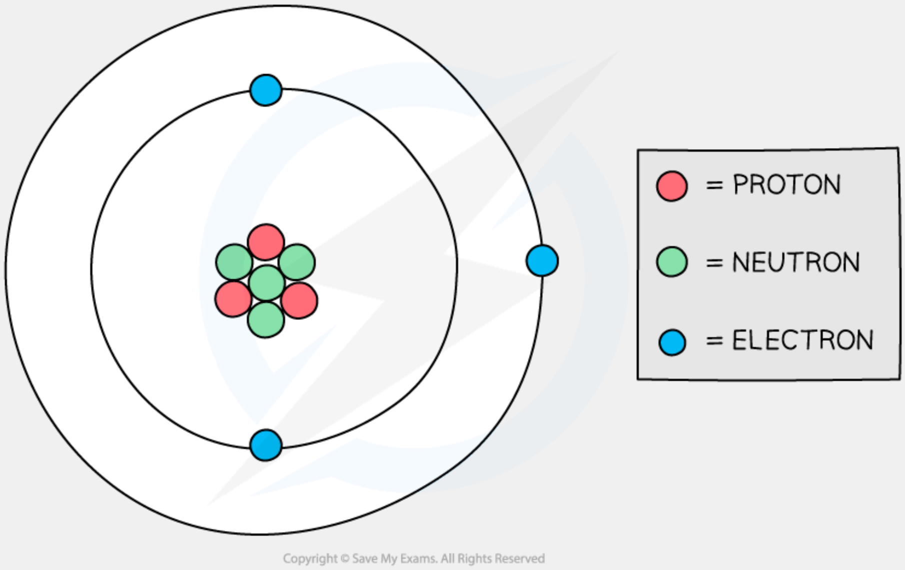
# 4.2 Electrical Quantities

## Electric Charge

### Positive & negative charges

- **Charge** is a fundamental physical property of matter
  - Other examples of fundamental properties of matter includes mass and volume
- There are two types of electric charge: **positive** and **negative**
- Inside an atom, there are
  - negatively charged **electrons**
  - positively charged **protons**
  - neutral (no charge) **neutrons**
- Atoms contain equal numbers of protons and electrons as they have equal and opposite charges
- These charges cancel out so the overall charge of an atom is zero
- Electric charge is measured in units called **coulombs (C)**

### Structure of an atom

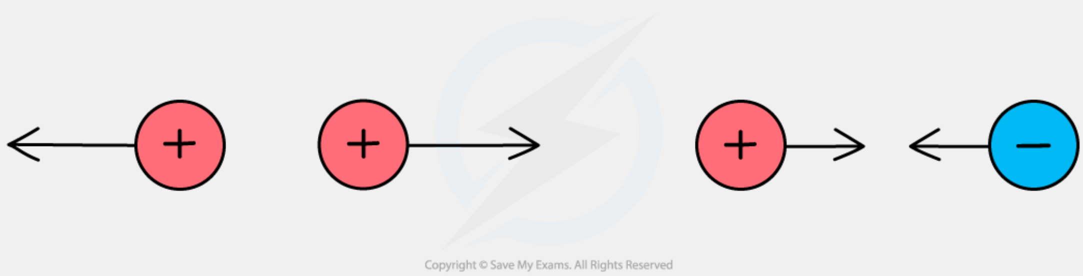



*The number of negative electrons in an atom balances the number of positive protons*

## Attraction and repulsion

- When two charges are close together, they exert a **force** on each other, this could be:
  - **Attractive** (the objects get closer together)
  - **Repulsive** (the objects move further apart)

### Electric forces between charges




*Opposite charges attract, like charges repel*

- Whether two objects attract or repel depends on their **charge**
  - If the charges are the **opposite**, they will **attract**
  - If the charges are the **same**, they will **repel**

- It has a similar pattern as magnets

## Examiner Tips and Tricks

Remember the saying "**opposites attract**" when answering questions about forces between charged particles.

While electrostatic forces share many similarities with magnetic forces, they are different phenomena **– do not confuse the two!**

# Demonstrating Electric Charges

## Charging by friction

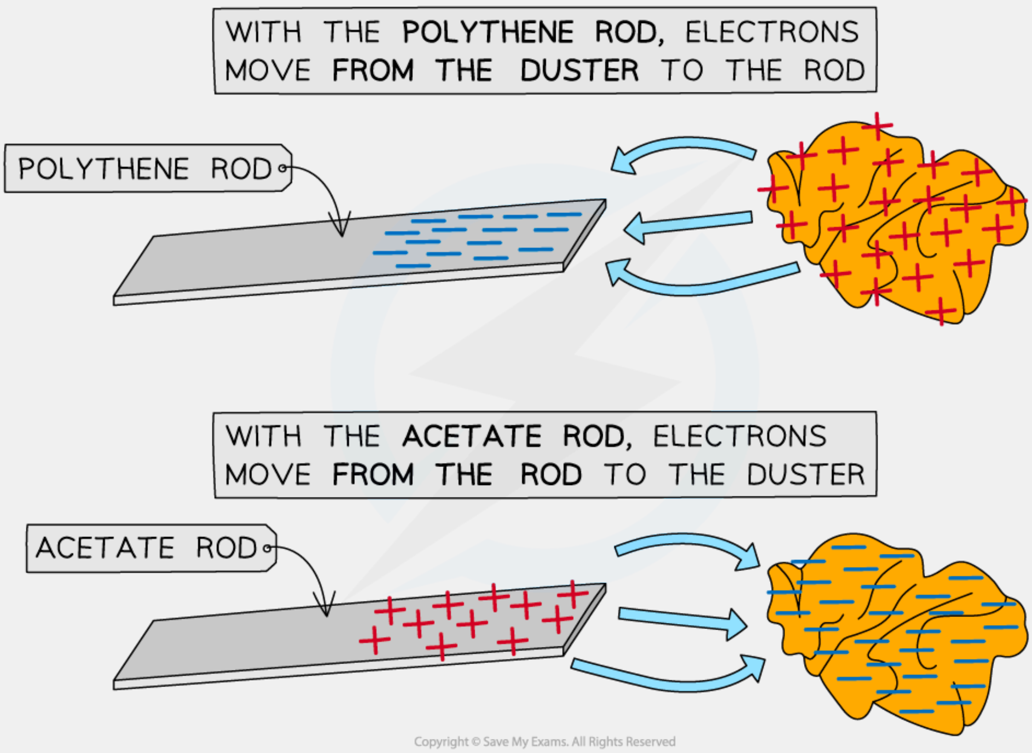
- When certain insulating solids are rubbed against each other, they can become **electrically charged**
  - This is called **charging by friction**
- The charges remain on the insulators and cannot immediately flow away
  - One gains a net **positive charge** and the other gains a net **negative charge**
  - When charges build up on the material and cannot flow away, it is said to have built up **static electricity (also known as static charge)**
- An example of this is a plastic or polythene rod being charged by rubbing it with a cloth
  - Both the rod and cloth are insulating materials

### Charging solids by friction


*A polyethene rod may be given a charge by rubbing it with a cloth*

- When an uncharged cloth is rubbed against an uncharged polythene rod
  - **Electrons** are **transferred** away **from** the **cloth to** the **rod**
    - The cloth has lost electrons, so it becomes positively charged
    - The polythene rod has gained electrons, so it becomes negatively charged
  - These **oppositely charged** objects are also **attracted** to each other

- When an uncharged cloth is rubbed against an uncharged acetate plastic rod, however
  - **Electrons** are **transferred** away **from** the acetate **rod to** the **cloth**
    - The cloth has gained electrons so it becomes negatively charged
    - The rod has lost electrons so it becomes positively charged




***Electrons are transferred away from the acetate rod to the cloth but transferred away from the cloth to the polythene rod***

## Examiner Tips and Tricks

At this level, if you are asked to explain how charge is gained or lost, you must reference **electrons**. If an object gains electrons, it gains negative charge and if it loses electrons, it loses negative charge (and hence, gains positive charge)

Remember when charging by friction, it is only the **electrons** that can move, not any 'positive' charge, therefore if an insulator gains a negative charge, the other insulator must have gained a positive charge

# Demonstrating static charges

## Experiment 1: investigating electrostatic charging by friction

- The aim of this experiment is to investigate how insulating materials can be charged by friction

## Variables

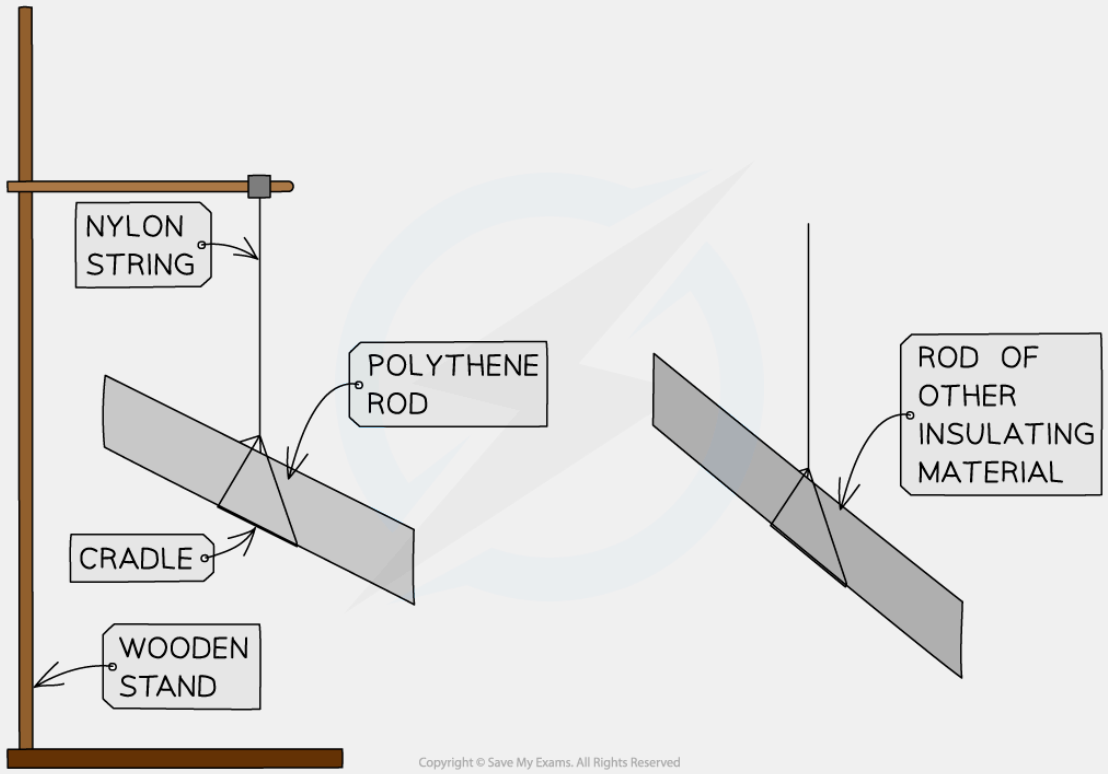
- **Independent variable** = Rods of different material
- **Dependent variable** = Charge on the rod
- Control variables:
    - Time spent rubbing the rod
    - Using the same type of cloth
    - Using the same length of rod

## Equipment

### Equipment list

| Equipment | Purpose |
|---|---|
| Polythene rod | to charge and hang from a cradle to test against each material |
| Rods of different materials (acrylic, acetate, glass, wood) | to observe the effects of these on the polythene rod |
| Cloths (one per material) | to rub the materials to charge them |
| Cradle | to suspend rods from, allowing them to move freely when subjected to a force |
| Nylon string | to hang the rods |
| Wooden stand | to suspend the string and cradle from |

## Method




*Apparatus for investigating charging by friction*

1. Take a polythene rod, hold it at its centre and rub both ends with a cloth

2. Suspend the rod, without touching the ends, from a stand using a cradle and nylon string
3. Take a second polythene rod and rub one end with a different cloth
4. Bring the second polythene rod close to the suspended rod
5. Record any observations of the suspended rod's motion, i.e. whether it is attracted or repelled by the second rod
6. Repeat using an acetate rod and rods of different materials

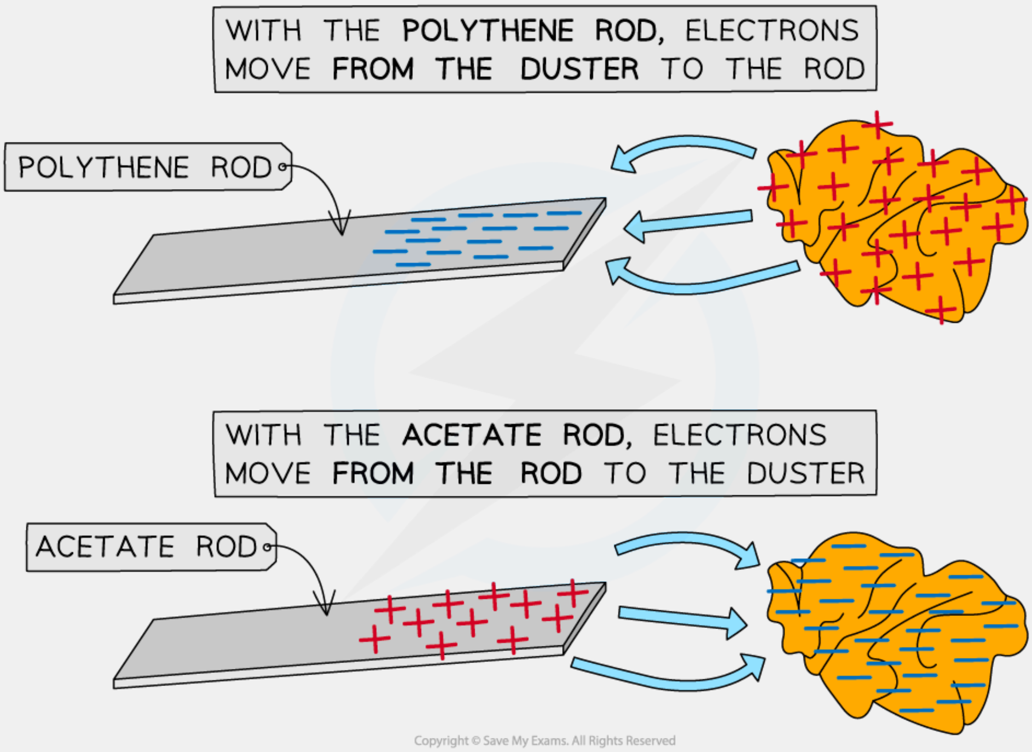
## Example results table

| charged material 1 | charged material 2 | attracted or repelled |
|---|---|---|
| polythene | polythene | |
| polythene | acetate | |

## Analysis of results

- When two insulating materials are rubbed together, negative charge (electrons) will transfer from one insulator to the other
- A polythene rod gains a **negative** charge when rubbed with a cloth
    - This is because electrons are transferred to the polythene from the cloth
- An acetate rod gains a **positive** charge when rubbed with a cloth
    - This is because electrons are removed from the acetate by the cloth

**Transfer of electrons between charged insulators**





***Electrons are transferred to the polythene rod giving it a negative charge, and they move from the acetate rod giving it a positive charge***

- If the material is **repelled** by the polythene rod, then the materials have the **same charge**
  - For example, the polythene rod would be repelled by a second polythene rod, as they have the same charge
- If the material is **attracted** to the polythene rod, then they have **opposite charges**
  - For example, the polythene rod would be attracted to an acetate rod, as they have opposite charges

## Evaluating the experiment

- Reduce the effects of environmental factors (e.g. close windows to reduce drafts) to ensure the motion of the polythene rod is due to electric forces only
- Make sure not to touch the ends of the rods once they have been charged (if the ends are touched, the rods will **discharge** and the forces will no longer be present)

- Produce greater deflections by rubbing the rods for a longer period to transfer more charge (ensuring that the time spent rubbing each rod is the same)

## Experiment 2: detecting charge using a gold-leaf electroscope

- The aim of this experiment is to detect charge using a gold leaf electroscope

## Variables

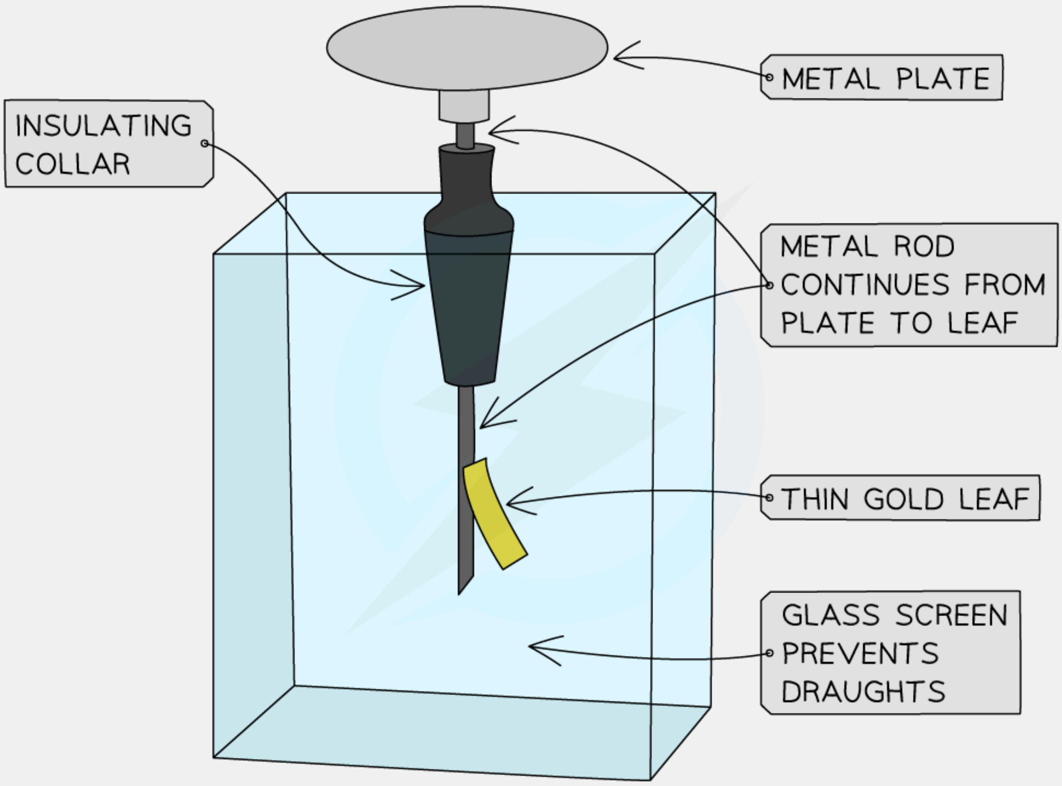
- **Independent variable** = Rods of different material
- **Dependent variable** = Charge on the rod

## Equipment

### Equipment list

| Equipment | Purpose |
|---|---|
| Gold-leaf electroscope | to detect charge |
| Polythene and acetate rods (or strips) | to observe the effects of these on the gold-leaf electroscope when charged |
| Cloths (one per material) | to charge the rods (or strips) by rubbing them |

## Method




***The gold-leaf electroscope is a device consisting of a metal plate, a metal stem and a thin gold leaf. The stem and leaf are housed in an airtight container to prevent draughts.***

1. Before beginning the experiment, ensure the plate of the electroscope is uncharged by touching it with your finger. The leaf should hang straight down next to the stem
2. Charge a polythene rod by rubbing it with a cloth
3. Bring the charged rod towards the plate of the electroscope and record any observations
4. Bring the charged rod away from the plate of the electroscope and record any observations
5. Touch the charged rod to the plate of the electroscope and record any observations
6. Repeat using an acetate rod

## Example results table

| charged material | action | gold leaf rises or falls | movement of electrons |
|---|---|---|---|
| polythene | moved towards plate | | |
| polythene | moved away from plate | | |
| polythene | touched plate | | |
| acetate | moved towards plate | | |
| acetate | moved away from plate | | |
| acetate | touched plate | | |

## Analysis of results

- When a charged object is brought near the plate of the electroscope, the leaf **rises**
  - The negatively charged polythene rod **repels** electrons away from the surface of the plate down the stem and leaf, giving them a **negative** charge, hence, they repel
  - The positively charged acetate rod **attracts** electrons to the surface of the metal plate from the stem and leaf, giving them a **positive** charge, hence, they repel
- When the charged object is moved away from the plate, the leaf **falls**
  - Electrons in the electroscope are no longer repelled or attracted by the rod so they redistribute themselves
  - The stem and leaf become electrically **neutral**
- When a charged object **touches** the plate of the electroscope, the leaf **stays risen**
  - The charge from the rod is transferred to the metal plate and travels down the stem and leaf of the electroscope
  - The stem and leaf therefore carry the **same charge** and repel each other

- The electroscope has been **charged**
- When a finger touches the plate, the leaf **falls**
  - The charge from the electroscope is transferred to the person and travels to the earth
  - The stem and leaf become electrically neutral
  - The electroscope has been **discharged**

## Evaluating the experiment

- Make sure not to touch the ends of the rods once they have been charged (if the ends are touched, the rods will **discharge**)
- When the electroscope is charged by contact with a rod, it should stay risen. If it doesn't, repeat the process but ensure to press harder and draw the rod along the edge of the plate

## Examiner Tips and Tricks

Experimental demonstrations, such as the one above, are different from experiments in which you have to take measurements. In the case of this demonstration your results are your **observations**.

When describing a demonstration you should **state a conclusion** – in other words, explain what you expect to happen and what it means.

# <u>Electric Fields</u>

- An electric field is defined as:

  **A region of space in which an electric charge experiences a force**

- The direction of an electric field at a point is defined as:

  **The direction of the force on a positive charge at that point**

- Charged objects **create** electric fields around themselves
  - This is similar to how magnets create magnetic fields
- An electric field is a **vector** quantity as it has both **magnitude** (strength) and **direction**

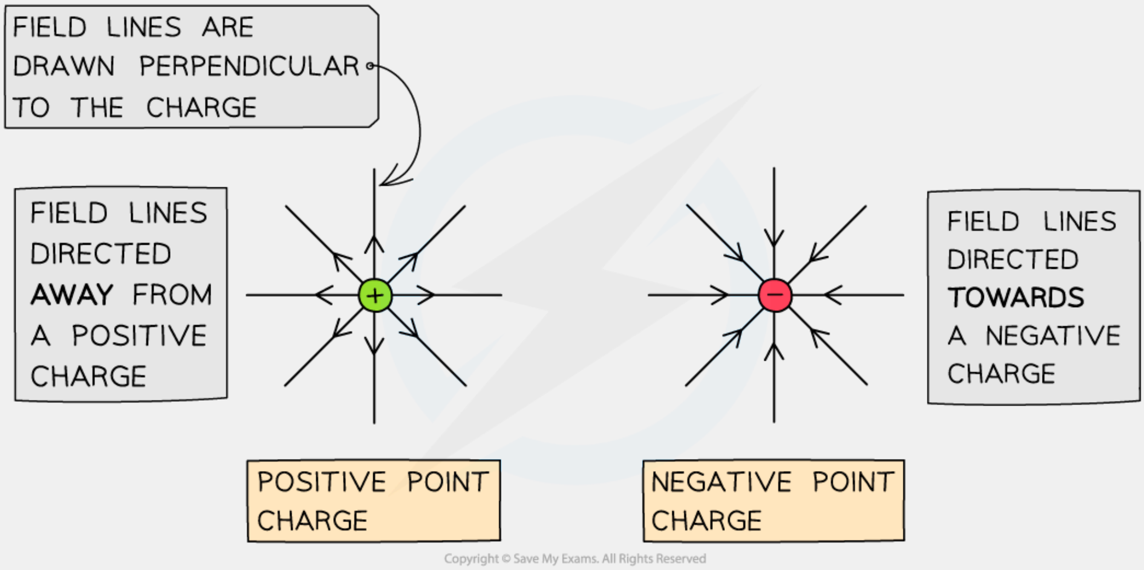
## Electric field patterns

- Electric field lines are
  - used to represent the **direction** and **magnitude** of an electric field
    - The direction is **relative to the positive charge**
    - If the charge is **negative**, the force experienced will be **opposite** to the field lines
  - always directed from the **positive** charge **to** the **negative** charge

### Electric field around a point charge

- Around a **point charge**, 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**

**Electric field lines around positive and negative point charges**



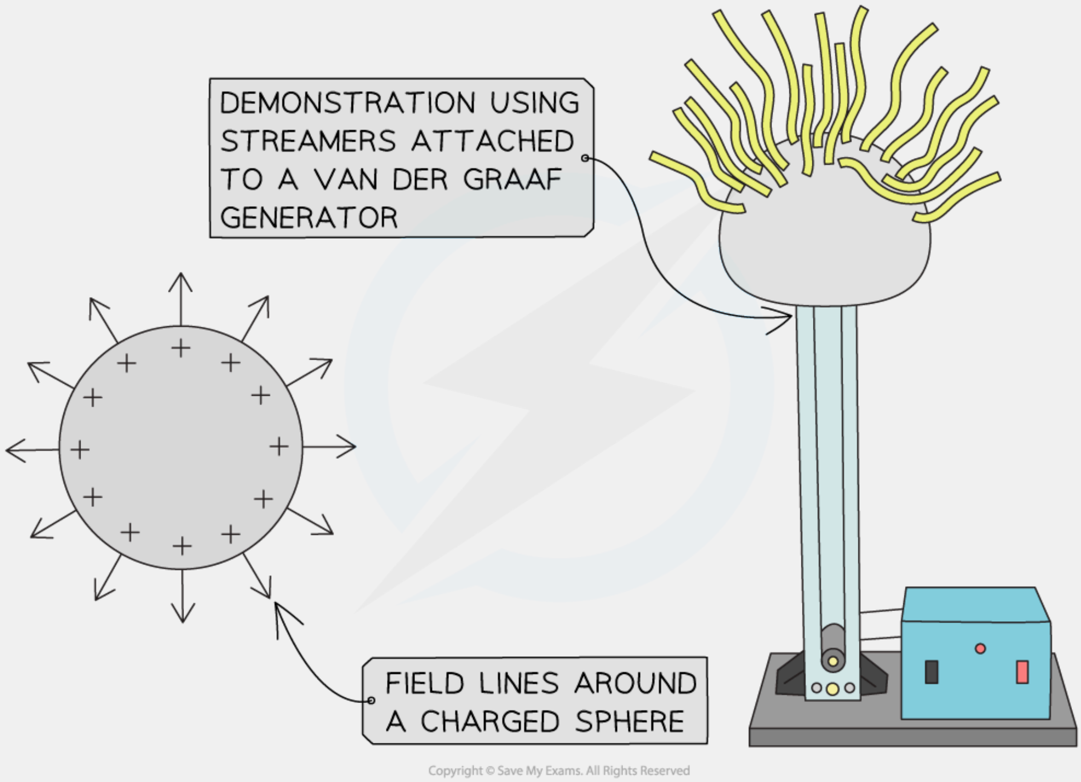

***Electric field lines around a point charge are directed away from a positive charge and towards a negative charge***

## Electric field around a charged conducting sphere

1. The field lines around a charged conducting sphere are similar to that of a point charge
    - This is because the charges on the surface of the sphere will be evenly distributed
    - The charges are the same, so they repel
    - The surface is conducting, allowing them to move

- Field lines are **always perpendicular** (at right angles) to the surface of a conducting sphere

### Electric field lines around a positively charged sphere

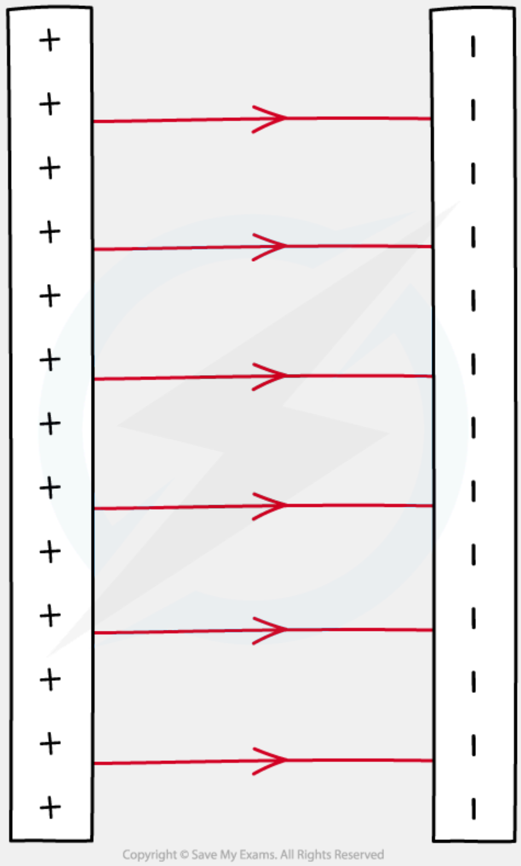



***The electric field pattern around a conducting can be demonstrated using a Van der Graaff generator***

## Electric field between two parallel plates

- The electric field between two parallel plates is a **uniform electric field**
- The field lines are:
  - directed from the **positive** to the **negative** plate
  - parallel
  - straight lines

#### Electric field lines between two oppositely charged parallel plates




*Electric field lines between two parallel plates are directed from the positive to the negative plate. A uniform electric field has equally spaced field lines*

## Examiner Tips and Tricks

Instead of memorising the electric field patterns of each scenario individually, just remember two things:

1. The arrows are relative to a positive charge
2. Like charges repel, unlike charges attract

If the point charge is positively charged, it will repel other positive charges around it. Hence, the field lines are directed away from the point charge.

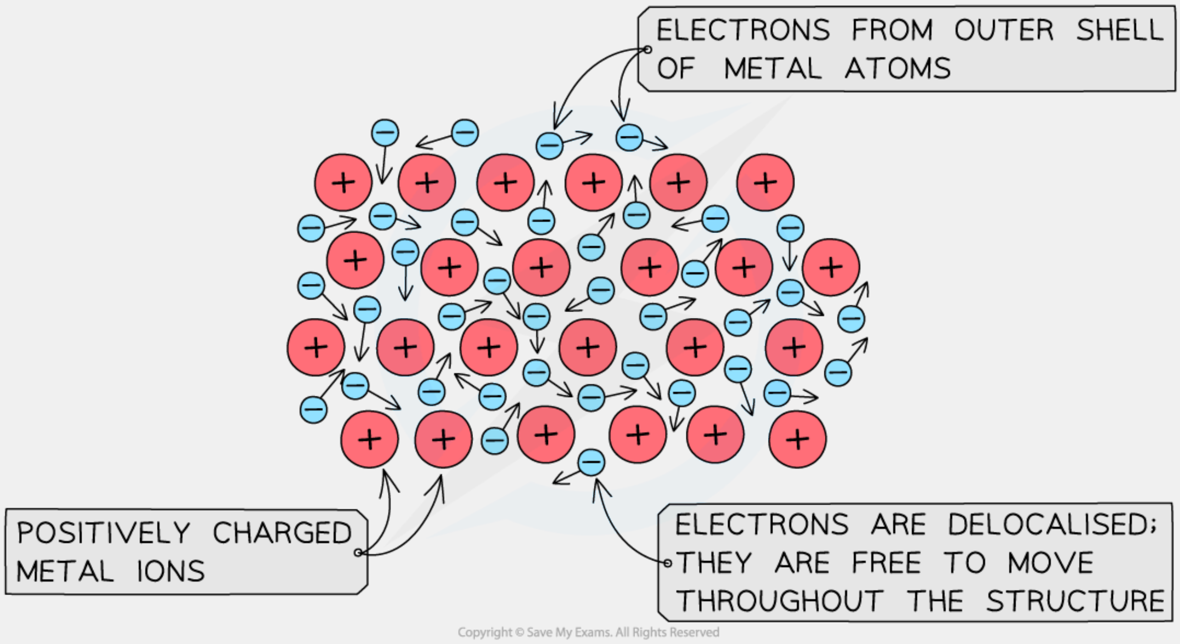
If the point charge is negatively charged, it will attract other positive charges around it. Hence, the field lines are directed towards the point charge.

# Investigating Electrical Conductors & Insulators

## Conductors

- A **conductor** is a material that allows **charge** (usually electrons) to flow through it easily
- Some examples of conductors are:
  - silver
  - copper
  - aluminium
  - steel
- The best conductors tend to be **metals**
- On the atomic scale, metallic conductors are made up of positively charged metal ions with their outermost electrons **delocalised**
  - This means the electrons are free to move
- Metals conduct electricity very well because:
  - Current is the rate of flow of electrons
  - So, the more easily electrons are able to flow, the **better** the conductor

### Metallic lattice structure

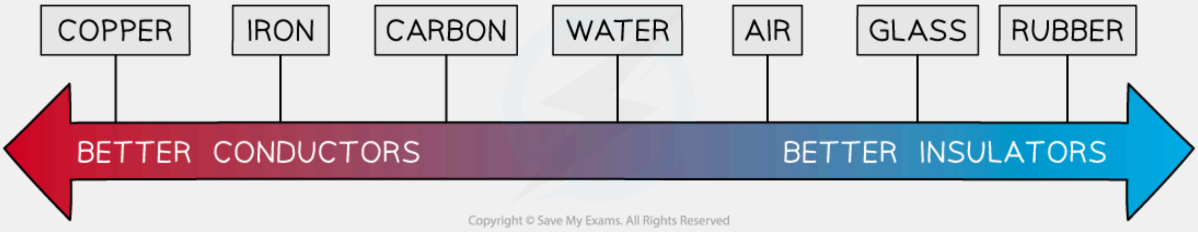



***The lattice structure of a conductor with positive metal ions and delocalised electrons***

## Insulators

- An **insulator** is a material that has **no free charges** and, hence does **not** allow the flow of charge through it very easily
- Some examples of insulators are:
  - rubber
  - plastic
  - glass
  - wood
- Some non-metals, such as wood, allow **some** charge to pass through them
- Although they are not very good at conducting, they do conduct a little in the form of **static** electricity
  - For example, two insulators can build up charge on their surfaces and if they touch this would allow that charge to be conducted away

### Conductors and insulators




***Different materials have different properties of conductivity***

## Investigating electrical conductors & insulators

### Aim of the experiment

- The aim of this experiment is to distinguish between good and bad conductors using a gold leaf electroscope

### Variables

- **Independent variable** = Different materials
- **Dependent variable** = Electrical conductivity of materials

### Equipment

#### Equipment list

| Equipment | Purpose |
|---|---|
| Gold-leaf electroscope | to distinguish between electrical conductors and insulators |
| Polythene rod | to charge the electroscope by contact |
| Cloth | to charge the rod by friction |
| Different conducting and insulating materials (metal, plastic, glass, wood) | to observe the effects of these on the gold-leaf electroscope when uncharged |

### Method

1. Before beginning the experiment, ensure the plate of the electroscope is uncharged by touching it with your finger. The leaf should hang straight down next to the stem
2. Charge a polythene rod by rubbing it with a cloth
3. Touch the charged rod to the plate of the electroscope. The leaf should stay risen if the electroscope has been successfully charged
4. Touch the plate of the charged electroscope with the first object to be tested and record any observations
5. Repeat for different materials

## Example results table

| material | gold leaf falls quickly or slowly | good or bad conductor |
| --- | --- | --- |
| metal | | |
| plastic | | |
| glass | | |
| graphite | | |
| wood | | |
| fabric | | |
| rubber | | |

## Analysis of results

- Good conductors, such as metals, allow charge to flow through them easily
    - Therefore, a good conductor will cause the leaf to fall **quickly** as it allows charge to flow to or from the plate
    - The **faster** the leaf falls, the **better** the conductor
- Poor conductors, such as glass, do not allow charge to flow as easily
    - Therefore, a poor conductor will cause the leaf to fall **slowly** as the charge is unable to flow as well

- If the leaf does not move at all, the material is a **good insulator**

- The expected results are shown in the table below:

**Table of conductors and insulators**

| good conductors | poor conductors (insulators) |
|---|---|
| metal | plastic |
| graphite | glass |
| | wood |
| | rubber |
| | fabric |

## Evaluating the experiment

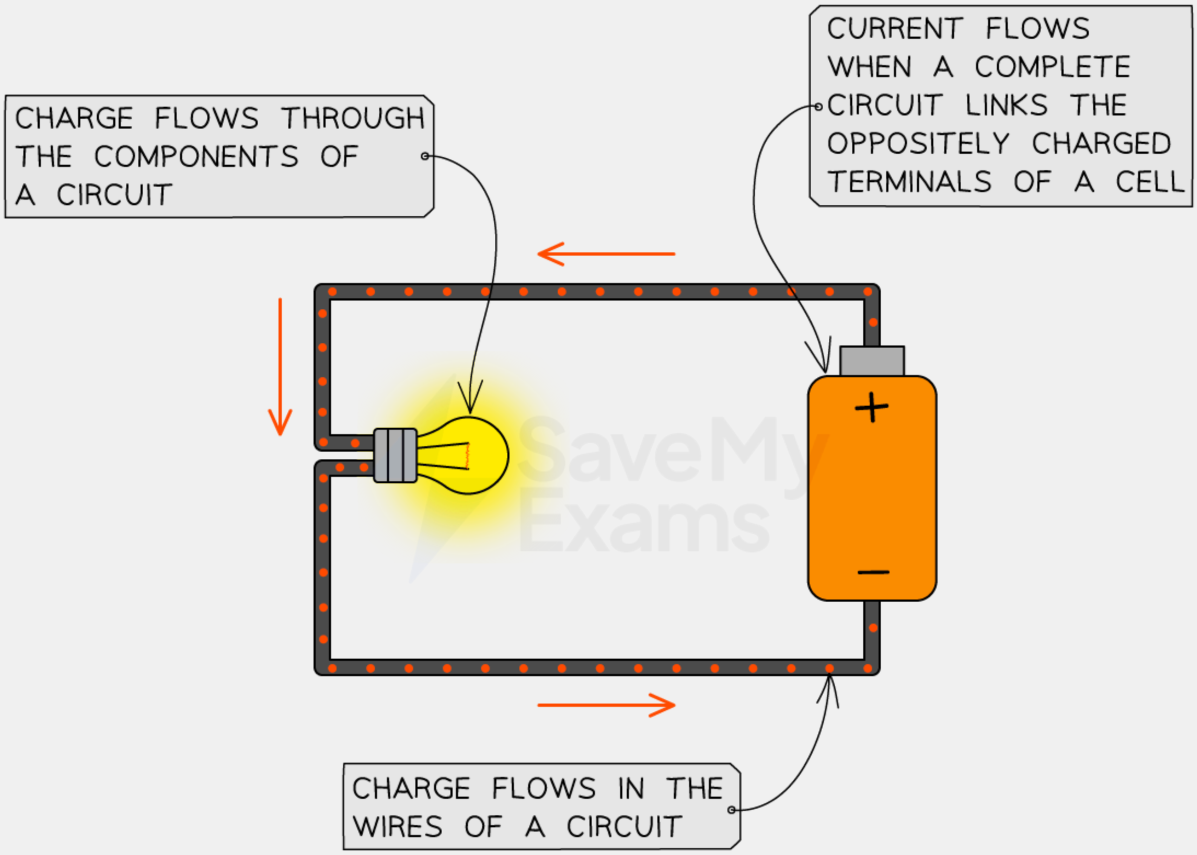
- An electrometer (electronic instrument capable of measuring electric charge) could be used instead of an electroscope to allow for numerical comparisons between good and poor conductors

## Current

- Electric current is defined as

**The rate of flow of electric charge**

- Current flows
  - when a **circuit** is formed e.g. when a wire connects the two oppositely charged terminals of a cell
  - from the **positive** terminal to the **negative** terminal of a cell

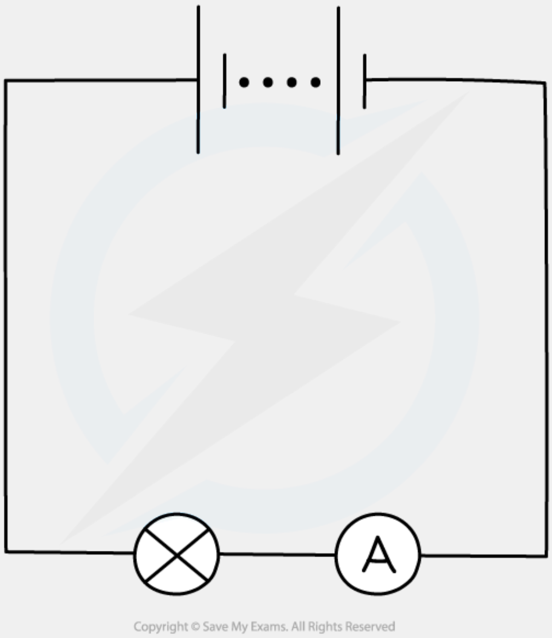




***Charge flows from the positive terminal to the negative terminal***

## Measuring current

- Current can be measured using an **ammeter**
- Ammeters must be connected in **series** with the component being measured

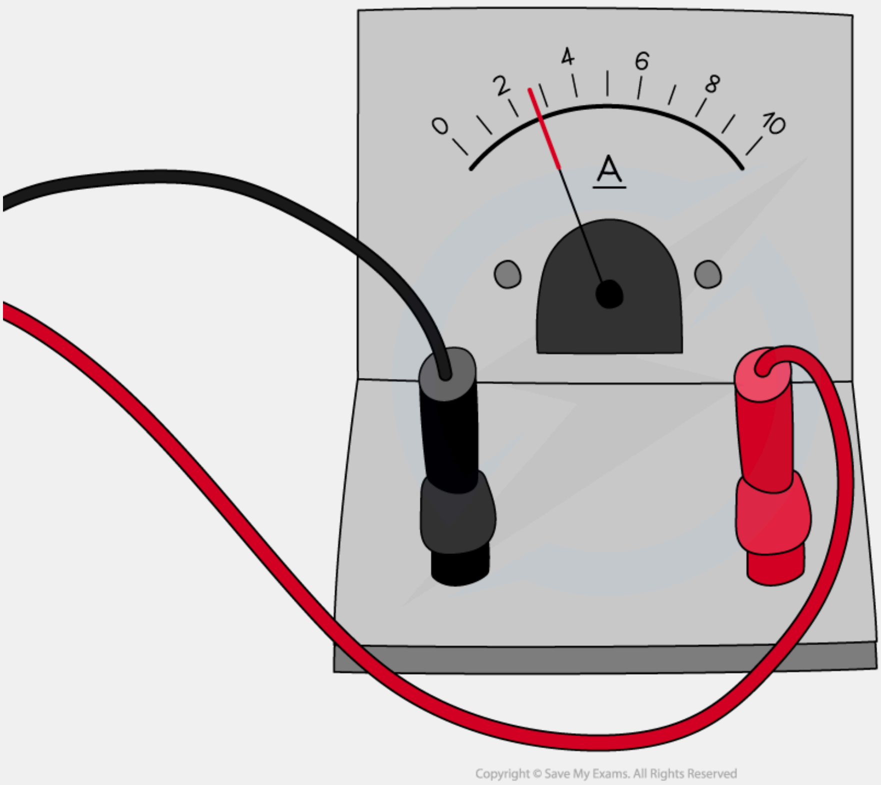



***An ammeter can be used to measure the current around a circuit***

- Ammeters can be
  - digital (with an electronic read out)
  - analogue (with a needle and scale)

## Analogue ammeters

- Typical ranges are 0.1-1.0 A and 1.0-5.0 A for analogue ammeters
  - Always double check exactly where the marker is before an experiment, if not at zero, you will need to subtract this from all your measurements. They should be checked for **zero errors** before using
- They are also subject to **parallax error**
  - Always read the meter from a position directly perpendicular to the scale



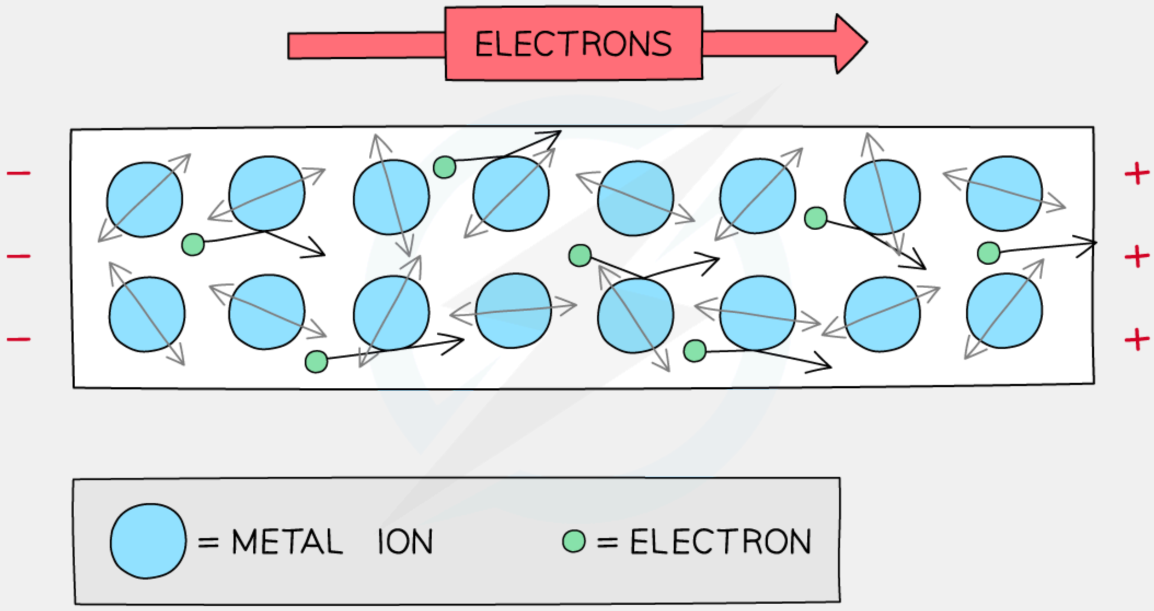

## Digital ammeters

- Digital ammeters can measure very small currents, in mA or μA
- Digital displays show the measured values as digits and are more accurate than analogue displays
- They're easy to use because they give a specific value and are capable of displaying more precise values
  - However digital displays may 'flicker' back and forth between values and a judgement must be made as to which to write down
- Digital ammeters should be checked for **zero error**
  - Make sure the reading is zero before starting an experiment, or subtract the "zero" value from the end results



## Electrical conduction in metals

- The wires in an electric circuit are made of **metal** because it is a good **conductor** of electric **current**
- In the wires, the current is a flow of **negatively charged electrons**





*In metal wires, the current is a flow of negatively charged electrons. When a potential difference is applied, electrons flow through the lattice of metal ions*

## Calculating current

- Electric current can be defined more precisely as:

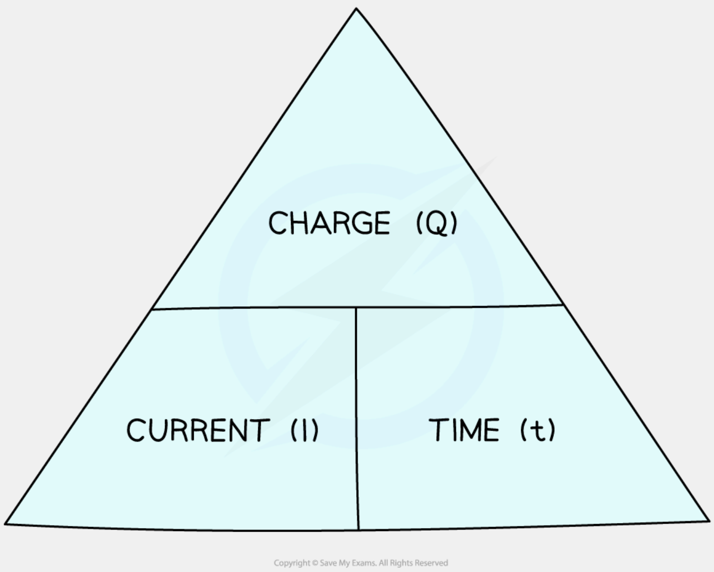
**The charge passing a point in a circuit per unit time**

- Current is measured in units of **amperes** or **amps (A)**
  - 1 amp is equivalent to a charge of 1 coulomb flowing in 1 second, or 1 A = 1 C/s
- This means the size of an electric current is the amount of charge passing through a component each second
- Current, charge and time are related by the equation:

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

- Where:
  - $Q$ = charge, measured in coulombs (C)
  - $I$ = current, measured in amps (A)
  - $t$ = time, measured in seconds (s)
- The current, charge and time equation can be rearranged with the help of the following formula triangle:

## Current charge time formula triangle




***Formula triangle for the charge, current and time equation***

## Worked Example

When will 8 A of current pass through an electrical circuit?

**A.** When 8 J of energy is used by 1 C of charge

**B.** When a charge of 4 C passes in 0.5 s

**C.** When a charge of 8 C passes in 0.1 s

**D.** When a charge of 1 C passes in 8 s

**ANSWER: B**

- The equation relating current, charge and time is:

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

- Consider option **B**, where $Q$ = 4 C and $t$ = 0.5 s:

$$I = \frac{4}{0.5} = 8\ A$$

- Therefore, the correct answer is **B**

**A** is incorrect as this is the definition of a voltage of 8 V between two points and does not describe current

**C** is incorrect as $I = \frac{8}{0.1} = 80\ A$

**D** is incorrect as $I = \frac{1}{8} = 0.125\ A$

## Examiner Tips and Tricks

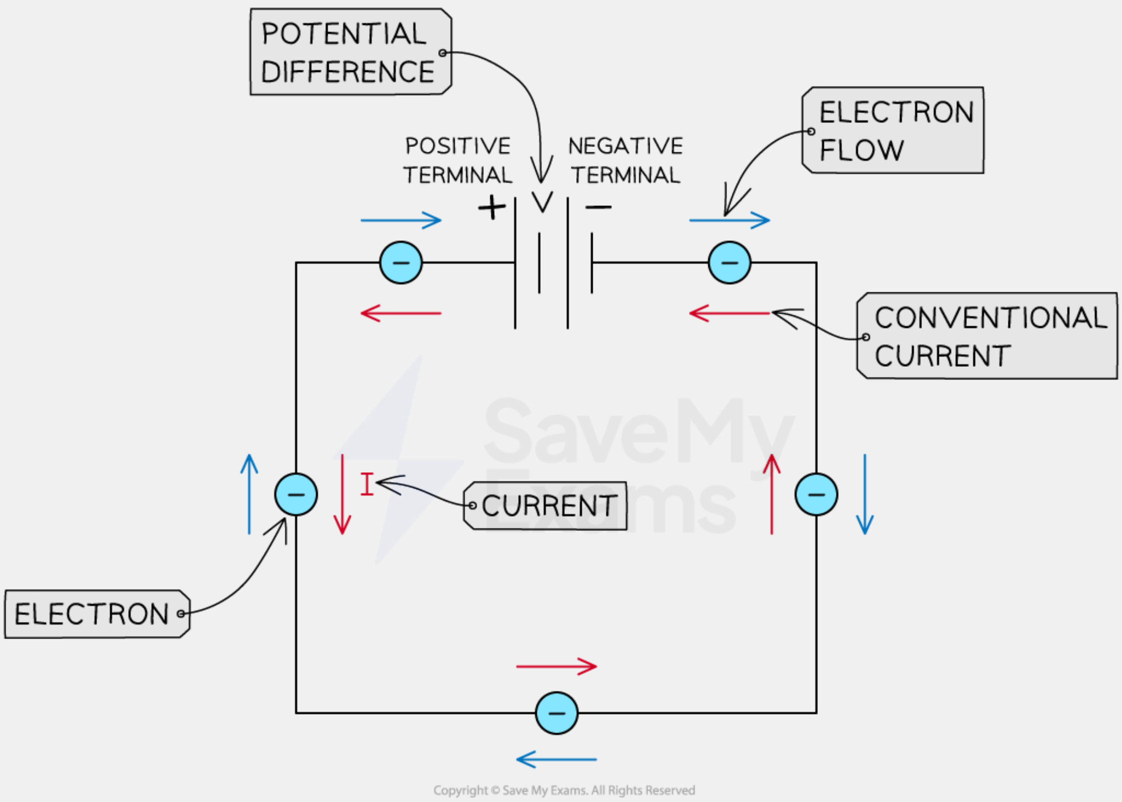
Electric currents in everyday circuits tend to be quite small, so it's common for examiners to throw in a **unit prefix** like 'm' next to quantities of current, e.g. 10 mA (10 milliamperes). Make sure you can convert these into standard units, e.g. 10 mA = 10 × $10^{-3}$ A.

Make sure to only use the triangle to help you **rearrange** the equation that links charge, current and time. Don't draw it if you are asked to write out the equation in full, such as $Q = I \times t$, as you may lose marks for doing so.

## Conventional current

- Current is the flow of **positive** charge i.e. from the **positive** terminal **to** the **negative** terminal of a cell
    - This is known as **conventional current**
- This is in the opposite direction to **electron flow**
    - Electrons are negatively charged, so they flow from the **negative** terminal **to** the **positive** terminal of a cell
    - Electrons are **repelled** from the negative terminal and **attracted** to the positive terminal

### Conventional current and electron flow




***By definition, conventional current always goes from positive to negative. This is in the opposite direction to the flow of electrons***

# Direct & Alternating Current

- There are **two** types of current
  - direct current (d.c.)
  - alternating current (a.c.)

## Direct current

- A direct current (d.c.) is defined as

**A steady current, constantly flowing in the same direction in a circuit, from positive to negative**

- The potential difference across a cell in a d.c. circuit travels in **one direction only**
  - The current travels from the positive terminal to the negative terminal
- A d.c. power supply has a **fixed** positive terminal and a fixed negative terminal
- Electric **cells**, or **batteries**, produce direct current (d.c.)

## Alternating current

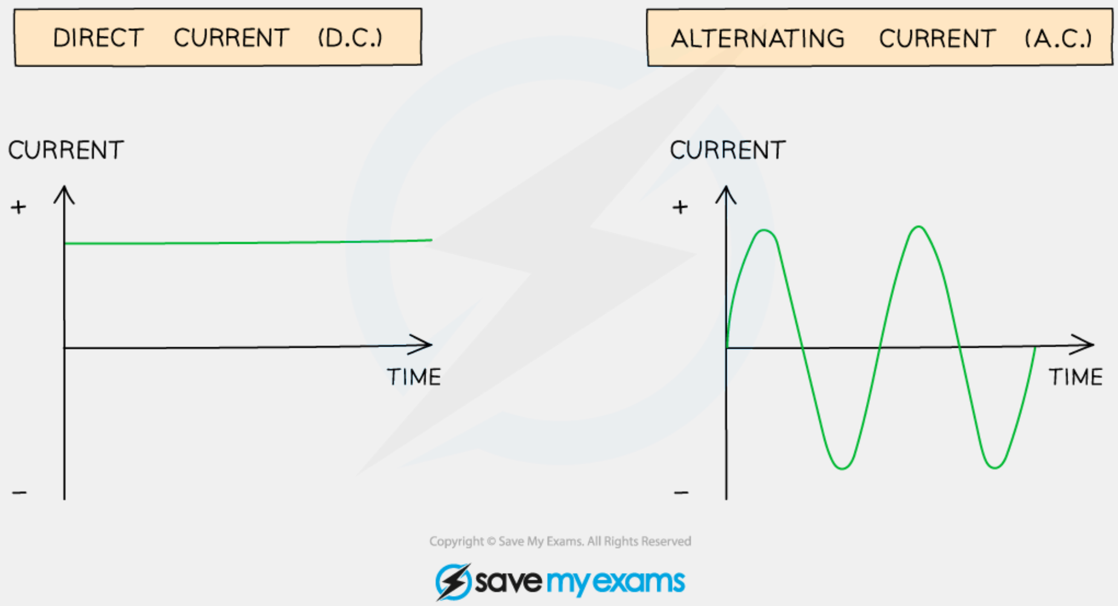
- An alternating current (a.c.) is defined as

**A current that continuously changes its direction, going back and forth around a circuit**

- An alternating current power supply has two identical terminals that **change** from positive to negative and back again
  - The alternating current always travels from the positive terminal to the negative terminal
  - Therefore, the current **changes direction** as the polarity of the terminals changes
- The **frequency** of an alternating current is the number of times the current changes direction back and forth each second

- In the UK, **mains electricity** is an **alternating** current with a frequency of 50 Hz and a potential difference of around 230 V

### Graphs of direct current and alternating current




*Two graphs showing the variation of current with time for alternating current and direct current*

## Comparing direct and alternating current

- The following table summarises the differences between d.c. and a.c.

### Direct current vs. alternating current table

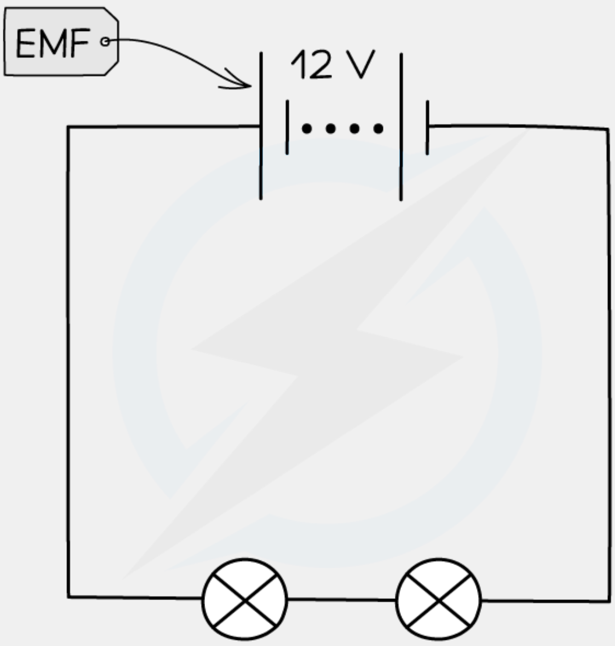
| Direct current (d.c.) | Alternating current (a.c.) |
|---|---|
| continuous and in one direction | constantly changing direction |
| produced by cells and batteries | produced by electrical generators i.e. mains electricity |
| involves a positive and negative terminal | involves two identical terminals |

## Electromotive Forces

- Electromotive force (e.m.f.) is the name given to the potential difference of the power source in a circuit
- It is defined as

**The electrical work done by a source in moving a unit charge around a complete circuit**

- Electromotive force (e.m.f.) is measured in volts (V)





***The e.m.f. is the voltage supplied by a power supply: 12 V in the above case***

## Calculating electromotive force

- The definition of e.m.f. can also be expressed using the equation:

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

- Where
  - $V$ = electromotive force (e.m.f.), measured in volts (V)

- *W* = energy transferred **to the charges** from the power source, measured in joules (J)
- *Q* = charge moved, measured in coulombs (C)

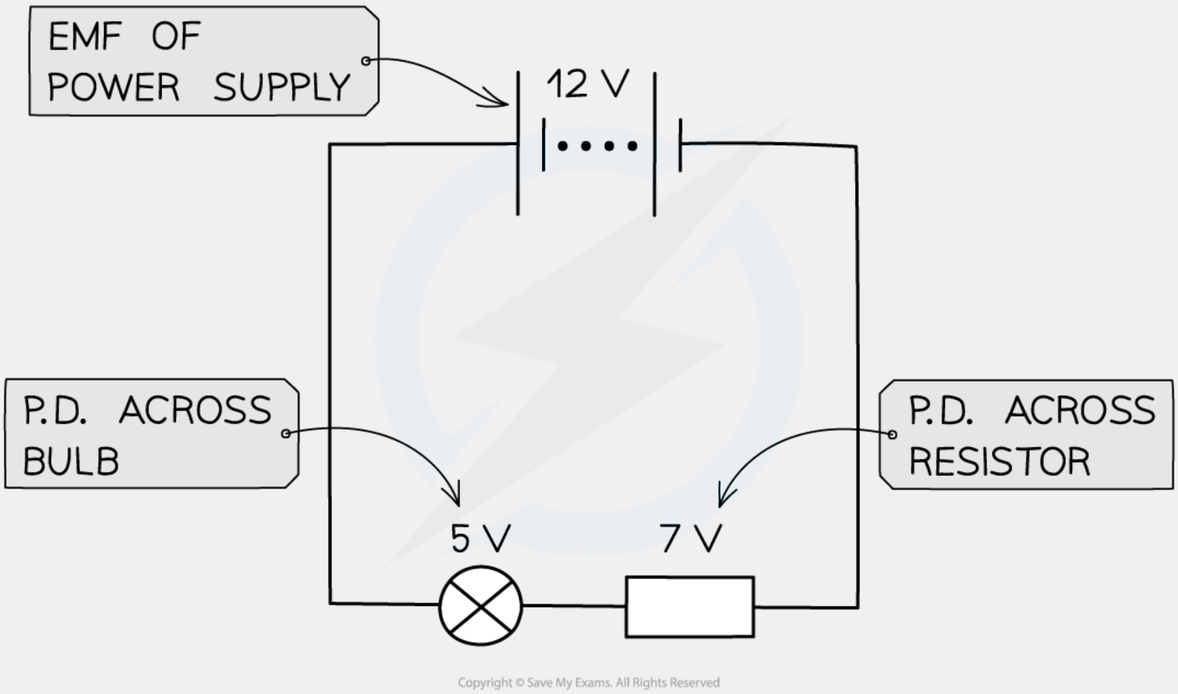
- This equation should be compared to the definition of potential difference as the two are closely related

## Potential Difference

- Potential difference is defined as:

**The work done by a unit charge passing through a component**

- Potential difference is measured in units of **volts (V)**
- The potential difference between two points in a circuit is related to the amount of **energy transferred** between those points

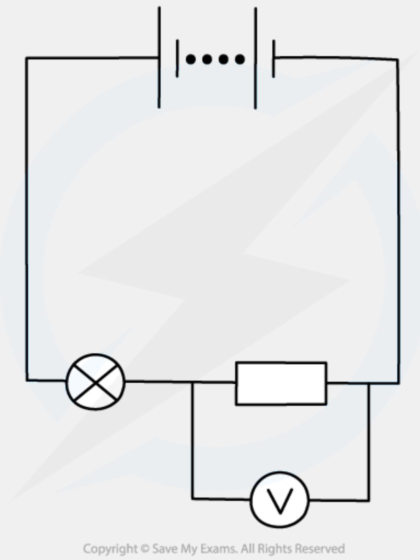



***The potential difference is the difference in the electrical potential across each component: 5 volts for the bulb (on the left) and 7 volts for the resistor (on the right)***

- As electrons flow through a cell, they **gain** energy
  - For example, in a 12 V cell, every coulomb of charge passing through gains 12 J of energy
- As electrons flow through a circuit, they **lose** energy
  - For example, after leaving the 12 V cell, each coulomb of charge will transfer 12 J of energy to the wires and components in the circuit

## Measuring potential difference

- Potential difference can be measured using a **voltmeter**
- Voltmeters must be set up in **parallel** with the component being measured
  - This is because potential difference is the **difference** in electrical potential between two points
  - Therefore, a voltmeter has to be connected to **two points** in the circuit



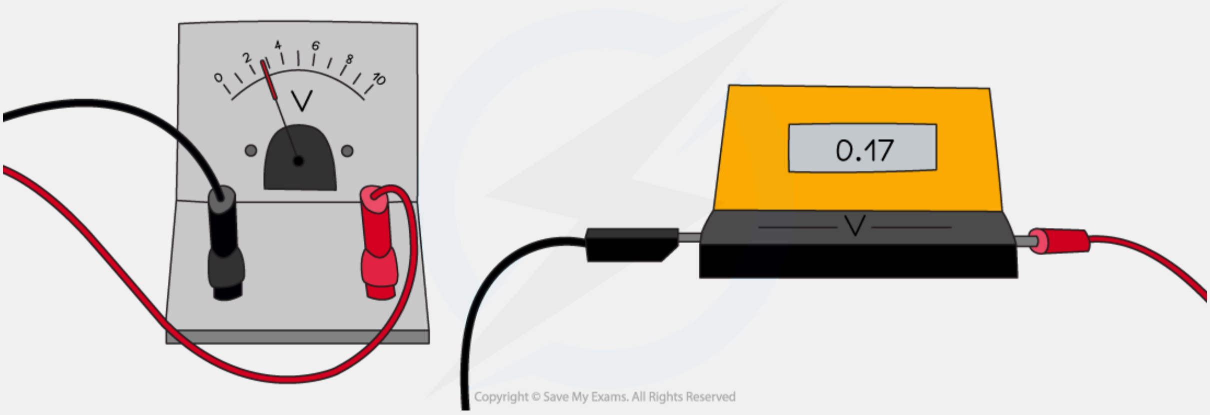

***Potential difference can be measured by connecting a voltmeter in parallel between two points in a circuit***

- Voltmeters can be
  - digital (with an electronic read out)
  - analogue (with a needle and scale)

## Analogue voltmeters

- Analogue voltmeters are subject to **parallax error**
  - Always read the meter from a position directly perpendicular to the scale
- Typical ranges are 0.1-1.0 V and 0-5.0 V for analogue voltmeters although they can vary

- Always double-check exactly where the marker is before an experiment, if not at zero, you will need to subtract this from all your measurements
- They should be checked for **zero errors** before using





***Voltmeters can be either analogue (with a scale and needle) or digital (with electronic read-out)***

## Digital voltmeters

- Digital voltmeters can measure very small potential differences, in mV or μV
- Digital displays show the measured values as digits and are more accurate than analogue displays
- They're easy to use because they give a specific value and are capable of displaying more precise values
  - However digital displays may 'flicker' back and forth between values and a judgement must be made as to which to write down
- Digital voltmeters should be checked for **zero error**
  - Make sure the reading is zero before starting an experiment, or subtract the "zero" value from the end results

## Examiner Tips and Tricks

You might sometimes see potential difference called voltage. Both mean the same thing, but it is best to use the term potential difference. This can be particularly useful when thinking about voltmeters as the potential difference describes a **difference** between **two** points, therefore the voltmeter has to be connected between **two** points in the circuit.

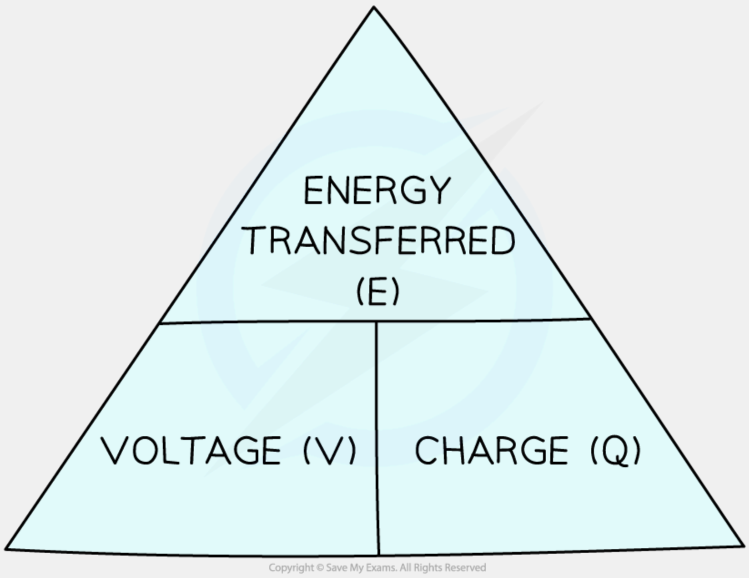
## Calculating potential difference

- Potential difference, energy transferred and charge are related by the equation:

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

- Where:
  - $V$ = potential difference, measured in volts (V)
  - $W$ = energy transferred to the components, measured in joules (J)
  - $Q$ = charge moved, measured in coulombs (C)
- One volt is equivalent to the transfer of 1 joule of electrical energy by 1 coulomb of charge, or 1 V = 1 J/C
- This can be rearranged using the formula triangle below:

### Energy charge and potential difference formula triangle




***Formula triangle for the energy transferred, voltage and charge equation***

- Check out the revision note on **1.2 Motion** under *speed, distance and time* if you need a reminder on how to use formula triangles

## Worked Example

The normal operating voltage for a lamp is 6 V.

Calculate how much energy is transferred in the lamp when 4200 C of charge flows through it.

**Answer:**

**Step 1: List the known quantities**

- Voltage, $V$ = 6 V
- Charge, $Q$ = 4200 C

**Step 2: State the equation linking potential difference, energy and charge**

- The equation linking potential difference, energy and charge is:

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

**Step 3: Rearrange the equation and substitute the known values**

$$W = V \times Q$$

$$W = 6 \times 4200 = 25\,200\ J$$

- Therefore, **25 200 J** of energy is transferred in the lamp

## Examiner Tips and Tricks

Don't be confused by the symbol for voltage (the **symbol** *V*) being the same as its unit (the **volt**, V). Remember that one volt is equivalent to 'a joule per coulomb'.

Make sure to learn this equation and understand how it is similar (and different) to the equation for e.m.f. by comparing their respective definitions. Both p.d. and e.m.f. both use the symbol *V*, as they are both quantifying energy transferred per charge. If using the same symbol for both quantities confuse you, it may be helpful to use *E* to symbolize e.m.f.. However, do be aware that this may cause you to confuse e.m.f. with energy!

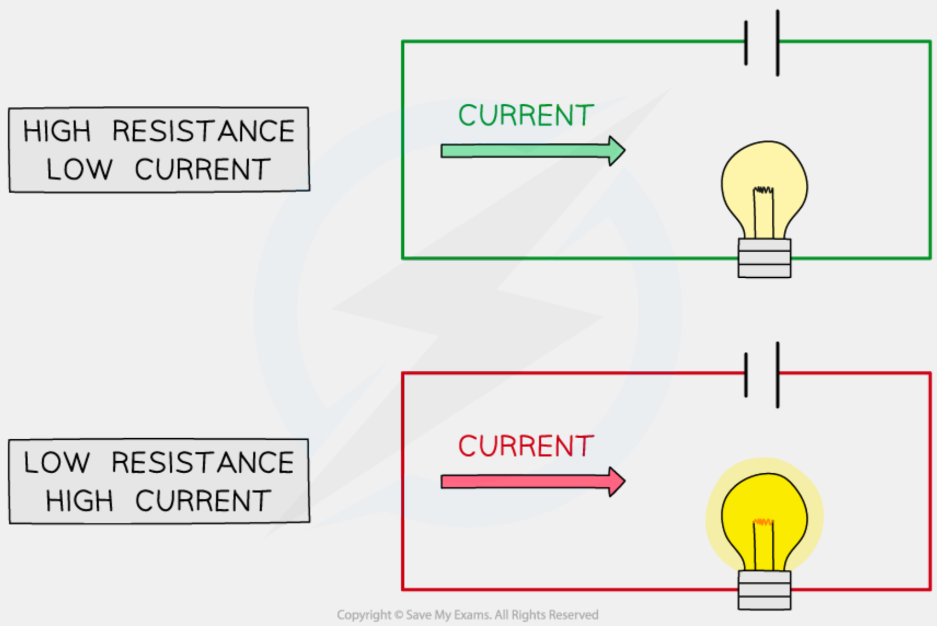
# <u>Resistance</u>

- **Resistance** is defined as:

**The opposition to current**

- Resistance occurs because the free **electrons** flowing in the circuit (current) **collide** with the metal ions in the wire
- These collisions **slow down** the electrons, or, in other words, **resist** their flow
  - The **higher** the resistance of a circuit, the **lower** the current
  - This means that good conductors have a **low** resistance and insulators have a **high** resistance
- The resistance of a circuit can be **increased** by adding resistors (or variable resistors) to it
- Every electrical component has a resistance, even wires
  - In exam questions, the resistance of the wires and batteries are assumed to be negligible

### The effect of resistance on the current in a circuit




***When a circuit has a high resistance, a lower current will flow, and vice versa***

## Ohm's law

- Current, $I$, potential difference, $V$, and resistance, $R$, all affect one another
- Changing any **one** of these in a circuit, changes **all** of them
- Current and resistance are **inversely proportional**
  - If the resistance is doubled, current will halve
- This relationship is described by the following equation, known as Ohm's law

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

- Where
  - $R$ = resistance, measured in ohms (Ω)
  - $V$ = potential difference, measured in volts (V)
  - $I$ = current, measured in amperes or amps (A)

### Consequences of Ohm's law

- Resistors are used in circuits to control either:
  - the current in branches of the circuit (through certain components)
  - the potential difference across certain components
- This is due to the consequences of Ohm's Law
  - The current in an electrical conductor decreases as its resistance increases (for a constant p.d.)
  - The p.d. across an electrical conductor increases as its resistance increases (for a constant current)

### Worked Example

A 12 Ω resistor has a current of 0.3 A flowing through it.

Determine the potential difference across the resistor.

**Answer:**

**Step 1: List the known quantities**

- Resistance, $R = 12\ \Omega$
- Current, $I = 0.3\ A$

**Step 2: Write out the equation for Ohm's law and rearrange to make potential difference the subject**

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

$$V = IR$$

**Step 3: Substitute in the known values to calculate**

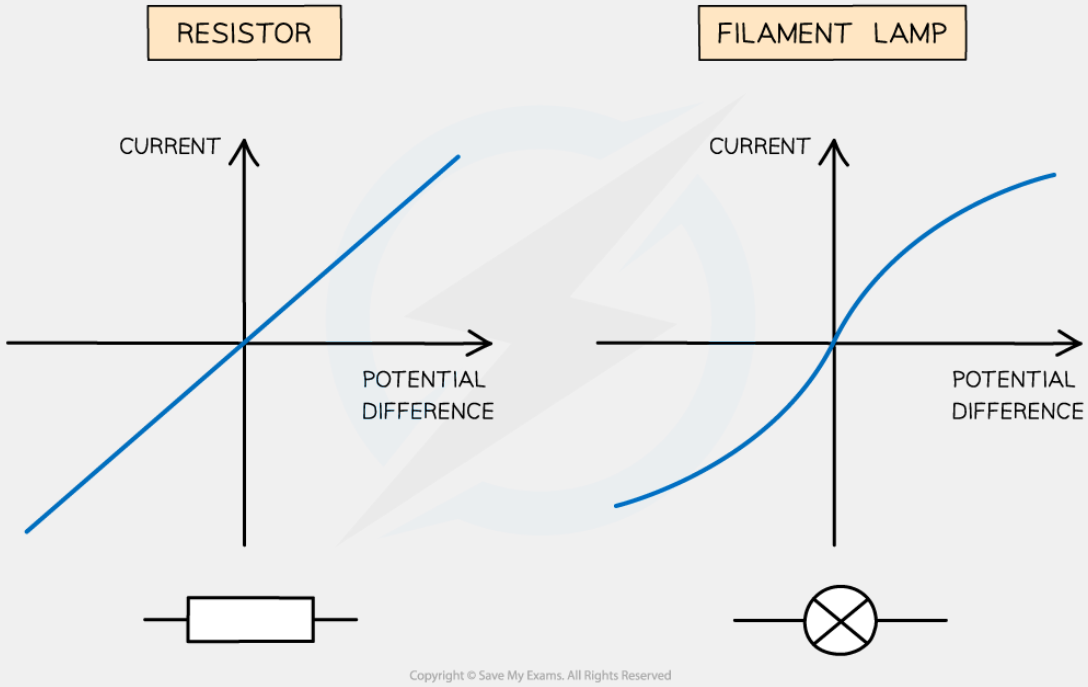
$$V = 0.3 \times 12$$

$$V = 3.6\ V$$

## Current-voltage graphs

- The relationship between current and potential difference of a component can be shown on a current-voltage (*I*-*V*) graph
- When the relationship between current and potential difference is **linear**:
  - the *I*-*V* graph is a **straight line** which passes through the **origin**
  - the resistance is **constant**
  - these are known as **ohmic resistors**
- When the relationship between current and voltage is **non-linear**:
  - the *I*-*V* graph that is **not** a straight line
  - the resistance is **not** constant
  - these are known as **non-ohmic resistors**

### Current-voltage (I-V) graph for a resistor and a filament lamp



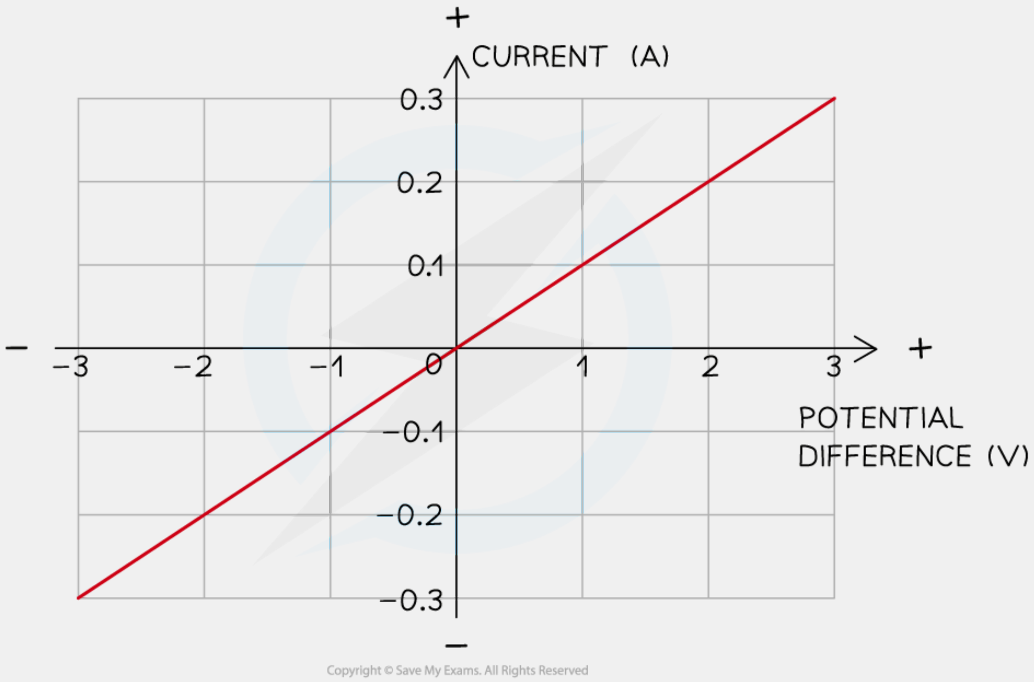

***Linear IV graphs are straight lines through the origin, indicating a constant resistance. Non-linear IV graphs are curved, indicating a variable resistance***

- Components with **linear** *I-V* graphs (ohmic resistors) include:
  - fixed resistors (at constant temperature)
  - wires (at constant temperature)
- Components with **non-linear** *I-V* graphs (non-ohmic resistors) include:
  - filament lamps
  - diodes
  - LDRs
  - thermistors

## I-V graph for ohmic conductors

- The relationship between current and voltage for a wire or fixed resistor is linear, or **directly proportional**, which means
  - the IV graph is a straight line, so voltage and current increase (or decrease) by the same amount
  - the slope of the graph is constant, so resistance is **constant**

**I-V graph for a wire of fixed resistor**

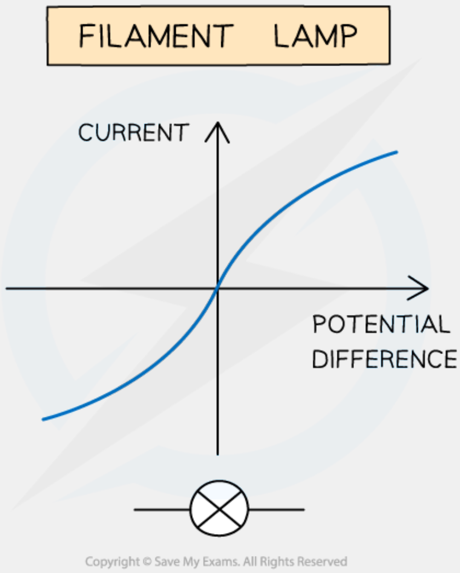



***The current is directly proportional to the potential difference (voltage) as the graph is a straight line through the origin***

## I-V graph for a filament lamp

- The relationship between current and voltage for a filament lamp is non-linear, or **not** directly proportional, which means
  - the *IV* graph is not a straight line, so voltage and current do **not** increase (or decrease) by the same amount
  - the slope of the graph is not constant, so resistance **changes**
- The *IV* graph for a filament lamp shows as voltage increases
  - the current increases at a proportionally **slower** rate
  - the resistance **increases**; the flatter the slope, the higher the resistance

**I-V graph for a filament lamp**




***As current flows through a filament lamp, the lamp heats up; resistance increases with temperature, causing the S-shaped curve***

- As current through a filament lamp increases, the resistance **increases** because:
  - the higher current causes the **temperature** of the filament to increase
  - the higher temperature causes the atoms in the metal lattice of the filament to **vibrate** more
  - this causes an increase in resistance as it becomes more difficult for **free electrons** (the current) to pass through
  - since resistance **opposes** the current, this causes it to increase at a **slower** rate

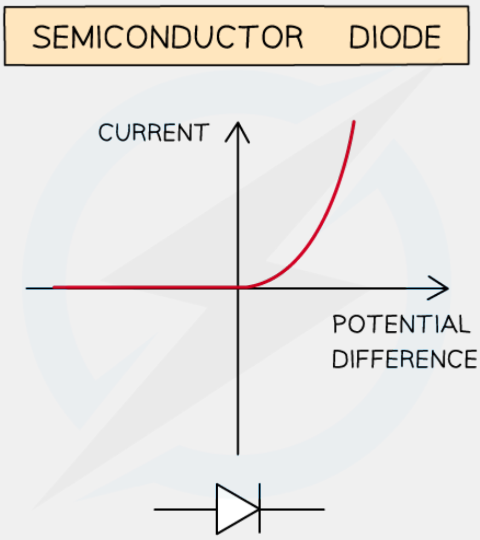
## I-V graph for a diode

- A diode allows current to flow in **one** direction only
  - This is called **forward bias**
- In the reverse direction, the diode has very **high resistance**, and therefore **no** current flows
  - This is called **reverse bias**
- When the current is in the direction of the arrowhead symbol, this is **forward bias**

- On the IV graph, this is shown by a sharp increase in voltage and current on the right side of the graph
- This shows the resistance is very **low**

- When the diode is switched around, this is **reverse bias**
    - On the IV graph, this is shown by a zero reading of current or voltage on the left side of the graph
    - This shows the resistance is very **high**

**I-V graph for a diode**





***The current is zero at all potential differences in the negative quadrants because current only flows one way through a diode; this gives the diode I-V graph its distinct shape***

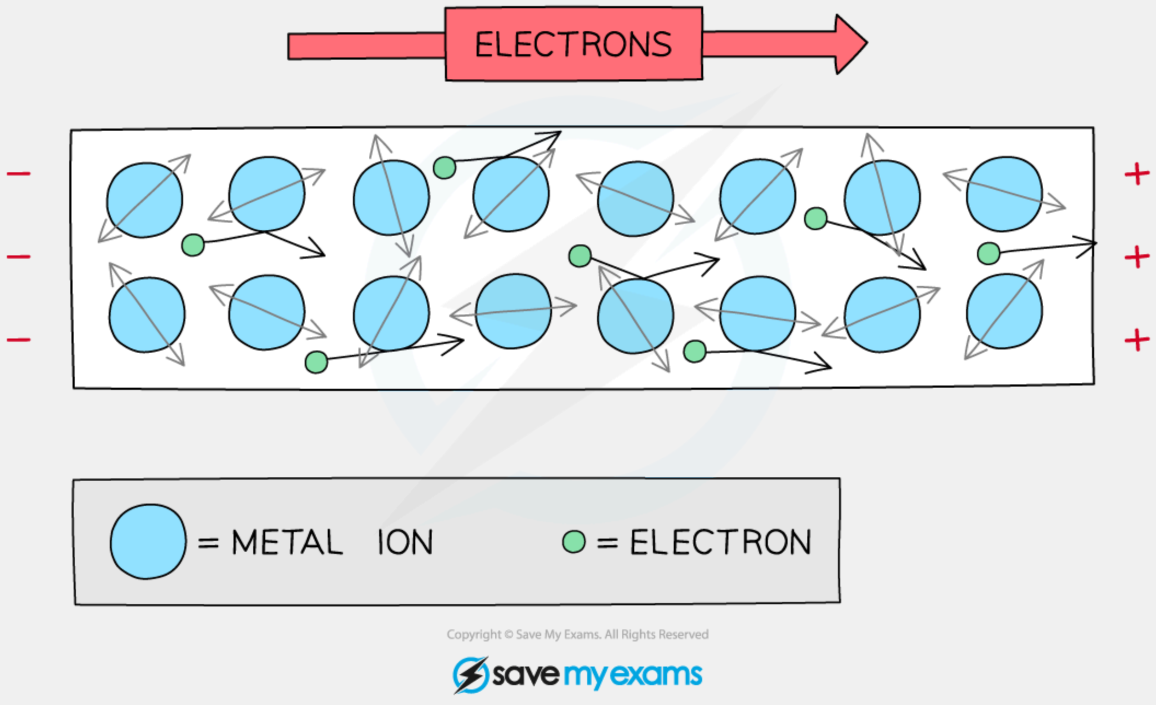
## Examiner Tips and Tricks

In your IGCSE exam, you could be asked to recognise, sketch or explain the I-V graphs for a wire / fixed resistor (ohmic conductors), a filament lamp and a diode.

# Resistance of a Wire

- As electrons pass through a wire, they **collide** with the metal ions in the wire
- These collisions transfer energy away from the kinetic store of the electrons, which causes them to **slow down**
- The energy from the electrons is transferred to the kinetic store of the vibrating metal ions
    - This causes the vibration of the ions to increase (increased temperature)
    - As the vibration of the ions increases, the more the electrons collide with them (increased resistance)

## Electron collisions in a metal wire




***Electrons collide with metal ions, which resist their flow***

- If the wire is longer, each electron will collide with more ions, and so there will be more resistance:
    - **The longer a wire, the *greater* its resistance**

- If the wire is thicker (greater diameter) there is more space for the electrons and so more electrons can flow:
    - **The thicker a wire, the *smaller* its resistance**
- If the wire is hotter (at a higher temperature), the metal ions are vibrating more, hence there are more collisions between the flowing electrons and the metal ions, slowing the flow of electrons:
    - **The greater the temperature of the wire, the *greater* its resistance**
        - Take note that thermistors have the opposite relationship, meaning its resistance decreases with increasing temperature

## Proportionality relationships for electrical conductors

- The relationship between resistance, length and cross-sectional area can be represented mathematically
- Resistance is **directly** proportional to **length**
    - Doubling the length will double the resistance and vice versa

$$R \propto L$$

- Resistance is **inversely** proportional to **cross-sectional area** (width, or thickness)
    - Doubling the cross-sectional area will halve the resistance

$$R \propto \frac{1}{A}$$

- Different materials have **different conductivity**, even if their length and cross-sectional area is the same
    - For example, copper will have a **lower resistance** than aluminium even if the wire has the same length and area

$$R \propto \rho$$

    - ρ is a symbol for resistivity, which is a constant showing how conductive a material is at a certain temperature

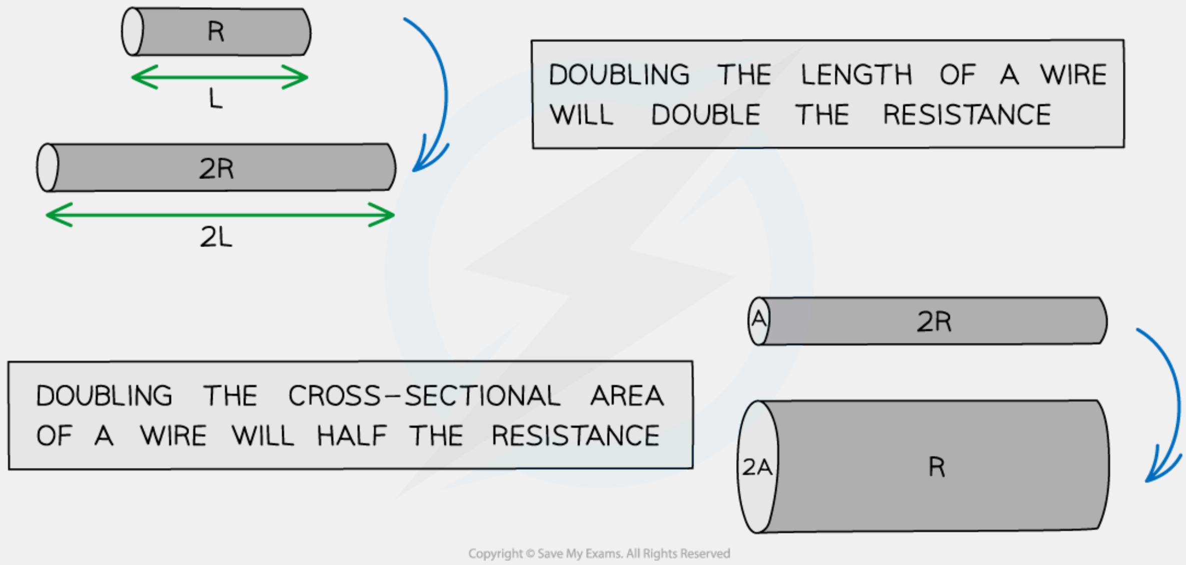
- Combining the above three relationships, we can obtain the equation:

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

- Where:

- $R$ = resistance, measured in ohms (Ω)
- ρ = resistivity, measured in ohm metre (Ω m)
- $A$ = cross-sectional area, measured in metre squared ($m^2$)

### Effect of length and cross-sectional area on resistance



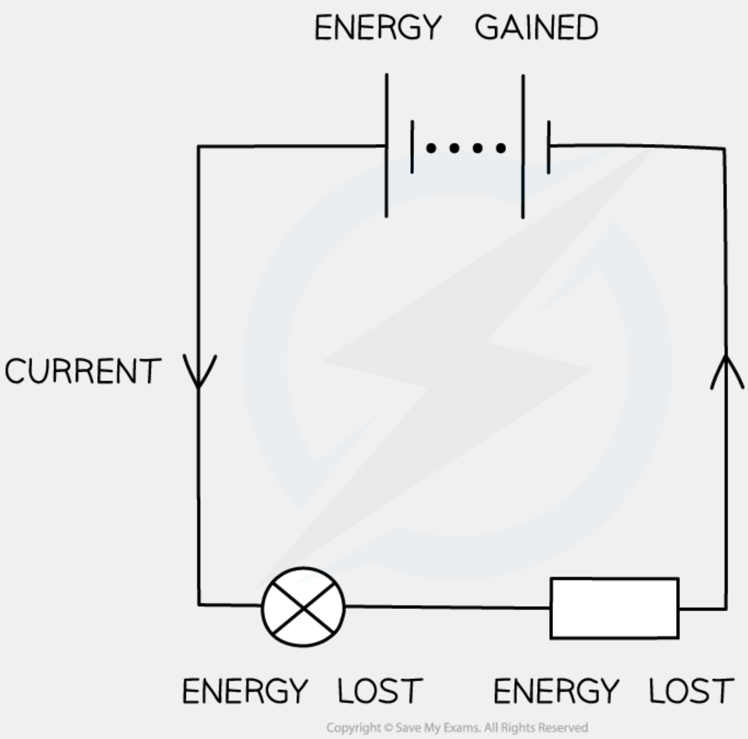

***The mathematical relationship between length and width of the wire and the resistance***

# Electrical Energy

## Energy transfer in electrical circuits

- As charge (electrons) flows around a circuit, energy is transferred from the power source to the various components
  - As electrons pass through the power supply, energy is transferred to the electrons
  - As the electrons pass through each component, energy is transferred from the electrons to the component
  - The component will often dissipate some of that energy to the surroundings

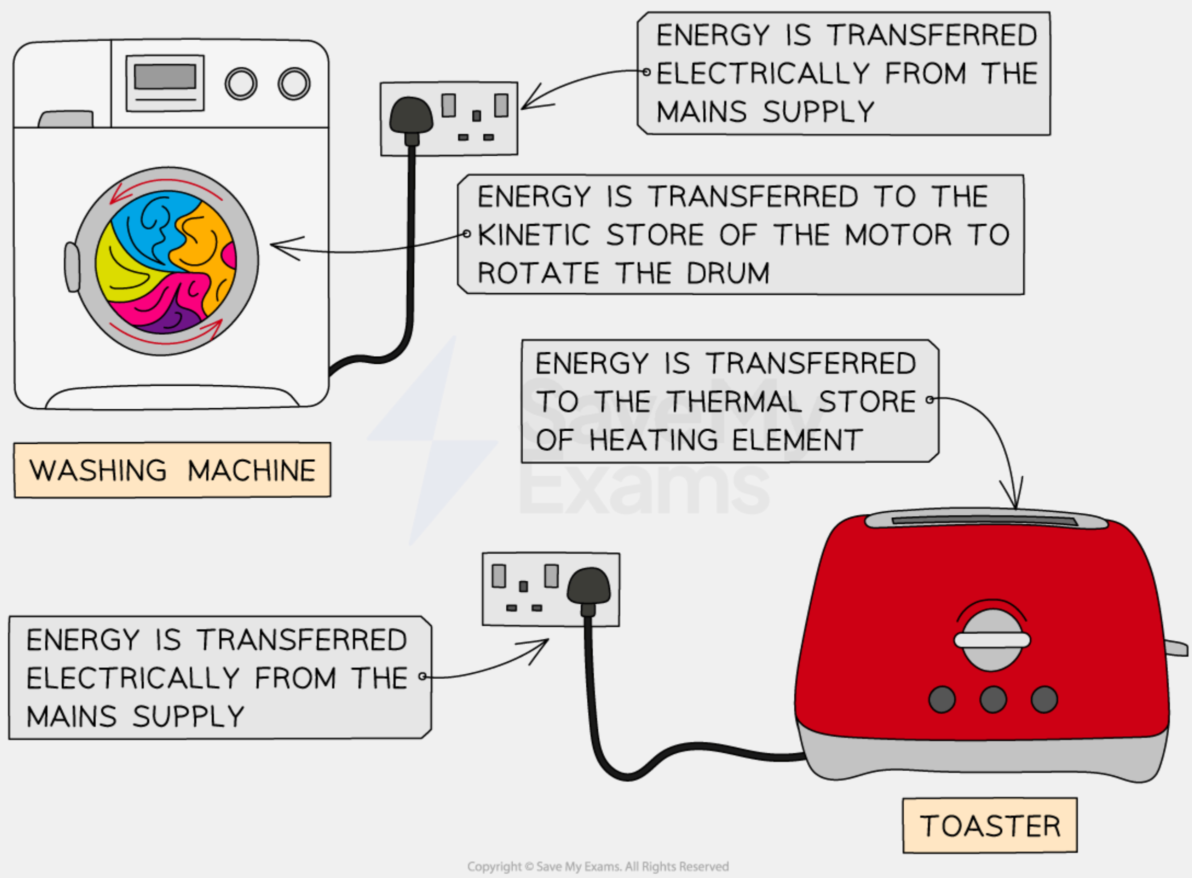
### Energy transfers in a circuit




*Charge gains energy from the power supply, and transfers the energy to the components*

- Some domestic appliances transfer energy from the chemical store of cells and batteries, such as mobile phones, laptops, and remote controls
- Most larger household appliances transfer energy electrically from the mains supply
- Lots of household appliances contain motors
    - Vacuum cleaners: to create the suction to suck in dust and dirt off carpets
    - Washing machines: to rotate the drum to wash (or dry) clothes
    - Refrigerators: to compress the refrigerant chemical into a liquid to reduce the temperature
- Energy is transferred electrically from the mains supply to the kinetic store of the motor in the appliance
- Lots of household appliances contain heaters
    - Toasters: to heat up food
    - Kettles: to boil water
    - Boiler in a central heating system: hot water is pumped from the boiler so the radiator can heat up a room
- Energy is transferred electrically from the mains supply to the thermal store of the heater.

## Energy transfers in common household appliances




***Energy is transferred electrically from the mains supply to the kinetic store of the motor in a washing machine, or to the thermal store of the heating element in a toaster***

## Electrical energy equation

- The amount of energy transferred by an electrical appliance depends on:
  - how long the appliance runs for
  - the power rating of the appliance
- Electrical energy can be calculated using the following equation:

$$E = VIt$$

- Where:
  - $E$ = energy, measured in joules (J)
  - $V$ = potential difference, measured in volts (V)
  - $I$ = current, measured in amps (A)

- $t$ = time, measured in seconds (s)

## Worked Example

A washing machine runs a cycle for 3 hours and 16 minutes. The potential difference of the mains supply is 230 V. A current of 10.0 A flows through the washing machine for the duration of the cycle.

Determine the amount of energy transferred from the mains supply during the cycle. Give your answer in MJ.

**Answer:**

**Step 1: List the known quantities**

- Potential difference, $V = 230\,V$
- Current, $I = 10.0\,A$
- Time, $t = 3\,hrs\,16\,min$

**Step 2: Convert the time to seconds**

- 1 hour = 60 mins

$$3 \times 60 = 180\,min$$

$$180 + 16 = 196\,min$$

- 1 min = 60 s

$$196 \times 60 = 11\,760\,s$$

**Step 3: Write out the equation for electrical energy**

$$E = VIt$$

**Step 4: Substitute in the known values to calculate**

$$E = 230 \times 10 \times 11\,760$$

$$E = 27\,048\,000\,J$$

**Step 5: Give your answer in MJ**

- 1 MJ = 1 000 000 J

$$E = 27\,MJ$$

# Electrical Power

## Electrical power equation

- The **power** of an appliance is defined as:

**The rate at which energy is transferred by an appliance**

- Power can be calculated in terms of energy:

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

- Where:
    - $P$ = power, measured in watts (W)
        - The watt is equivalent to joules per second (J/s)
    - $E$ = energy transferred, measured in joules (J)
    - $t$ = time, measured in seconds (s)
- Power can also be calculated in terms of work done:

$$P = \frac{W}{t}$$

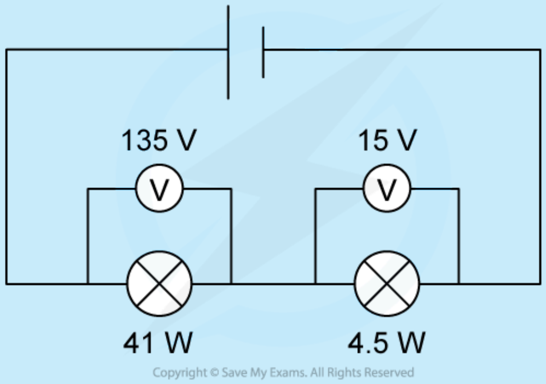
- Where:
    - $W$ = work done, which is equivalent to energy transferred, measured in joules (J)
- The power of an electrical device is the **energy transferred per second** by the device
- The power dissipated by an electrical component can be calculated by:

$$P = IV$$

- Where:
    - $P$ = dissipated power, measured in watts (W)
    - $I$ = current, measured in amps (A)
    - $V$ = potential difference, measured in volts (V)

## 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**

**Step 1: Calculate the current required for both lamps to operate**

- For the 41 W lamp, with 135 V

$$P = IV$$

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

$$I = \frac{41}{135}$$

$$I = 0.3\ A$$

- For the 4.5 W lamp, with 15 V

$$I = \frac{4.5}{15}$$

$$I = 0.3\ A$$

**Step 2: Determine the outcome of the bulbs**

- For both bulbs to operate at their normal brightness, a current of 0.3 A is required

- The lamps are connected in series, so the same current would flow through both
- Therefore, the lamps will light at their normal brightness
  - This is option **A**

### Examiner Tips and Tricks

When doing calculations involving electrical power, remember the unit is Watts W, therefore, you should **always** make sure that the time is in **seconds**

## Measuring energy usage

### Energy measured in joules

- Electrical energy transferred is often calculated with units of joules
  - One joule is equivalent to one-watt second
- Consider an average lightbulb with a power of 60 W, which is left on for 6 hours in a house
  - 1 hour is 3600 s
  - The energy transferred over this time is $1.296 \times 10^6$ J
- This number is large and that is only one lightbulb for a single day
  - A household uses many appliances all year round; the energy transferred per month in joules would be inconveniently large

Energy measured in kilowatt-hours

- To make these large values more relatable to daily use:
  - Power can be measured in kilowatts (kW)
  - Time can be measured in hours (h)
- In this case, energy has units of kilowatt-hours (kW h)
  - The lightbulb from before receives 0.36 kW h of energy over the 6 hours

- This value is much easier to understand for consumers and energy providers; thinking in terms of hours of use is more practical than seconds

## Calculating with kWh

- As has been stated previously, the equation for energy transferred is:

$$E = Pt$$

- But here, different units are considered:
  - $E$ = energy transferred, measured in kilowatt hours (kW h)
  - $P$ = power of the appliance, measured in kilowatts (kW)
  - $t$ = time, measured in hours (h)
- The usual unit of energy is joules (J), which is one watt-second
- To find the number of joules in 1 kW h, convert the power and time to watts and seconds

$$1\ kW\ h = 1000\ W \times 3600\ s = 3.6 \times 10^6\ J$$

- Therefore, 1 kWh = $3.6 \times 10^6$ J

- To convert from kW h to J:

$$E\ (kW\ h) \times \left(3.6 \times 10^6\right) = E\ (J)$$

- To convert from J to kW h:

$$E\ (J) \div \left(3.6 \times 10^6\right) = E\ (kW\ h)$$

- The kW h is a large unit of energy, and is mostly used for energy in homes, businesses and factories

### Worked Example

A cooker transfers $1.2 \times 10^9$ J of energy electrically to the thermal store of the heating element during its use over a year.

Assume that 1 kW h costs 14.2 p.

100 p = £1 (100 pence = 1 pound)

Calculate the cost of using the oven for the year.

**Answer:**

**Step 1: List the known quantities**

- Energy in joules, $E(J) = 1.2 \times 10^9\ J$
- Cost per kW h, $1\ kW\ h = 14.2\ p$

**Step 2: Convert the energy used from J to kW h**

$$E(kW\ h) = \frac{1.2\times10^9}{3.6\times10^6} = 333.3333 ... kW\ h$$

**Step 3: Calculate the price**

$$1\ kW\ h = 14.2\ p$$

$$333.3333 \times 14.2 = 4733\ p = £47.33$$

## Examiner Tips and Tricks

The kilowatt hour is a tricky concept to get your head around, so make sure you are comfortable with the conversions between kW h and J well before your exam.