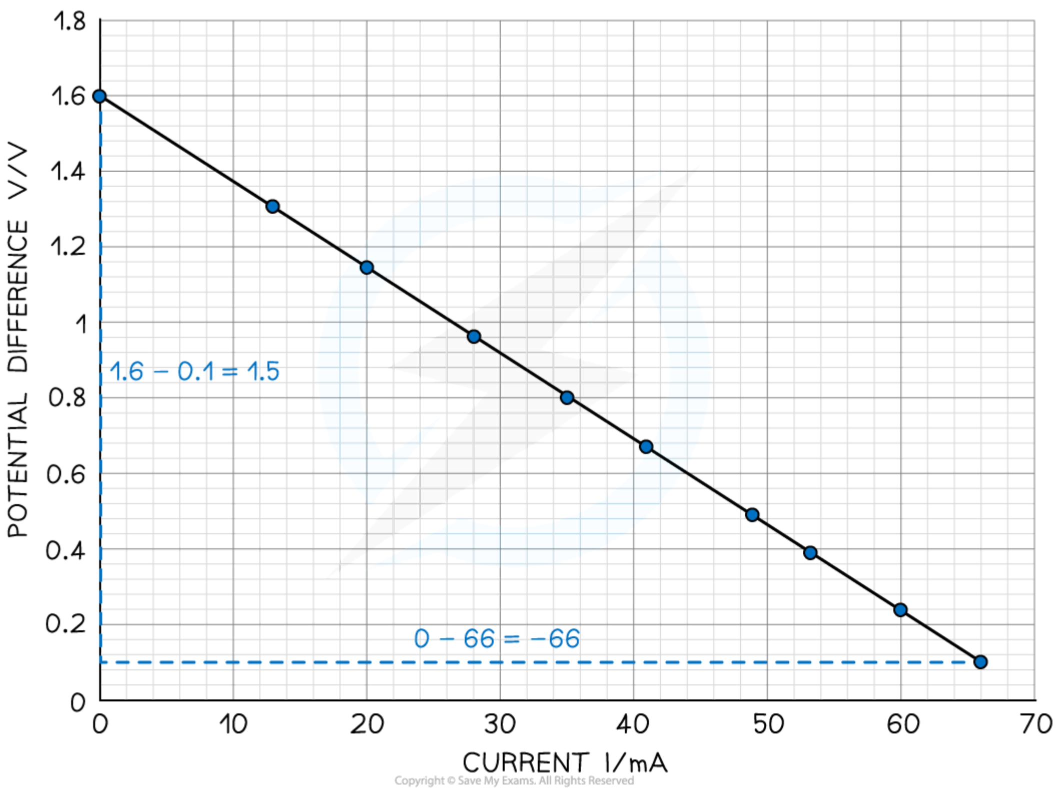


Step 2: Draw the largest triangle possible in order to calculate the gradient



$$\text{Gradient} = \frac{\Delta y}{\Delta x} = \frac{1.6 - 0.1}{-66 \times 10^{-3}} = -22.7\ \Omega\ (3\text{ s.f.})$$

Step 3: Determine the e.m.f. and the internal resistance from the graph

$$V = -rI + E$$

- From this equation:
  - Gradient = $-r$ (Ω)
  - Y-intercept = E (V)
- Therefore:
  - Internal resistance, r = 22.7 Ω
  - E.m.f. E = 1.60 V

YOUR NOTES
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YOUR NOTES
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5.4 Magnetic Effects of Electric Currents

5.4.1 Magnetic Fields

Magnetic Fields

Magnetic Field Definition

- A magnetic field is a **field of force** that is created either by:
  - **Moving** electric charge
  - **Permanent** magnets

- Permanent magnets are materials that produce a magnetic field
- A stationary charge will **not** produce a magnetic field
- A magnetic field is sometimes referred to as a **B-field**
- A magnetic field is created around a **current carrying wire** due to the movement of electrons
- Although magnetic fields are invisible, they can be observed by the force that pulls on magnetic materials, such as iron or the movement of a needle in a plotting compass

Representing Magnetic Fields

- Magnetic fields are represented by magnetic field lines
  - These can be shown using iron filings or plotting compasses

- Field lines are best represented on **bar magnets**, which consist of a north pole on one end and south pole on the other
- The magnetic field is produced on a bar magnet by the movement of electrons within the atoms of the magnet
- This is a result of the electrons circulating around the atoms, representing a tiny current and hence setting up a magnetic field
- The direction of a magnetic field on a bar magnet is always from **north to south**

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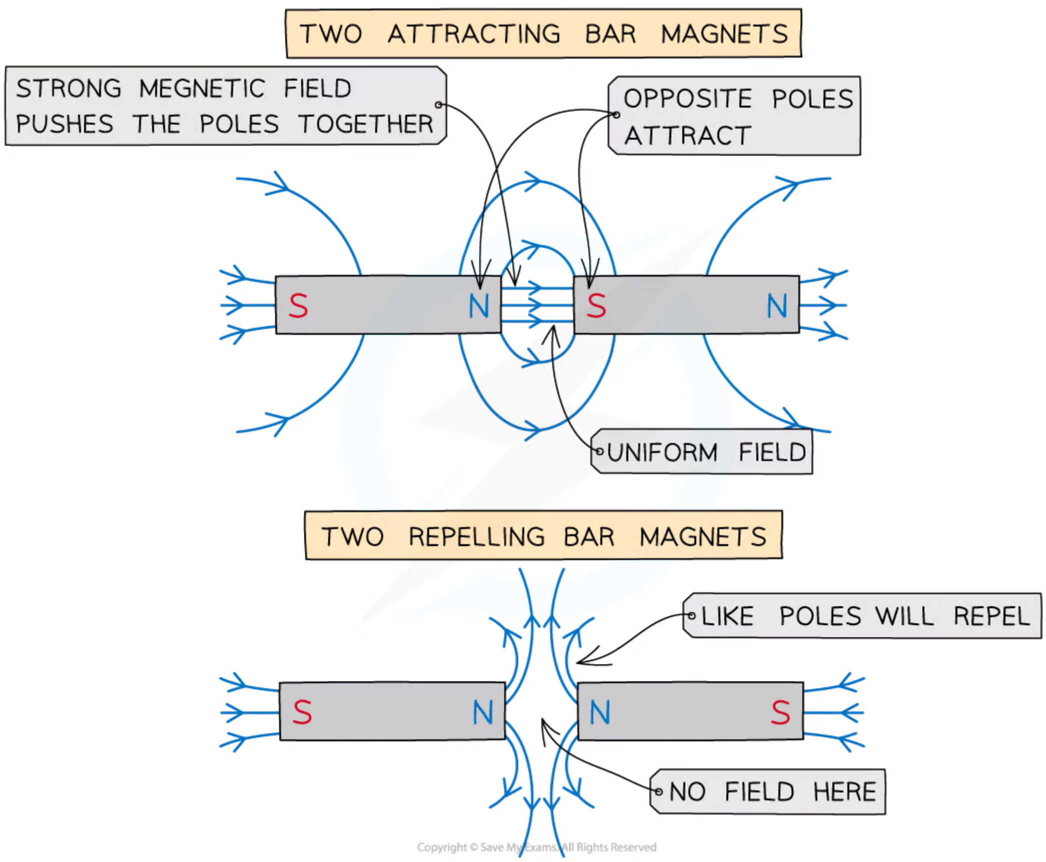
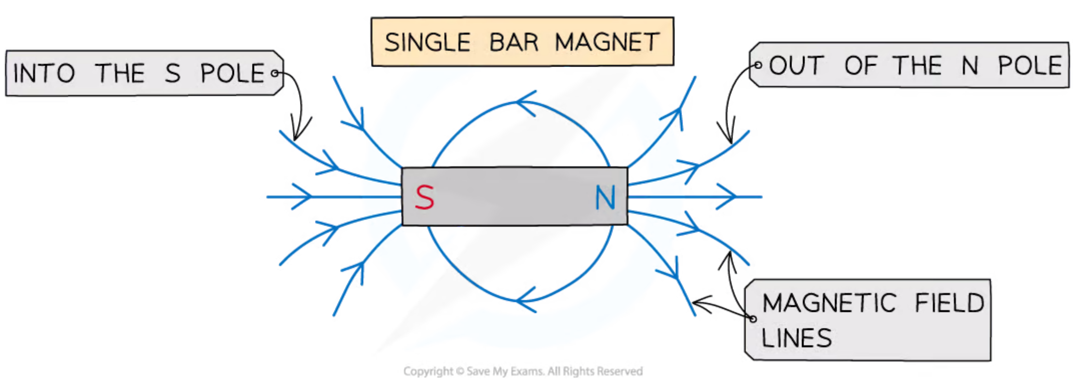


Magnetic field lines are directed from the north pole to the south pole

- When two bar magnets are pushed together, they either attract or repel each other:
  - Two **like** poles (north and north or south and south) **repel** each other
  - Two **opposite** poles (north and south) **attract** each other



Two opposite poles attract each other and two like poles repel each other

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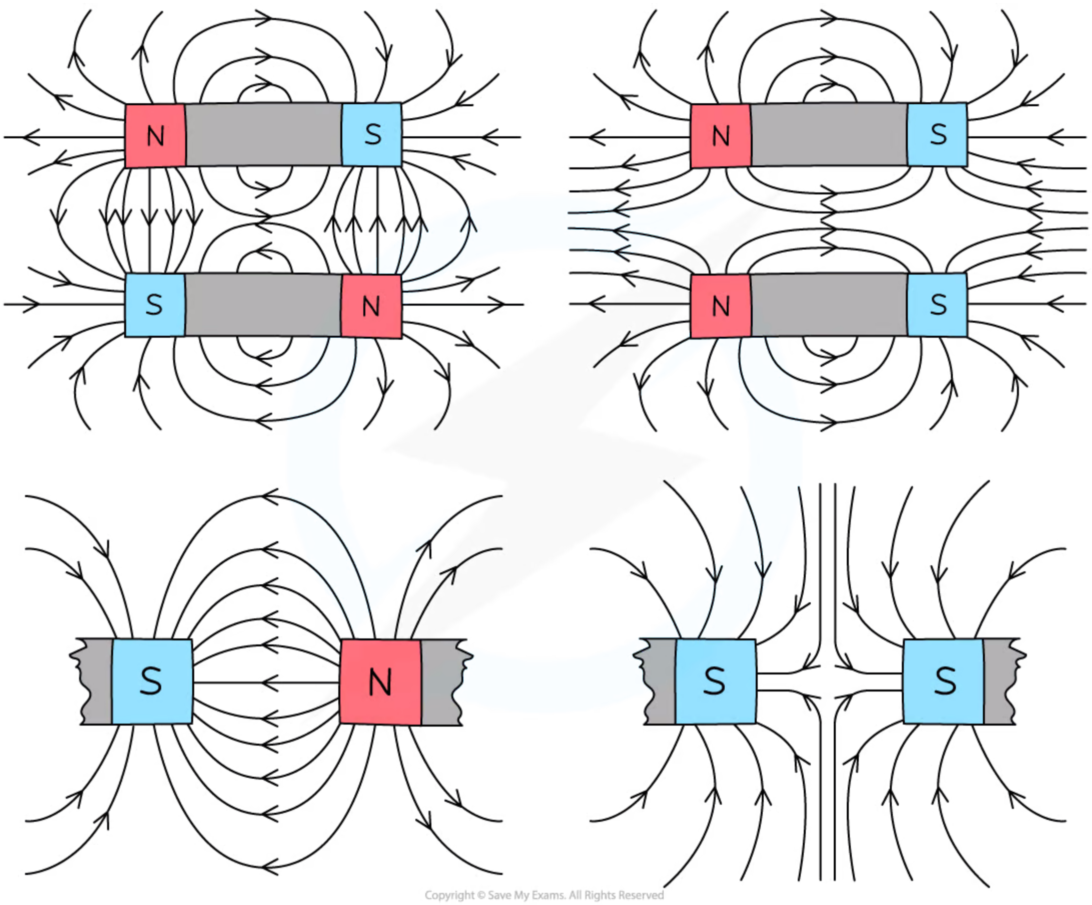

Magnetic field lines between two bar magnets

- **The key aspects of drawing magnetic field lines:**
  - The lines come **out** from the north poles and **into** the south poles
  - The direction of the field line shows the direction of the force that a free magnetic north pole would experience at that point
  - The field lines are **stronger** the **closer** the lines are together
  - The field lines are **weaker** the **further apart** the lines are
  - Magnetic field lines **never** cross since the magnetic field is unique at any point
  - Magnetic field lines are **continuous**
- A uniform magnetic field is where the magnetic field strength is the same at all points
  - This is represented by equally spaced parallel lines, just like electric fields
- The direction of the magnetic field into or out of the page in 3D is represented by the following symbols:
  - Dots (sometimes with a circle around them) represent the magnetic field directed **out** of the plane of the page
  - Crosses represent the magnetic field directed **into** the plane of the page

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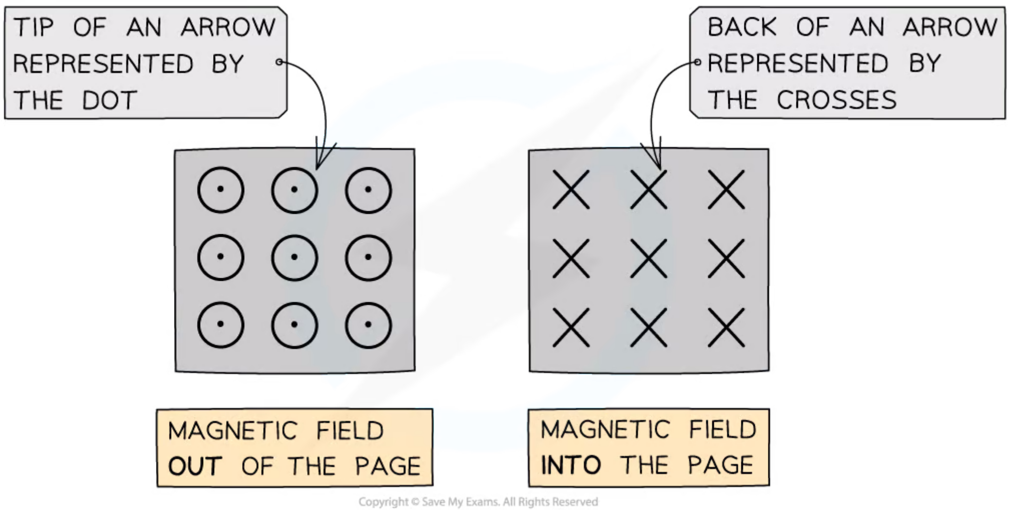

The magnetic field into or out of the page is represented by circles with dots or crosses

Exam Tip

The best way to remember which way around to draw magnetic fields in 3D is by imagining an arrow coming towards or away from you

- When the head of an arrow is coming towards you, you see the tip as a dot representing the arrow coming **'out'** of the page
- When an arrow is travelling away from you, you see the cross at the back of the arrow representing the arrow going **'into'** the page

Right Hand Rule

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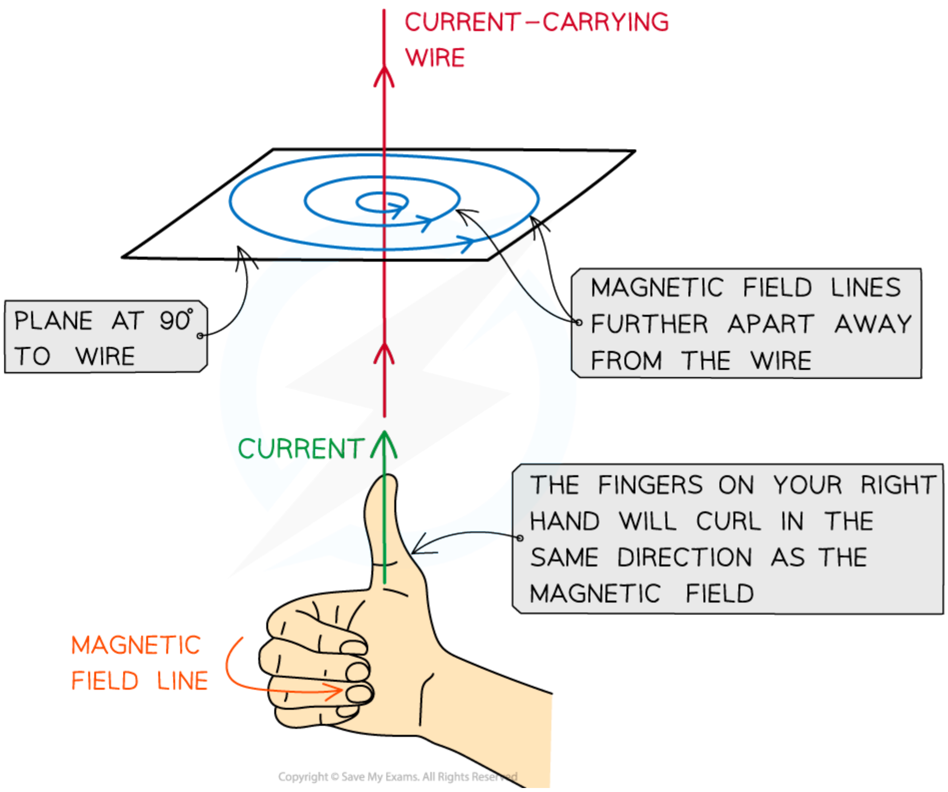
Magnetic Fields in Wires, Coils & Solenoids

- Magnetic field patterns are not only observed around bar magnets, magnetic fields are formed wherever current is flowing, such as in:
  - Long straight wires
  - Long solenoids
  - Flat circular coils

Field Lines in a Current-Carrying Wire

- Magnetic field lines in a current carrying wire are circular rings, centered on the wire
- The field lines are strongest near the wire and become further part away from the wire
- Reversing the current reverses the direction of the field



The direction of magnetic field lines on a current carrying wire can be determined by the right hand thumb rule

- The field lines are clockwise or anticlockwise around the wire, depending on the direction of the current
- The direction of the magnetic field is determined by **Maxwell's right hand screw rule**
  - This is determined by pointing the **right-hand** thumb in the direction of the current in the wire and curling the fingers onto the palm
  - The direction of the curled fingers represents the direction of the magnetic field around the wire
  - For example, if the current is travelling vertically upwards, the magnetic field lines will be directed anticlockwise, as seen from directly above the wire

YOUR NOTES
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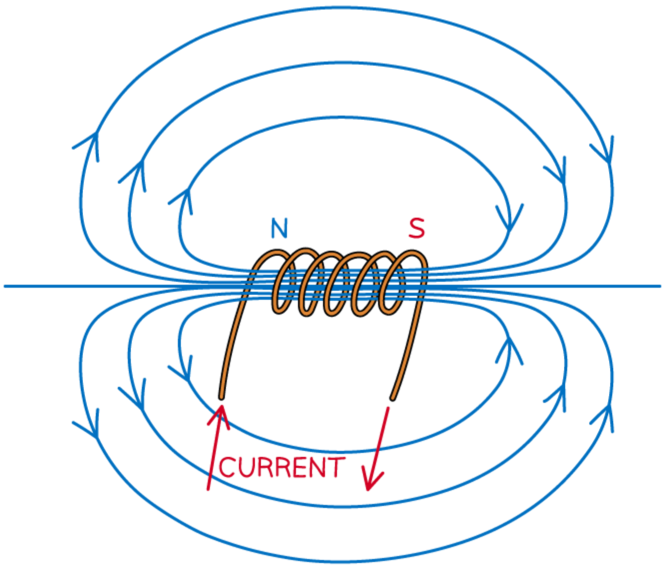
- **Note:** the direction of the current is taken to be the conventional current ie. from **positive** to **negative**, **not** the direction of electron flow

Field Lines in a Solenoid

- As seen from a current carrying wire, an electric current produces a magnetic field
- An electromagnetic makes use of this by using a coil of wire called a **solenoid** which concentrates the magnetic field
- One ends becomes a north pole and the other the south pole



Magnetic field lines around a solenoid are similar to a bar magnet

- Therefore, the magnetic field lines around a solenoid are very similar to a bar magnet
  - The field lines **emerge** from the **north** pole
  - The field lines **return** to the **south** pole
- Which is the north or south pole depends on the direction of the current
  - This is found by the **right-hand grip rule**
- This involves gripping the electromagnet so the fingers represent the direction of the current flow of the wire
- The thumb points in the direction of the field lines inside the coil, or in other words, point towards the electromagnet's **north pole**

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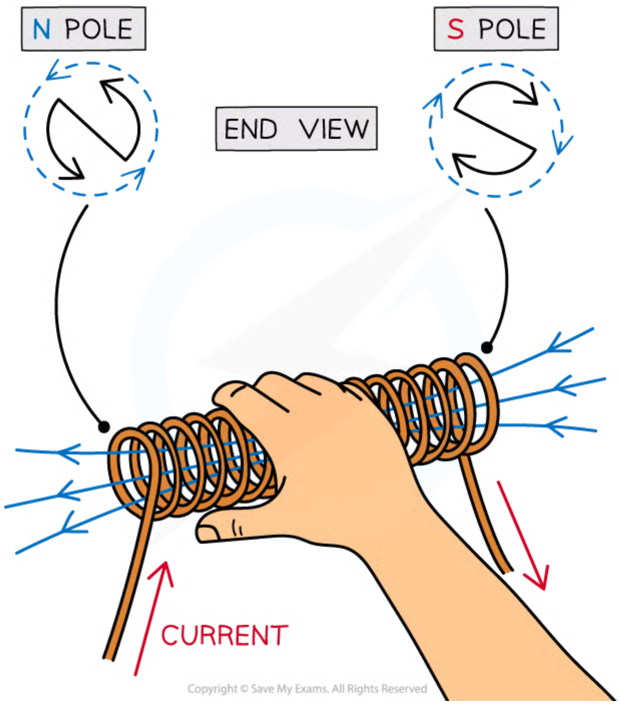
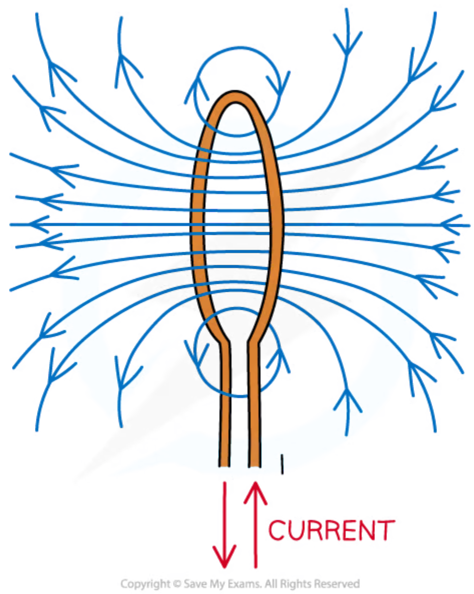


Poles of a Solenoid

Field Lines in a Flat Circular Coil

- A flat circular coil is equal to one of the coils of a solenoid
- The field lines will emerge through one side of the circle (north pole) and leave the other (south pole)
- As before, the direction of the north and south pole depends on the direction of the current
  - This can be determined by using the **right-hand thumb rule**
  - It is easier to find the direction of the magnetic field on the straight part of the circular coil to determine which direction the field lines are passing through

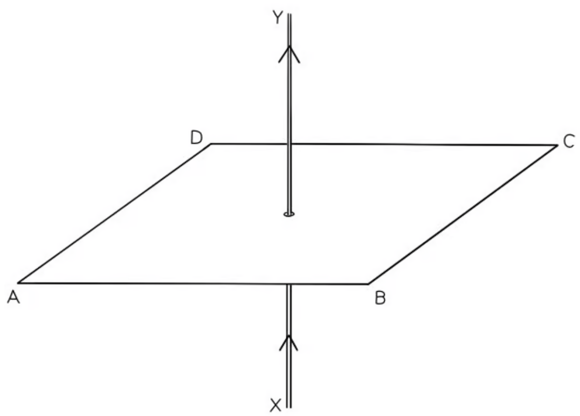


Magnetic field lines of a single circular coil are added up together to make to make the field lines of a solenoid

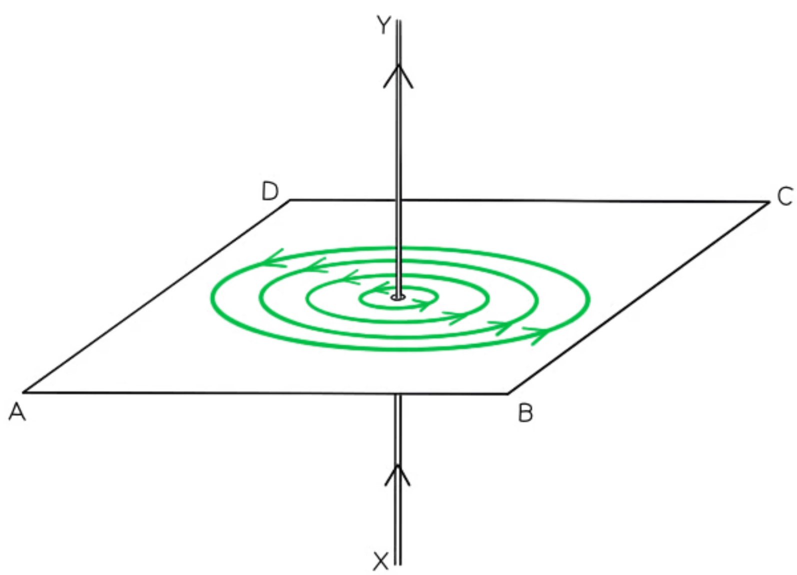
YOUR NOTES

Worked Example

The current in a long, straight vertical wire is in the direction XY, as shown in the diagram.



Sketch the pattern of the magnetic flux in the horizontal plane ABCD due to the current-carrying wire. Draw at least four flux lines.



✓ Concentric circles

✓ Increasing separation between each circle

✓ Arrows drawn in anticlockwise direction

Exam Tip

Remember to draw the arrows showing the direction of the field lines on every single field line you draw. Also, ensure that in a uniform magnetic field, the field lines are equally spaced.

YOUR NOTES
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YOUR NOTES
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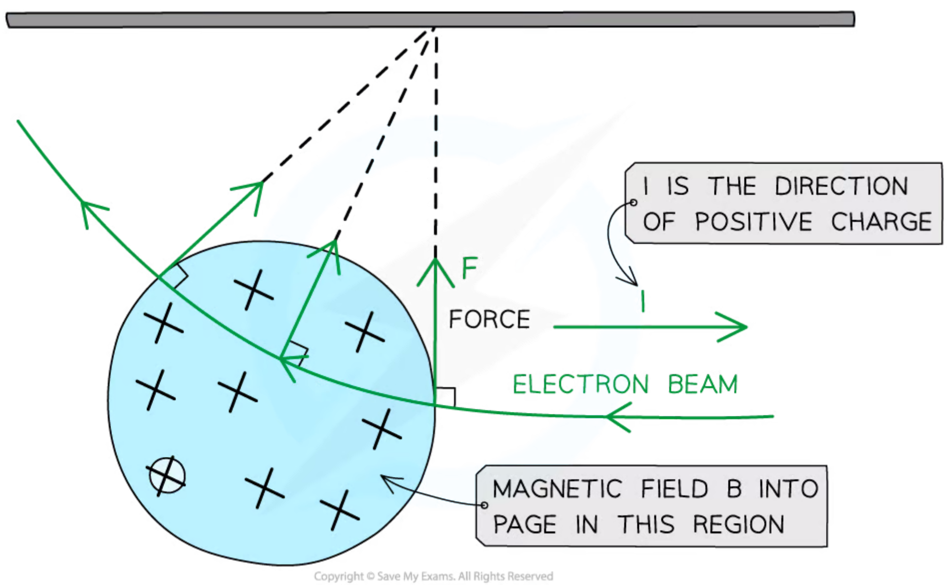
Magnetic Force on a Charge

Calculating Magnetic Force on a Moving Charge

- The magnetic force on an isolating moving charge, such an electron, is given by the equation:

$$F = BQv \sin\theta$$

- Where:
  - F = force on the charge (N)
  - B = magnetic flux density (T)
  - Q = charge of the particle (C)
  - v = speed of the charge (m s^{-1})
  - θ = angle between charge's velocity and magnetic field (degrees)



The force on an isolated moving charge is perpendicular to its motion and the magnetic field B

- Equivalent to the force on a wire, if the magnetic field *B* is perpendicular to the direction of the charge's velocity, the equation simplifies to:

$$F = BQv$$

- According to Fleming's left hand rule:
  - When an electron enters a magnetic field from the **left**, and if the magnetic field is directed **into the page**, then the force on it will be directed **upwards**
- The equation shows:
  - If the direction of the electron changes, the magnitude of the force will change too
- The force due to the magnetic field is always perpendicular to the velocity of the electron

YOUR NOTES
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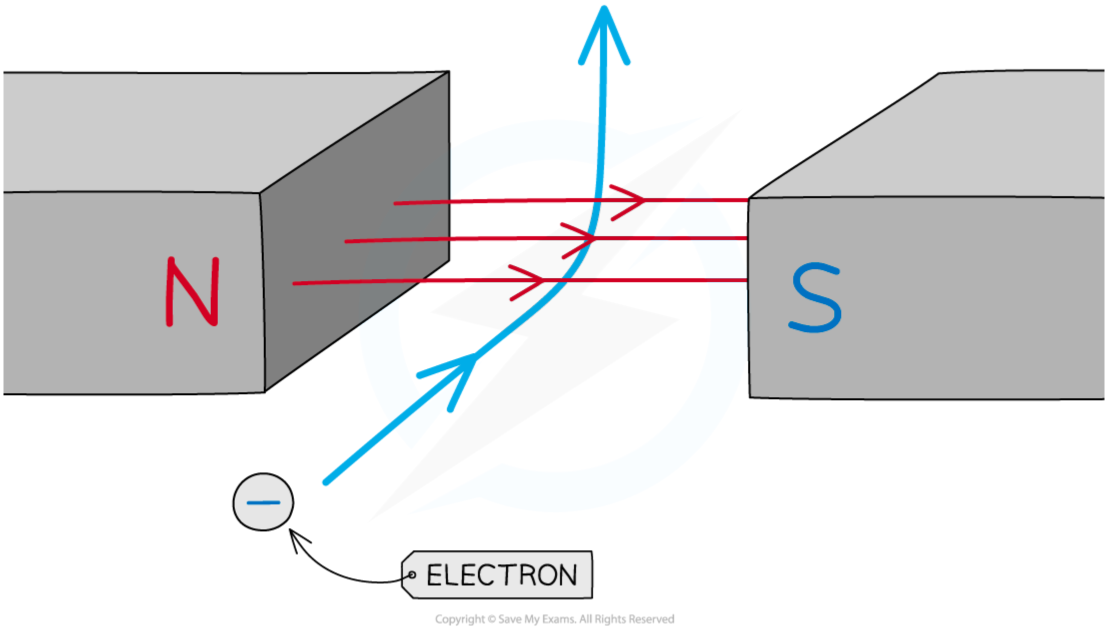
- **Note:** this is equivalent to circular motion

- Fleming's left-hand rule can be used again to find the direction of the force, magnetic field and velocity
  - The key difference is that the second finger representing current *I* (direction of positive charge) is now the **direction of velocity v** of the positive charge



The electron experiences a force upwards when it travels through the magnetic field between the two poles

Worked Example

An electron is moving at 5.3×10^{7} m s^{-1} in a uniform magnetic field of flux density 0.2 T.Calculate the force on the electron when it is moving at 30° to the field, and state the factor it increases by compared to when it travels perpendicular to the field.

Step 1: Write out the known quantities

Speed of the electron, $v = 5.3 \times 10^{7}$ m s^{-1}

Charge of an electron, $Q = 1.60 \times 10^{-19}$ C

Magnetic flux density, B = 0.2 T

Angle between electron and magnetic field, $\theta = 30^{\circ}$

Step 2: Write down the equation for the magnetic force on an isolated particle

$$F = BQv \sin\theta$$

Step 3: Substitute in values, and calculate the force on the electron at 30°

$$F = (0.2) \times (1.60 \times 10^{-19}) \times (5.3 \times 10^{7}) \times \sin(30) = 8.5 \times 10^{-13} \text{ N}$$

Step 4: Calculate the electron force when travelling perpendicular to the field

$$F = BQv = (0.2) \times (1.60 \times 10^{-19}) \times (5.3 \times 10^{7}) = 1.696 \times 10^{-12} \text{ N}$$

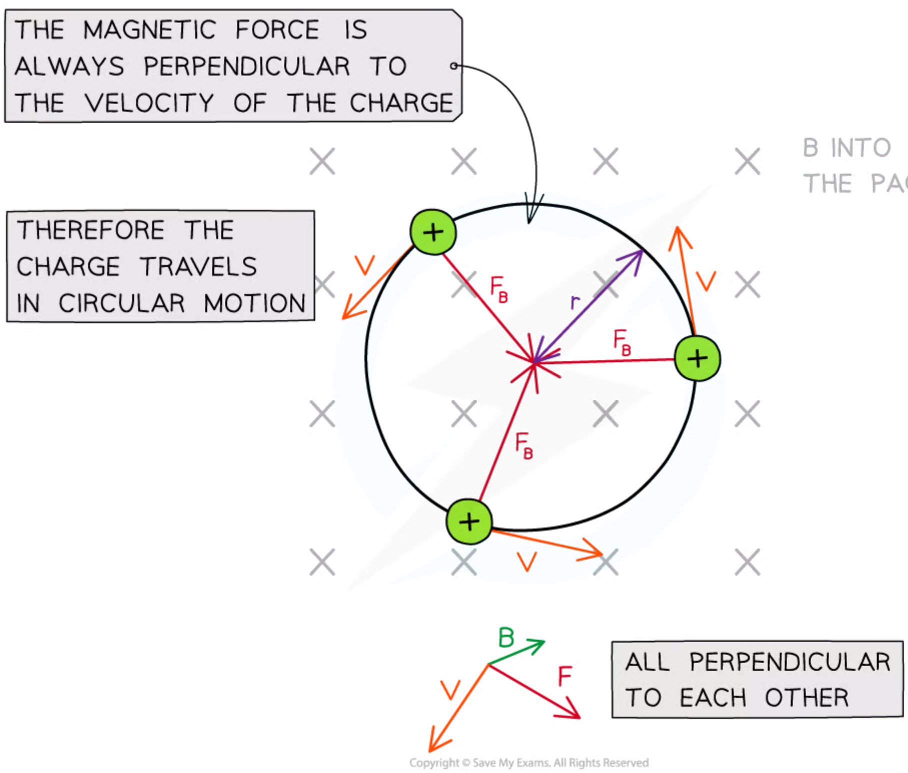
Step 5: Calculate the ratio of the perpendicular force to the force at 30°

$$\frac{1.696 \times 10^{-12}}{8.5 \times 10^{-13}} = 1.995 = \mathbf{2}$$

Therefore, the force on the electron is twice as strong when it is moving perpendicular to the field than when it is moving at 30° to the field

Motion of a Charged Particle in a Uniform Magnetic Field

- A charged particle in uniform magnetic field which is perpendicular to its direction of motion travels in a **circular** path
- This is because the magnetic force F_B will always be perpendicular to its velocity v
  - F_B will always be directed towards the centre of the path



A charged particle moves travels in a circular path in a magnetic field

- The magnetic force F_B provides the **centripetal force** on the particle
- Recall the equation for centripetal force:

$$F = \frac{mv^2}{r}$$

- Where:

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YOUR NOTES
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- m = mass of the particle (kg)
- v = linear velocity of the particle (m s^{-1})
- r = radius of the orbit (m)

- Equating this to the force on a moving charged particle gives the equation:

$$\frac{mv^2}{r} = Bqv$$

- Rearranging for the radius *r* obtains the equation for the radius of the orbit of a charged particle in a perpendicular magnetic field:

$$r = \frac{mv}{Bq}$$

- This equation shows that:
  - Faster moving particles with speed *v* move in larger circles (larger *r*): **r ∝ v**
  - Particles with greater mass *m* move in larger circles: **r ∝ m**
  - Particles with greater charge *q* move in smaller circles: **r ∝ 1 / q**
  - Particles moving in a strong magnetic field *B* move in smaller circles: **r ∝ 1 / B**

Worked Example

An electron with charge-to-mass ratio of 1.8×10^{11} C kg^{-1} is travelling at right angles to a uniform magnetic field of flux density 6.2 mT. The speed of the electron is 3.0×10^6 m s^{-1}. Calculate the radius of the circle path of the electron.

Step 1: Write down the known quantities

$$\text{Charge-to-mass ratio} = \frac{q}{m} = \mathbf{1.8 \times 10^{11}\ C\ kg^{-1}}$$

Magnetic flux density, B = 6.2 mT

Electron speed, v = 3.0×10^6 m s^{-1}

Step 2: Write down the equation for the radius of a charged particle in a perpendicular magnetic field

$$r = \frac{mv}{Bq}$$

Step 3: Substitute in values

$$\frac{m}{q} = \frac{1}{1.8 \times 10^{11}}$$

$$r = \frac{(3.0 \times 10^6)}{(1.8 \times 10^{11})(6.2 \times 10^{-3})} = 2.688 \times 10^{-3}\ \text{m} = \mathbf{2.7\ mm}\ (2\ \text{s.f.})$$

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Exam Tip

- Remember not to mix this up with F = BIL!
  - **F = BIL** is for a current carrying conductor
  - **F = Bqv** is for an isolated moving charge (which may be inside a conductor)
- It is important to note that when the **moving charge** is traveling **along the field direction** - precisely with or against the field lines - then there is **no magnetic force** on that charge!

5.4.3 Magnetic Force on a Current-Carrying Conductor

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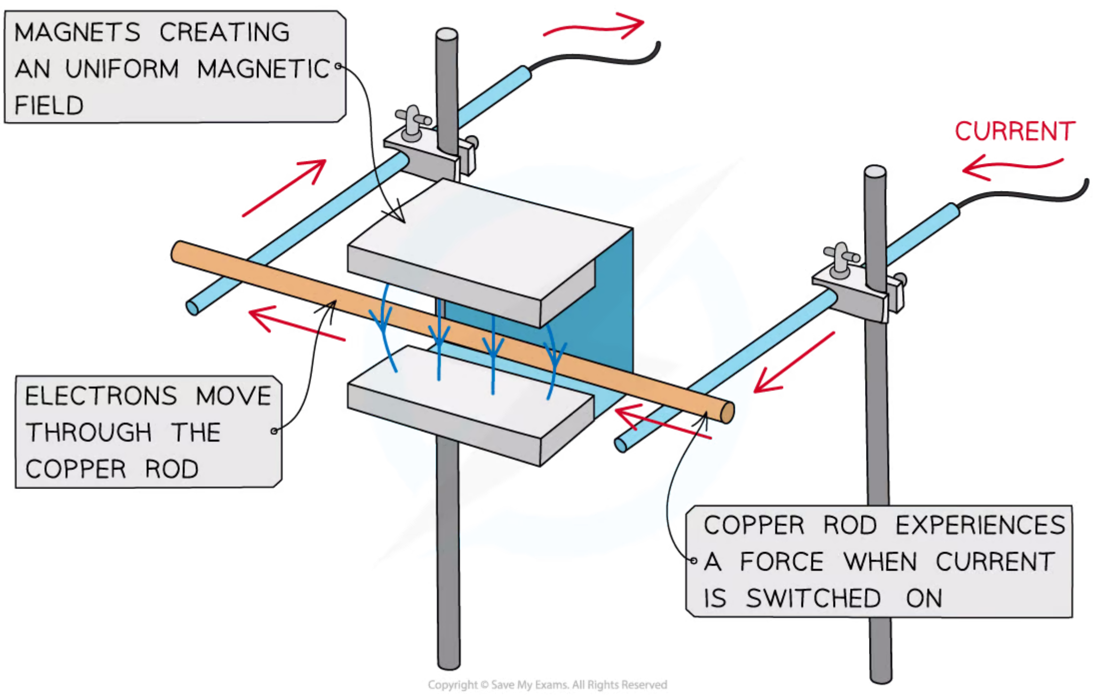
Magnetic Force on a Current-Carrying Conductor

- A current-carrying conductor produces its own magnetic field
  - When interacting with an external magnetic field, it will experience a **force**
- A current-carrying conductor will only experience a force if the current through it is **perpendicular** to the direction of the magnetic field lines
- A simple situation would be a copper rod placed within a uniform magnetic field
- When current is passed through the copper rod, it experiences a force that makes it move



A copper rod moves within a magnetic field when current is passed through it

Calculating Magnetic Force on a Current-Carrying Conductor

- The strength of a magnetic field is known as the **magnetic flux density, B**
  - This is also known as the magnetic field strength
  - It is measured in units of **Tesla (T)**
- The force *F* on a conductor carrying current *I* at right angles to a magnetic field with flux density *B* is defined by the equation

$$F = BIL \sin\theta$$

- Where:
  - F = force on a current carrying conductor in a B field (N)
  - B = magnetic flux density of external B field (T)
  - I = current in the conductor (A)
  - L = length of the conductor (m)

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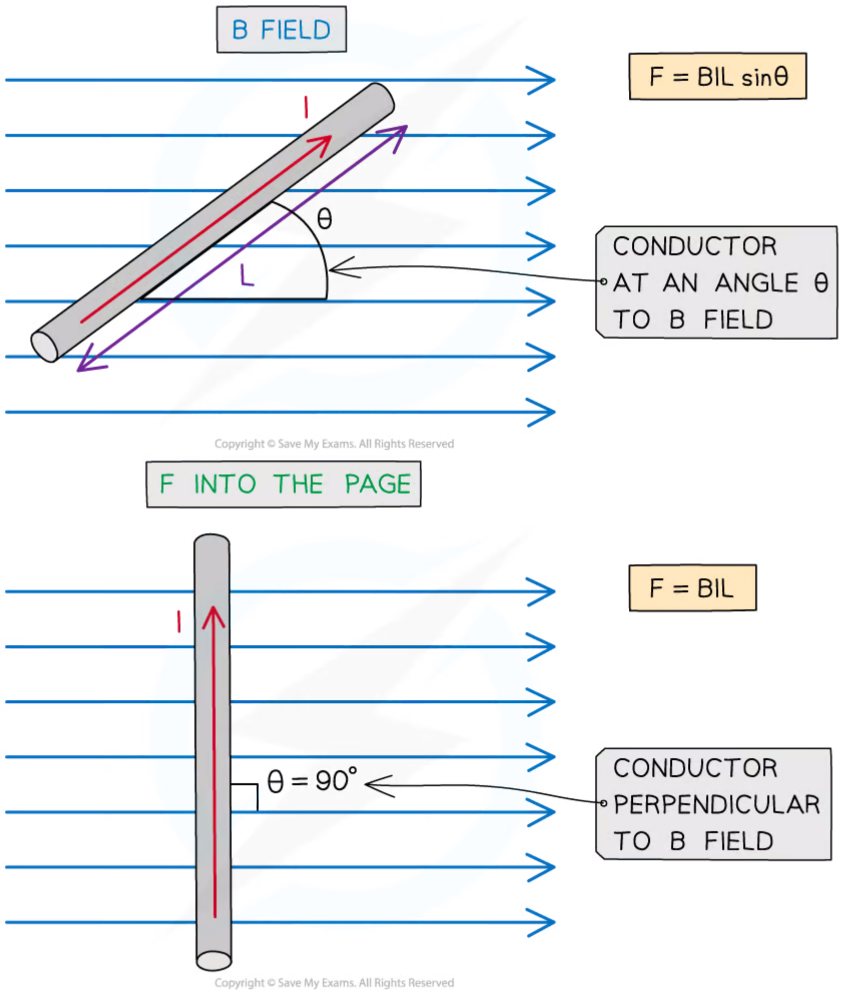
- θ = angle between the conductor and external B field (degrees)

- This equation shows that the greater the current or the magnetic field strength, the greater the force on the conductor



Magnitude of the force on a current carrying conductor depends on the angle of the conductor to the external B field

- The **maximum** force occurs when $\sin\theta = 1$
  - This means $\theta = 90°$ and the conductor is **perpendicular** to the B field
  - This equation for the magnetic force now becomes:

$$F = BIL$$

- The **minimum** force (0) is when $\sin\theta = 0$
  - This means $\theta = 0°$ and the conductor is **parallel** to the B field

- It is important to note that a current-carrying conductor will experience **no** force if the current in the conductor is parallel to the field

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Worked Example

A current of 0.87 A flows in a wire of length 1.4 m placed at 30° to a magnetic field of flux density 80 mT. Calculate the force on the wire.

Step 1: Write down the known quantities

Magnetic flux density, B = 80 mT = 80 × 10^{-3} T

Current, I = 0.87 A

Length of wire, L = 1.4 m

Angle between the wire and the magnetic field, θ = 30°

Step 2: Write down the equation for force on a current-carrying conductor

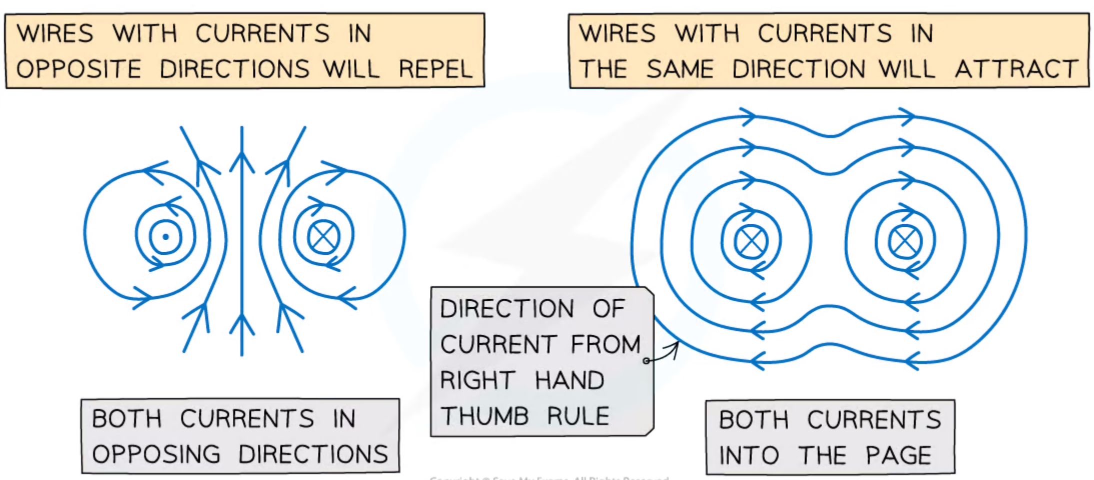
$F = BIL \sin\theta$

Step 3: Substitute in values and calculate

$F = (80 \times 10^{-3}) \times (0.87) \times (1.4) \times \sin(30) = 0.04872 = 0.049$ N (2 s.f)

Origin of the Forces Between Current-Carrying Conductors

- A current carrying conductor, such as a wire, produces a magnetic field around it
- The direction of the field depends on the direction of the current through the wire
  - This is determined by the **right hand thumb rule**
- Parallel current-carrying conductors will therefore either attract or repel each other
  - If the currents are in the **same** direction in both conductors, the magnetic field lines between the conductors cancel out – the conductors will **attract** each other
  - If the currents are in the **opposite** direction in both conductors, the magnetic field lines between the conductors push each other apart – the conductors will **repel** each other



Both wires will attract if their currents are in the same direction and repel if in opposite directions

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- When the conductors **attract**, the direction of the magnetic forces will be **towards** each other
- When the conductors **repel**, the direction of the magnetic forces will be **away** from each other
- The magnitude of each force depend on the amount of current and length of the wire

Worked Example

Two long, straight, current-carrying conductors, WX and YZ, are held at a close distance, as shown in diagram 1.

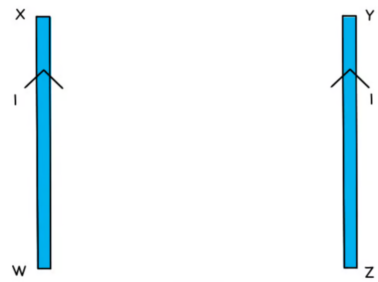

diagram 1

The conductors each carry the same magnitude current in the same direction. A plan view from above the conductors is shown in diagram 2.

diagram 2

On diagram 2, draw arrows, one in each case, to show the direction of:

- The magnetic field at X due to the current in wire YZ (label this arrow B_{YZ})
- The force at X as a result of the magnetic field due to the current in the wire YZ (label this arrow F_{YZ})
- The magnetic field at Y due to the current in wire WX (label this arrow B_{WX})
- The force at Y as a result of the magnetic field due to the current in the wire WX (label this arrow F_{WX})

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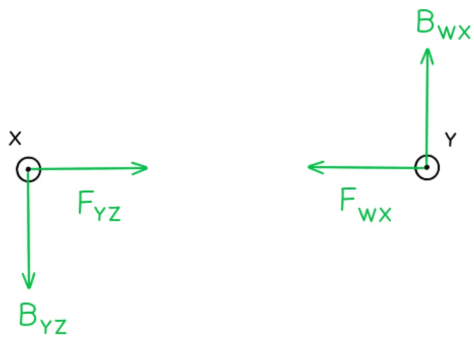

- Newton's Third Law states:
  - When two bodies interact, the force on one body is **equal but opposite** in direction to the force on the other body
- Therefore, the forces on the wires act in equal but opposite directions

Exam Tip

Remember that the direction of current flow is the flow of **positive** charge (positive to negative), and this is in the **opposite direction** to the flow of electrons

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Solving Problems Involving Magnetic Forces

- There is a lot of mathematics surrounding magnetism and magnetic forces
- The key equations are:

Force on a current-carrying conductor:
$$F = BIL$$

Force on a moving charge:
$$F = Bqv$$

Radius of a moving charge in a magnetic field:
$$r = \frac{mv}{qB}$$

- Below are two worked examples demonstrating different situations involving magnetic forces

Worked Example

A 5 cm length of wire is at 90° to the direction of an external magnetic field. When a current of 1.5 A flows through the wire it experiences a force of 0.06 N from the motor effect.

Calculate the magnetic flux density of the magnet.

Step 1: List the known quantities

- Length, L = 5 cm = 0.05 m
- Current, I = 1.5 A
- Force, F = 0.06 N

Step 2: Write out the equation for magnetic force

$$F = BIL$$

Step 3: Rearrange the equation to make B the subject

$$B = \frac{F}{IL}$$

Step 4: Substitute values into the equation

$$B = \frac{0.06}{1.5 \times 0.05} = 0.8\ T$$

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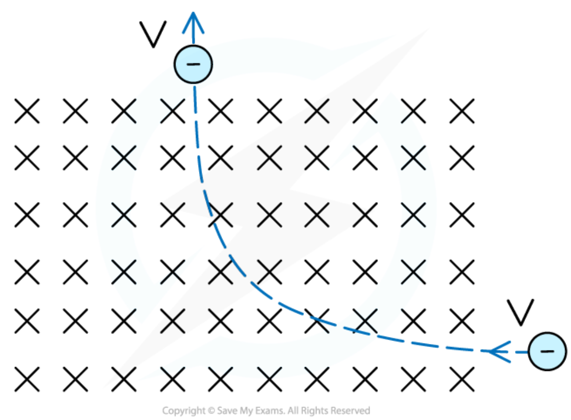
Worked Example

This question is about the movement of an electrically charged particle into a magnetic field. An electron enters a magnetic field and moves in an approximately circular path as shown below.



1. Explain whether the speed of the proton is the same when entering and exiting the magnetic field.
2. The magnetic field has a strength of 0.3 T and the velocity of the electron before entering the magnetic field is 8.6×10^6 m s^{-1} to the left. Show that the radius of the motion of the electrons is 1.63 cm.

Part (a)

- The answer is that the work done by the magnetic force on the charge must be zero
- This is because the force itself is at right angles to the velocity
- Since the work done is zero, therefore the kinetic energy does not change between entering and leaving the magnetic field
- Therefore the speed is the same

Part (b)

Step 1: List the known quantities

- Magnetic field strength, B = 0.3 T
- Velocity of electron (before entering field), $v = 8.6 \times 10^6$ m s^{-1} to the left
- Radius of motion to be shown, r = 1.63 cm

Step 2: Equate the magnetic force and the force of circular motion

- This can be done for the situation since the circular motion is caused by the magnetic force

$$qvB = \frac{mv^2}{r}$$

Step 3: Rearrange the equation to find the radius

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$$qvBr = mv^2$$
$$qBr = mv$$
$$r = \frac{mv}{qB}$$

Step 4: Substitute in the values

$$r = \frac{(9.1 \times 10^{-31}) \times (8.6 \times 10^{6})}{(1.6 \times 10^{-19}) \times (3 \times 10^{-3})} = 1.63 \times 10^{-2}\ m$$

Step 5: State final answer

R = 1.63×10^{-2} m = **1.63 cm** in a circular motion