A Level Physics Edexcel

3. Electric Circuits

CONTENTS

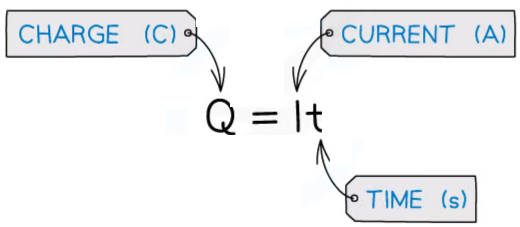
Electric Current

Electric Current

- Electric current is defined as:

    The rate of flow of charge

- It is measured in units of **amperes (*A*)** or **amps**
- The charge, current and time are related by the equation:



- There are several examples of electric currents, including in household wiring and electrical appliances

Electric Charge

- Electric charge is a property of some particles
    - For example, **protons** have a **positive** charge and **electrons** have a **negative** charge
- Charge has the unit Coulombs, C
- In electric circuits, **electrons** are usually the **charge carriers**
    - They have a charge of 1.6×10^{-19} C
- Charge, Q, can be calculated using the equation

$$Q = ne$$

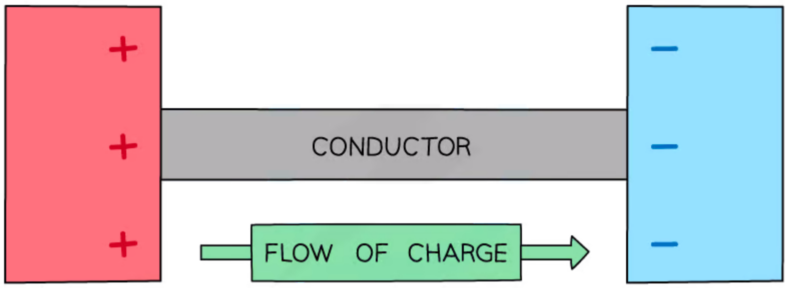
- Where:
    - Q = charge (C)
    - *n* = number of electrons
    - e = electron charge (C)

- If 1 electron has a charge of 1.6×10^{-19} C
    - Then, 1 C of charge contains 6.25×10^{18} electrons

- Charge is sometimes written as ΔQ which means 'change in charge'
    - Similarly, time is written as Δ*t* means 'change in time'

- When two oppositely charged conductors are connected together (by a length of wire), charge will flow between the two conductors, causing a current
- Therefore, rearranging for current, *I* gives the equation:

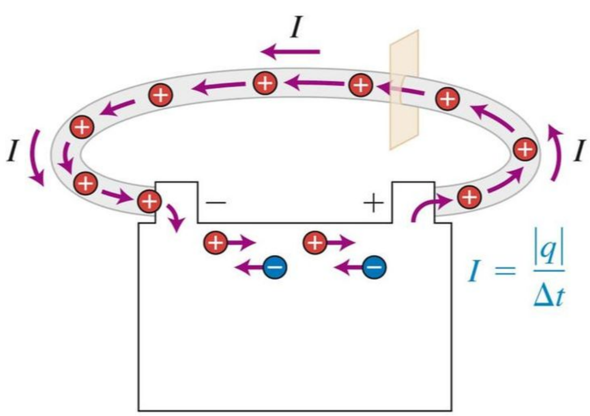
$$I = \frac{\Delta Q}{\Delta t}$$



Charge can flow between two conductors. The direction of conventional current in a metal is from positive to negative

Direction of Flow of Charge

- In electrical wires, the current is a flow of **electrons**
- Electrons are negatively charged; they flow away from the negative terminal of a cell towards the positive terminal
- Conventional current is defined as the flow of **positive** charge from the **positive terminal of a cell to the negative terminal**
  - This is the opposite to the direction of electron flow, as the conventional current was described before electric current was really understood



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

Measuring Current

- Current is measured using an **ammeter**
- Ammeters should always be connected in **series** with the part of the circuit the current is to be measured through
  - This is because the current is the same in all components connected in series

Potential Difference

Potential Difference

- A cell makes one end of the circuit positive and the other negative
- This sets up a **potential difference** across the circuit
  - This is sometimes known as the **voltage**

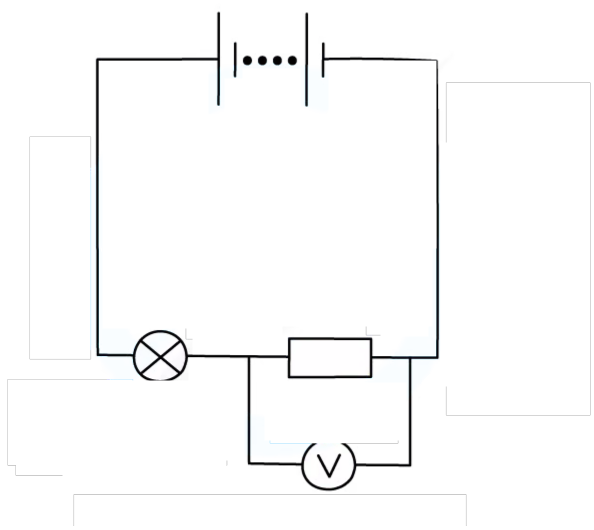
- The potential difference is defined as **the work done per unit charge** and is measured in units of **volts (*V*)**

$$V = \frac{W}{Q} \quad or \quad V = \frac{E}{Q}$$

V = Potential Difference (Voltage)
W = Work done
E = Energy
Q = Charge

Measuring Voltage

- Potential difference (or voltage) is measured using a **voltmeter**
- A voltmeter is always set up **in parallel to** (also called 'across') the component being measured
  - Potential difference across components in parallel is always the same due to conservation of energy



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

Worked Example

A resistor is connected to a battery which provides a potential difference of 10 V.

Calculate the work done when a charge of 2 C passes through the resistor.

Step 1: Write down the known quantities

- Potential difference, V = 10 V
- Charge, Q = 2 C

Step 2: Write down the equation relating potential difference, work done and charge

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

Step 3: Rearrange the equation to make work done the subject

$$W = VQ$$

Step 4: Substitute in the values and calculate W

$$W = 10 \times 2 = 20\ J$$

Exam Tip

Think of potential difference as being the **energy per coulomb** of charge transferred between two points in a circuit

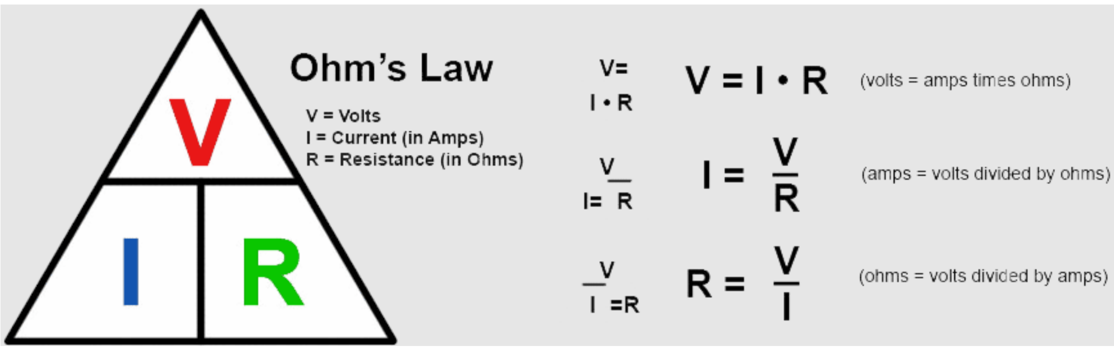
Defining Resistance

Resistance

- Resistance is defined as the **opposition** to current
- It is further defined by Ohm's Law, which says that the resistance of a conductor is given by the ratio of potential difference across it to the current flowing in it

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

- For a given potential difference, then, **the higher the resistance the lower the current**

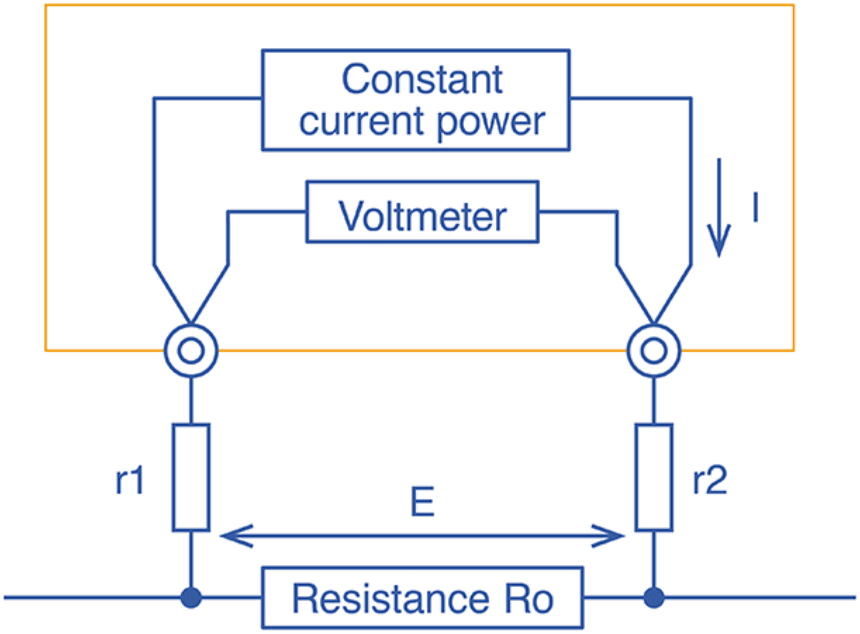


Resistance of a component is the ratio of the potential difference and current

- Resistance is measured in **Ohms (Ω)**
- An Ohm is defined as **one volt per ampere**
- The resistance controls the size of the current in a circuit
  - A **higher** resistance means a **smaller** current
  - A **lower** resistance means a **larger** current
- All electrical components, including wires, have some value of resistance

Measuring Resistance

- To find the resistance of a component, a simple circuit can be used, containing:
  - A power supply
  - A component (such as a lamp or resistor)
  - An ammeter in series with the component
  - A voltmeter in parallel with the compenent



A circuit to determine the resistance of a component

- The power supply should be set to a low voltage to avoid heating the component, typically 1–2 V
- Measurements of the potential difference and current should then be taken from the voltmeter and ammeter respectively
- Finally, these readings should be substituted into the resistance equation

Charge Conservation in Circuits

The Electric Current Rule (Kirchhoff's First Law)

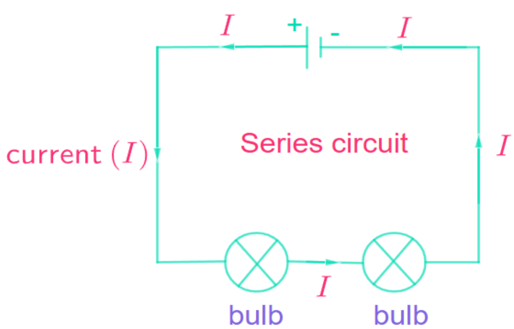
- The electric current rule is defined as:

The algebraic sum of the currents entering and leaving a junction is equal to zero

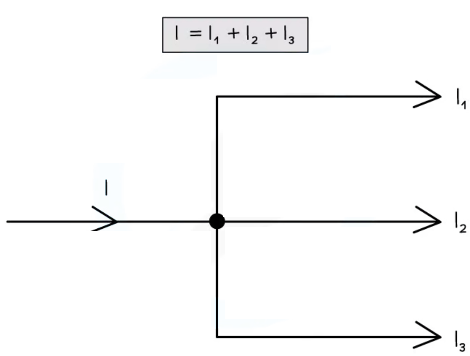
- This is a consequence of conservation of **charge –** current shouldn't decrease or increase in a circuit when it splits

Series and Parallel

- In a circuit:
  - A **junction** is a point where at least three circuit paths meet
  - A **branch** is a path connecting two junctions

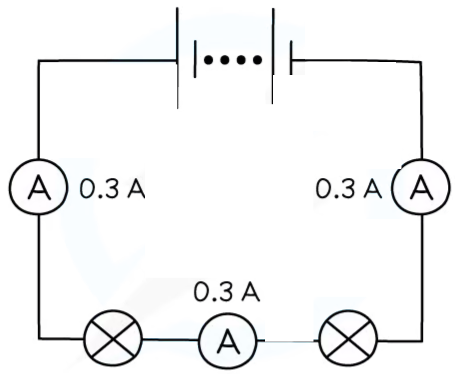


- If a circuit splits into two **branches**, then the current before the circuit splits should be equal to the current after it has split
- A typical circuit might have a setup where $I = I_1 + I_2 + I_3$ where:
  - I represent the current in the circuit before it branches
  - I_1, I_2 and I_3 represent the current in the respective three branches



The current I into the junction is equal to the sum of the currents out of the junction

- The charge is conserved on both sides of the junction
- In a **series** circuit, the current is the same at any point



The current is the same at all points in a series circuit

- In a **parallel** circuit, the current divides at the junctions and each branch has a different value.
- The electric current rule applies at each junction
  - The sum of the currents before the junction will equal the sum of the currents after the junction

Exam Tip

Junctions only appear in parallel circuits as circuits become more complex. It can be confusing to work out which currents are going into the junction and which are coming out. Drawing arrows on the diagram for the current flow (making sure it's from positive to negative) at each junction, such as in the worked example, will help with this.

The electric current rule is also known as Kirchhoff's First Law, and you may come across this phrase.

3.5 Energy Conservation in Circuits

Energy Conservation in Circuits

The Electrical Voltages Rule (Kirchhoff's Second Law)

- Energy is never used up or lost in a circuit, since everything follows the Law of Conservation of Energy
- The electrical voltages rule is defined as:

> **The sum of the e.m.f.s in a closed circuit loop is equal to the sum of the potential differences around that loop**

- Each closed circuit loop can be treated like a series circuit
- A typical circuit might have a setup where $E_1 + E_2 = V_1 + V_2$ where:
  - E_1 and E_2 represent the e.m.f.s in the closed loop
  - V_1 and V_2 represent the potential differences in the closed loop

ELECTRICAL VOLTAGES RULE $E_1 + E_2 = V_1 + V_2$

The sum of the voltages is equal to the total e.m.f from the batteries

- In a **series** circuit, the voltage is split across all components depending on their resistance
  - The sum of the voltages is equal to the total e.m.f of the power supply

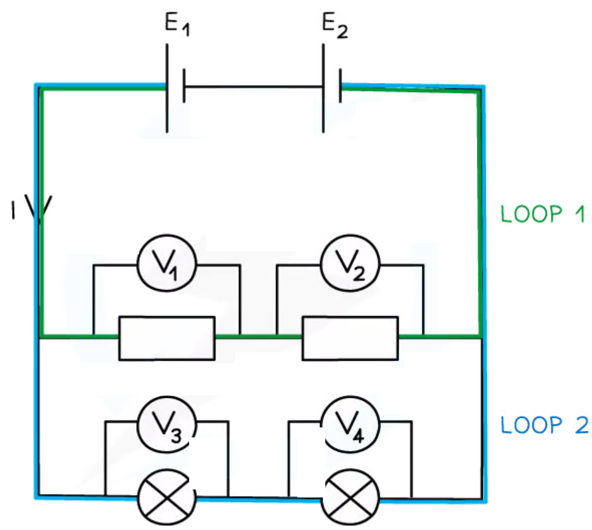
- In a **parallel** circuit, the voltage is the same across each closed loop
  - The sum of the voltages **in each closed circuit loop** is equal to the total e.m.f of the power supply:

ELECTRICAL VOLTAGES RULE: $E_1 + E_2 = V_1 + V_2 = V_3 + V_4$

The sum of the p.ds in each closed loop is equal to the total e.m.f of the power supply

- A closed-circuit loop acts as its own independent series circuit

- Each loop separates at a junction
- A parallel circuit is made up of two or more of these loops



Each circuit loops acts as a separate, independent series circuit

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

Exam Tip

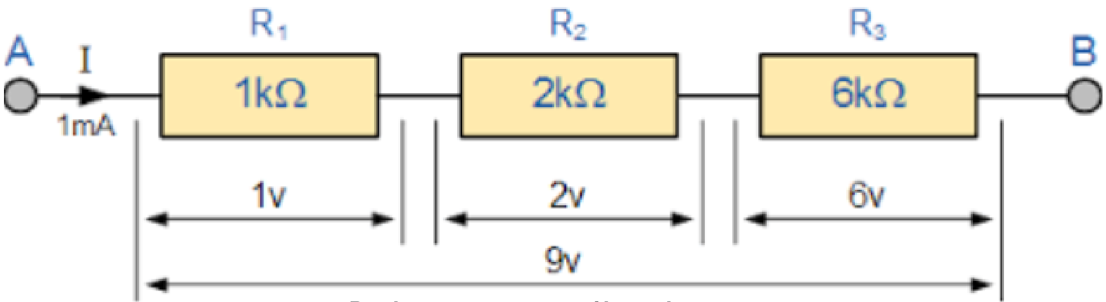
The Electrical Voltages Rules is sometimes known as Kirchhoff's Second Law.

Drawing the loops in different colours, as in the example above, can be a helpful way of identifying the different loops.

Deriving Equations for Resistance in Series & Parallel

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**



Resistors connected in series

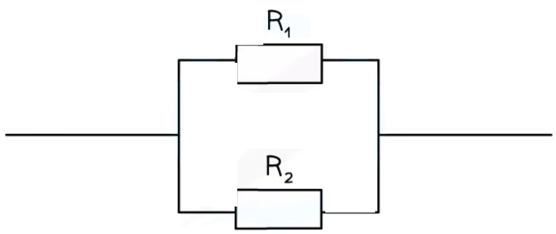
- The equation for combined resistors in series is derived using the electric current rule and the electrical voltages rule
- These rules describe that for a series circuit:
  - The current is the same through all resistors
  - The potential difference is split between all the resistors

- The equation for the combined resistance of resistors in series is therefore:

$$\text{COMBINED RESISTANCE IN SERIES} \quad R = R_1 + R_2 + R_3 \ldots$$

Resistors In Parallel

- In a parallel circuit, the combined resistance of the components requires the use of **reciprocals**
    - **the reciprocal of the combined resistance of two or more resistors is the sum of the reciprocals of the individual resistances**



Resistors connected in parallel

- The equation for combined resistors in series is derived using the electric current rule and the electrical voltages rule
- These rules describe that for a parallel circuit:
    - The current is the split at the junction (and therefore between resistors)
    - The potential difference is the same across all resistors

3.7 Electrical Power

Electrical Power

- Work is also defined as a transfer of energy
- When components transfer electrical energy to other stores, work must be done because energy is transferred
- Therefore, potential difference is the **work done per unit charge**

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

- Current is the **rate of flow of charge**

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

- These equations can be combined to give the work done by a component in an electric circuit

$$W = VIt$$

- Power *P* is defined as:

The rate of doing work

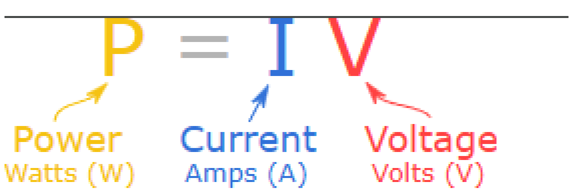
- In equation form this is

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

- This gives us

$$P = \frac{VIt}{t} = VI$$

- Therefore, the power dissipated (produced) by an electrical device is given by:



- Using ***V* = *IR*** to rearrange for either *V* or *I* and substituting into the power equation means we also write power in terms of resistance *R*

RESISTANCE (Ω)

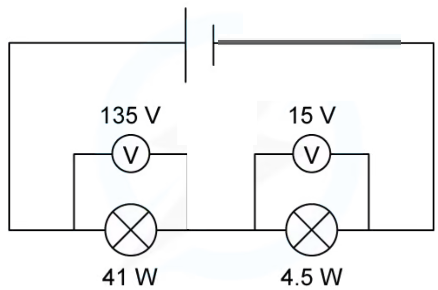
$$P = I^2R \qquad P = \frac{V^2}{R}$$

Power equation in terms of resistance

- The squared value for both current and voltage in these equations means that, for any given resistance, if the current or voltage **doubles**, the power will be **four** times as great
- Conversely, for a given power, if the resistance **doubles** then current will be 4 times **less** but voltage will be 4 times **greater**

Worked Example

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



Which statement is correct?

A. Both lamps light normally

B. The 15 V lamp blows

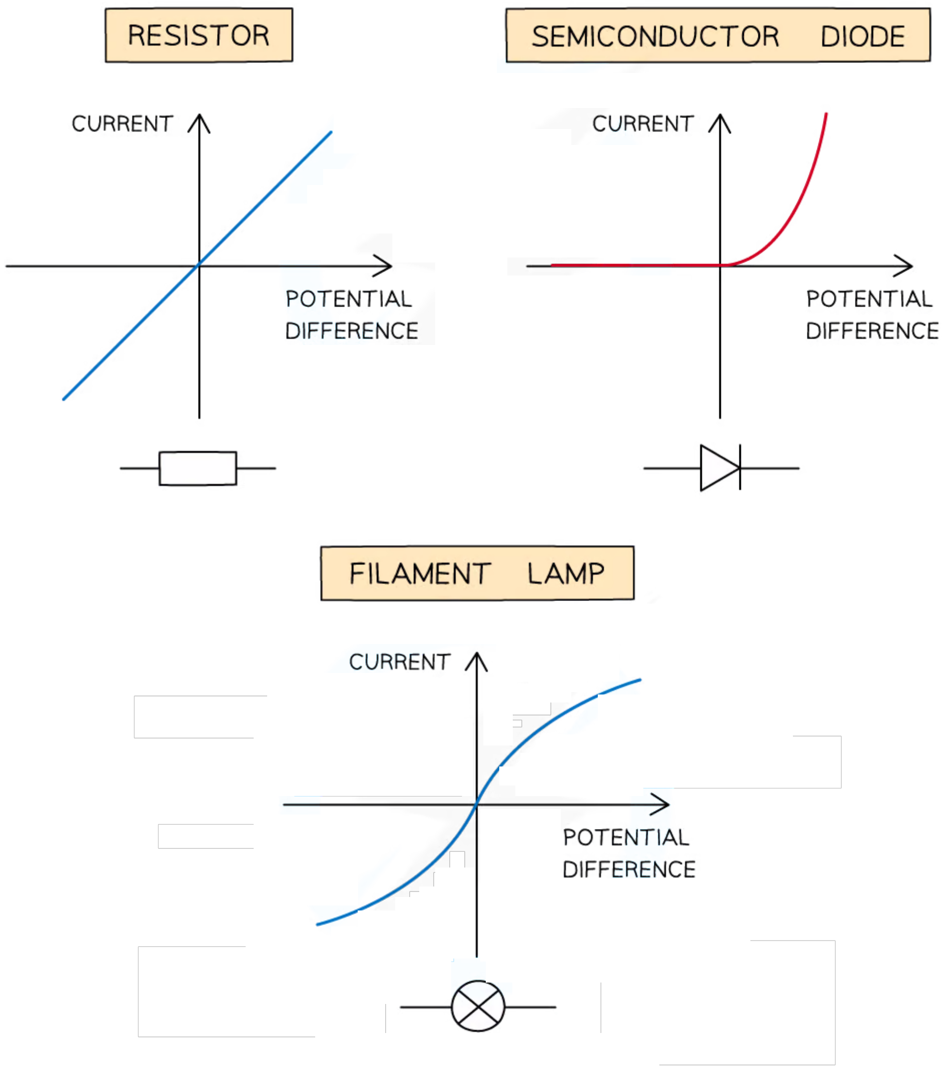
C. Only the 41 W lamp lights

D. Both lamps light at less than their normal brightness

ANSWER: A

Current–Potential Difference Graphs

- As the potential difference (voltage) across a component is increased, the current also increases (by Ohm's law)
- The precise relationship between voltage and current is different for different components and can be shown on a current-potential difference or *I*–*V* graph
  - For an ohmic conductor, the *I*–*V* graph is a straight line through the origin
  - For a semiconductor diode, the *I*–*V* graph is a horizontal line that goes sharply upwards
  - For a filament lamp, the *I*–*V* graph has an 'S' shaped curve



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

Ohmic Conductor

- The *I*–*V* graph for an ohmic conductor at constant temperature e.g. a resistor is very simple:

- The current is **directly proportional** to the potential difference
- This is demonstrated by the **straight-line** graph through the origin

Diode

- The *I–V* graph for a diode is slightly different.
- A diode is used in a circuit to allow current to flow only in a specific direction:
  - When the current is in the direction of the arrowhead symbol, this is **forward bias.** This is shown by the sharp increase in potential difference and current on the right side of the graph
  - When the diode is switched around, it does not conduct and is called **reverse bias.** This is shown by a zero reading of current or potential difference on the left side of the graph
  - The threshold voltage at which a diode starts to conduct is typically around 0.6V

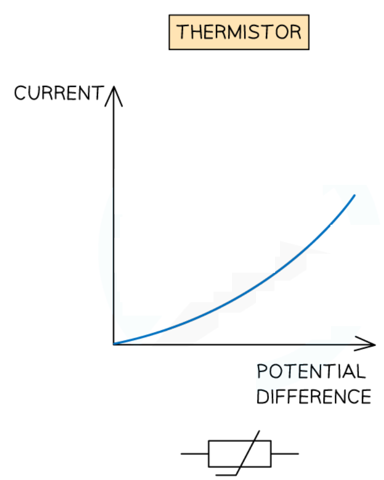
Filament Lamp

- The *I–V* graph for a filament lamp shows the current increasing at a proportionally slower rate than the potential difference
- This is because:
  - As the current increases, the **temperature** of the filament in the lamp **increases**
  - Since the filament is a metal, the higher temperature causes an **increase** in **resistance**
  - Resistance opposes the current, causing the **current** to **increase** at a **slower rate**

- Where the graph is a straight line, the resistance is constant
- The resistance increases as the graph curves
- The filament lamp obeys Ohm's Law for small voltages

Thermistor

- The *I–V* graph for a thermistor is a shallow curve upwards



- The increase in the potential difference results in an increase in current which causes the **temperature** of the thermistor to rise
- As its temperature rises, its resistance **decreases**
  - This means even more current is able to flow through

- Since the current is not directly proportional to the potential difference (the graph is still curved), the thermistor does **not** obey Ohm's Law

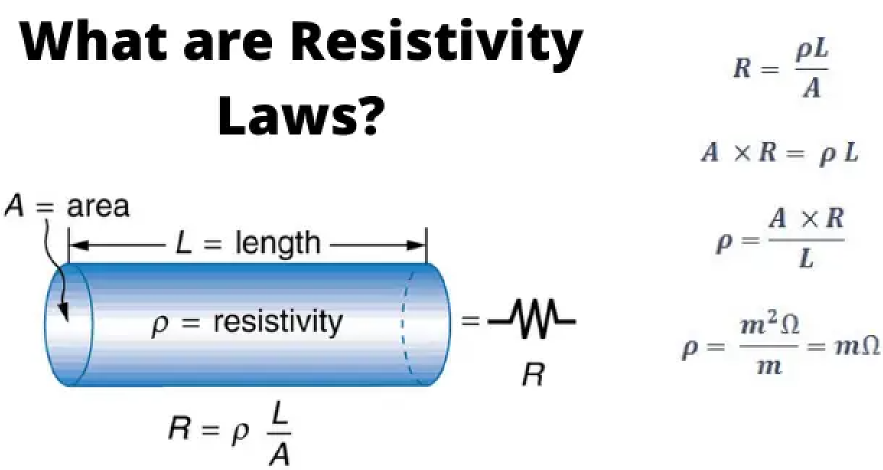
- The *I–V* graph for a thermistor shows the current increasing at a proportionally slower rate than the potential difference
- This is because:
  - As the current increases, the **temperature** of the thermistor **increases**
  - Which causes an **increase** in **resistance**
  - Resistance opposes the current, causing the **current** to **increase** at a **slower rate**

Resistance, Resistivity & Potential Dividers

3.9 Electrical Resistivity

Electrical Resistivity

- All materials have some **resistance** to the flow of charge
- As **free electrons move** through a metal wire, they collide with ions which get in their way
- As a result, they **transfer** some, or all, of their **kinetic energy** on **collision**, which causes electrical **heating**

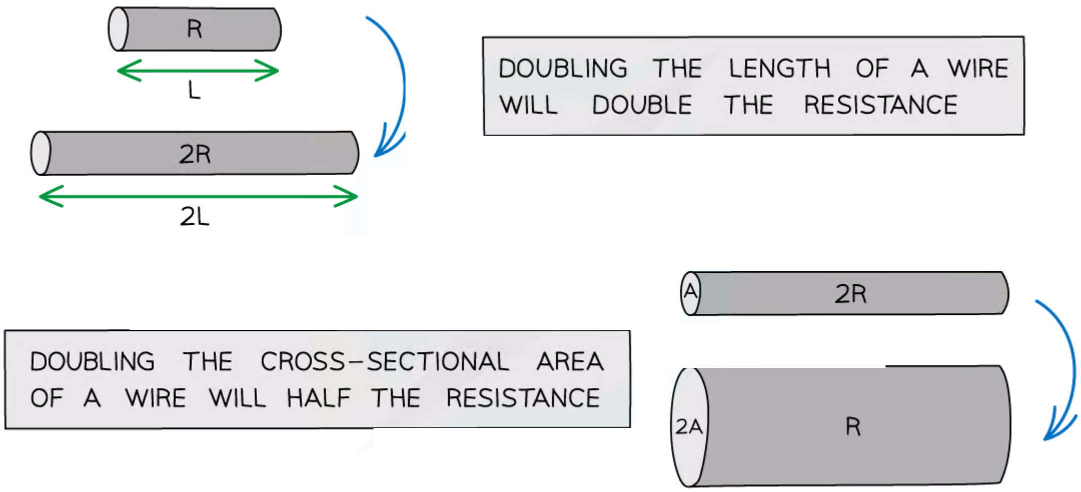


Free electrons collide with ions which resist their flow

- Since **current** is the **flow** of **charge**, the ions resisting their flow cause **resistance**
- Resistance depends on the **length** of the wire, the **cross-sectional area** through which the current is passing and the **resistivity** of the material

Electrical resistance equation

- The resistivity equation shows that:
  - The **longer** the wire, the **greater** its resistance
  - The **thicker** the wire, the **smaller** its resistance



The length and width of the wire affect its resistance

- Resistivity is a property that describes the extent to which a material opposes the flow of electric current through it
- It is a property of the material, and is dependent on temperature
- Resistivity is measured in **Ω m**

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

Resistivity of some materials at room temperature

- The higher the resistivity of a material, the higher its resistance

    - Copper has a relatively low resistivity at room temperature, and so is used for electrical wires
    - This is because current flows through it very easily
- Insulators have such a high resistivity that virtually no current will flow through them

Core Practical 2: Investigating Resistivity

Aims of the Experiment

- The aim of the experiment is to determine the resistivity of a length of wire

Variables

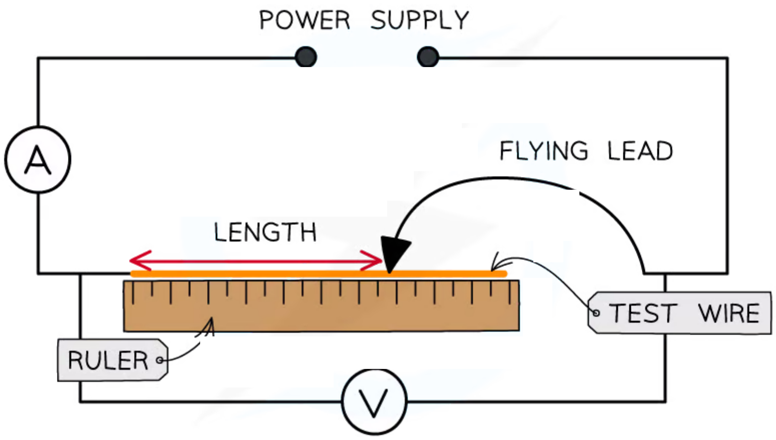
- Independent variable = Length, *L*, of the wire (m)
- Dependent variable = The current, *I*, through the wire (A)
- Control variables:
  - Voltage across the wire
  - The material the wire is made from

Equipment List

Equipment	Purpose
Ammeter	To determine the current through the wire
Voltmeter	To determine the voltage across the wire
2.0 m of wire	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 across 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



1. Measure the diameter of the 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 with 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 across the wire on the voltmeter
4. Read and record the current from the ammeter, then switch off the current immediately after the reading
    - This is to prevent the wire from heating up and changing the resistivity
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
    - In this example, a 2.0 m wire is used.
    - 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:
    - *R* = average resistance of the length of the wire (Ω)
    - *V* = potential difference across the circuit (V)
    - *I* = the average current through the wire for the chosen length (A)

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

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

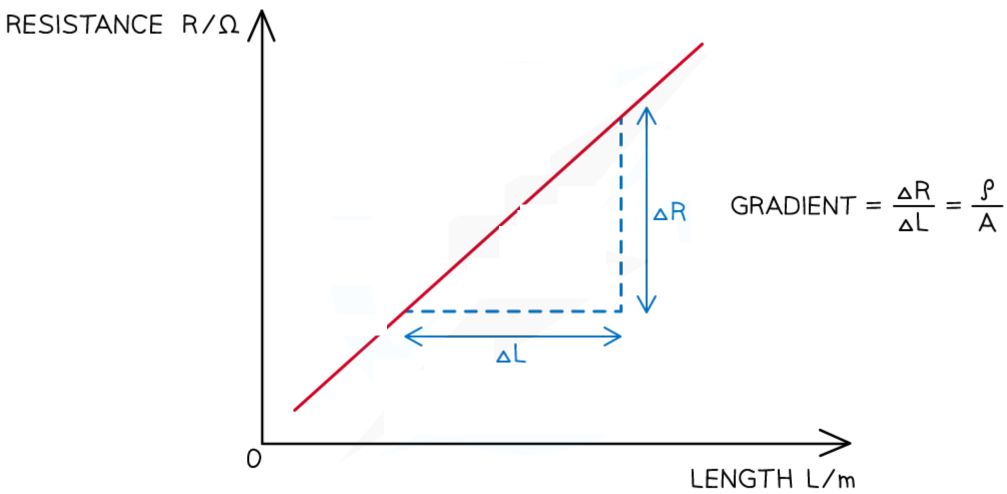
$$\rho = \frac{RA}{L}$$

- 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, gives:

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

- Comparing this to the equation of a straight line: y = mx
  - y = R
  - x = L
  - Gradient, m = ρ / A
- Therefore, to find resistivity:
  - Plot a graph of the length of the wire, L, against the average resistance of the wire
  - Draw a line of best fit
  - Calculate the gradient
  - Multiply the gradient by cross-sectional area, A

$$\rho = gradient \times A$$



- To calculate the cross-sectional area, *A*, of the wire

$$cross\ sectional\ area,\ A = \frac{\pi d^2}{4}$$

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
  - Therefore the temperature is kept constant by small currents
- The current should be switched off between readings
  - So that there isn't a temperature rise
- Calculate an average diameter
  - This will reduce random errors in the reading
  - Make at least 5–10 measurements of the diameter of the wire with the micrometer

Safety Considerations

- When there is a high current, and a thin wire, the wire will become very hot
  - Do not touch the wire directly when the circuit is switched on
- Switch off the power supply between readings, and immediately if you smell burning
- Keep liquids away from electrical equipment

3.11 Current & Drift Velocity

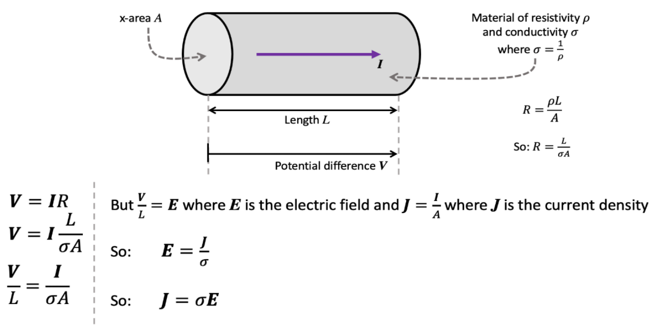
Calculating Current & Drift Velocity

Drift Velocity

- In a conductor, the current is due to the movement of charge carriers
  - The charge carriers can be negative or positive
  - However current is always taken to be in the **same** direction

- **Drift velocity** is the **average** velocity of the charge carriers travelling through the conductor
- In conductors, the charge carrier is usually free electrons
  - Free electrons only travel small distances before colliding with a metal ion
  - Therefore they have a relatively slow drift velocity of ~ 10^{-3} m s^{-1}

- In the diagram below, the current in each conductor is from right to left
  - In diagram **A** (positive charge carriers), the drift velocity is in the **same** direction as the current
  - In diagram **B** (negative charge carriers), the drift velocity is in the **opposite** direction to the current



Conduction in a current-carrying conductor

- The density n represents the number of free charge carriers (electrons) **per unit volume**
  - **Conductors**, such as metals, have a **high** value of n
  - **Insulators**, such as plastics, have a **low** value of n
- Since the density of charge carriers is so large in conductors, the flow of current flow appears to happen instantaneously

The Transport Equation

- The current can be expressed in the transport equation:

$$I = nqvA$$

- Where:
  - I = current (A)
  - n = number density (m^{-3})
  - q = the charge of the charge carrier (C)
  - v = drift velocity (m s^{-1})
  - A = cross sectional area of the wire (m^2), calculated using $\mathbf{A = \pi r^2}$

- The **same equation** is used whether the charge carriers are positive or negative
  - A negative value for *v* will indicate current in the opposite direction to the charge carriers
- The transport equation shows that *v* is **inversely proportiona**l to *n*
  - Since the more charge carriers available per unit volume the more the density will slow down their speed through the conductor
- The transport equation also shows that *I* is **directly proportional** to *n*
  - Greater *n* means a greater charge is flowing and therefore a larger current *I*
- When the value of *n* is lower, the charge carriers must **travel faster** to carry the same current

The Large Range of Material Resistivities

Resistivity

- The transport equation tells us that current, $I \propto$ number of charge carriers, n
    - Therefore, the **larger** the number of charge carriers, the **greater** the current will be for the same applied voltage
    - This is because resistivity has decreased with more charge carriers available
- Different materials have different numbers of charge carriers

- Insulators have **few** charge carriers:
    - They have such a high resistivity that virtually no current will flow through them
    - A perfect insulator would have no charge carriers, $n = 0$
    - A perfect insulator would have a current of zero regardless of the voltage applied

- Conductors have a **large number** of charge carriers
    - Metals are good conductors because they have **free electrons**
    - Free electrons are the atoms from the outer shell of each atom
    - Therefore there are lots of charge carriers per unit volume
    - This means resistivity is low

- Semiconductors have a **small number** of free electrons
    - There are **fewer** delocalised electrons in a semiconductor than in a metal
    - There are a greater number of free electrons at a higher temperature
    - Resistivity changes in a semiconductor, due to the variation with temperature in free electrons which are available as charge carriers
    - Silicon is an example of a semiconductor

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

The resistivity of some materials at room temperature

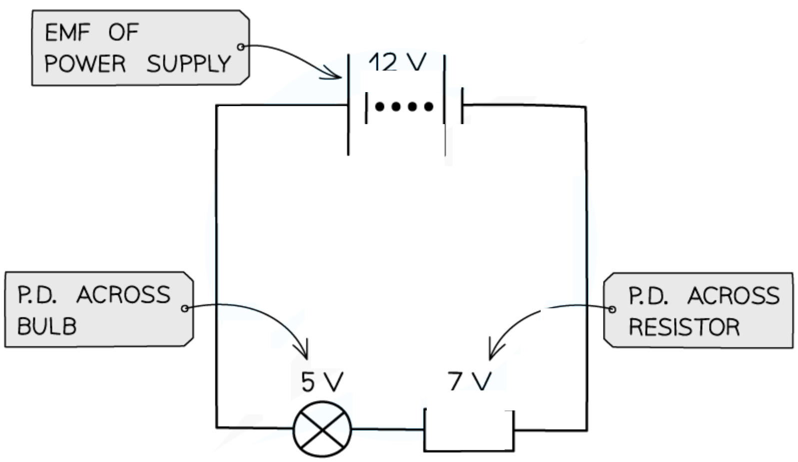
Potential Difference & Conductor Length

Potential Difference

- A cell makes one end of the circuit positive and the other negative. This sets up a **potential difference** across the circuit
- The potential difference across a component in a circuit is defined as;

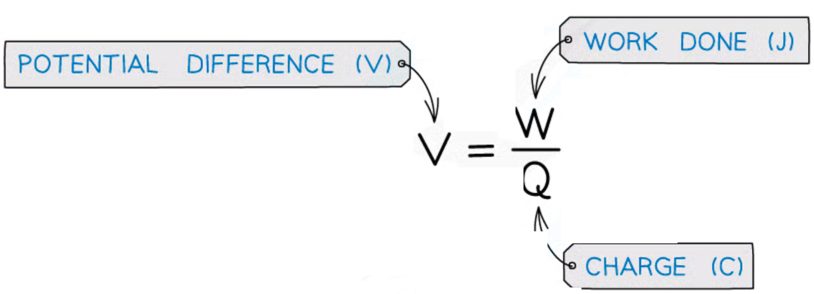
energy transferred per unit charge

- The energy is transferred is from electrical energy into other forms, depending on the component or device being used
- Potential difference is measured in **volts (V)** which are equivalent to **Joule per coulomb (J C^{-1})**
- 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

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

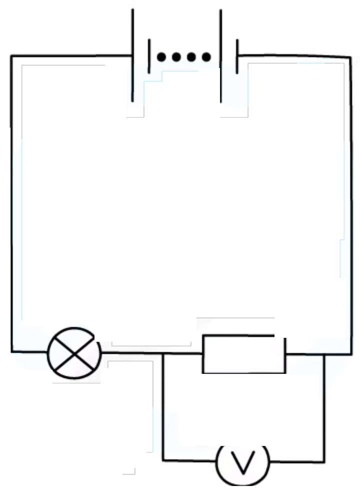


$$V = \frac{W}{Q}$$

Potential difference is the work done per unit charge

Measuring Potential Difference

- Potential difference or voltage is measured using a **voltmeter**
  - A voltmeter is always set up in parallel to the component being measured



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

Conductor Length

- The equation for resistivity is

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

- Where:
  - R = resistance (Ω)
  - ρ = resistivity (Ω m^{-1})
  - l = length (m)
  - A = area (m^{-2})

- Therefore, as the length of a uniform conductor at constant temperature increases, resistance also increases
- Voltage and current are linked by Ohm's Law

$$V = IR$$

- Where
  - V = potential difference (V)
  - I = current (A)
  - R = resistance (Ω)
- Therefore, as R increases, so must potential difference across the wire
  - Potential difference increases uniformly with length

3.13 Potential Dividers

Potential Dividers

- The electrical voltages rule is defined as:

  The sum of the e.m.f.s in a closed circuit loop is equal to the sum of the potential differences around that loop

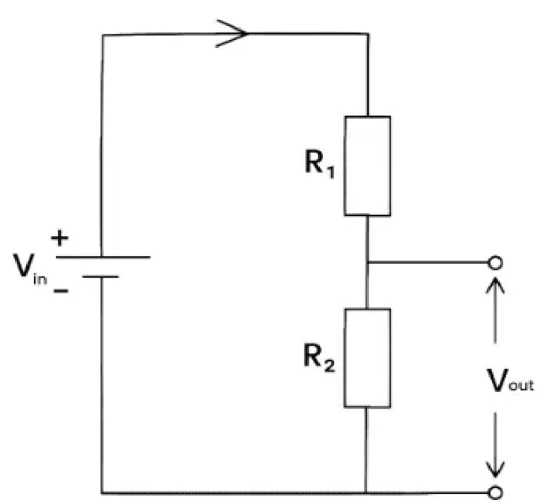
- Therefore, when two resistors are connected in series, the potential difference across the power source will be divided across the two resistors

- Potential dividers are circuits that produce an output voltage as a **fraction** of the input voltage
- This is done by using two resistors in series to split or divide the voltage of the supply in a chosen **ratio**
- Potential dividers have three main purposes:
  - 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 are used widely in volume controls and sensory circuits using LDRs and thermistors

- The link between the input voltage and the output voltage across each resistor is linked in an 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 across both resistors, which are in series

- The output voltage V_{out} is measured across one of the resistors, in this case resistor R_2
- The potential difference *V* across each resistor depends upon its resistance *R*:
  - The resistor with the **largest resistance** will have the **greater** potential difference across it
  - This is shown as a greater V_{out}
  - This is from ***V = IR***
- 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

- Since potential divider circuits are based on the ratio of voltage between components, and since V=IR, this is equal to the ratio of the resistances of the resistors
- Therefore, the ratios of the potential differences and resistances across each resistor can be linked

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

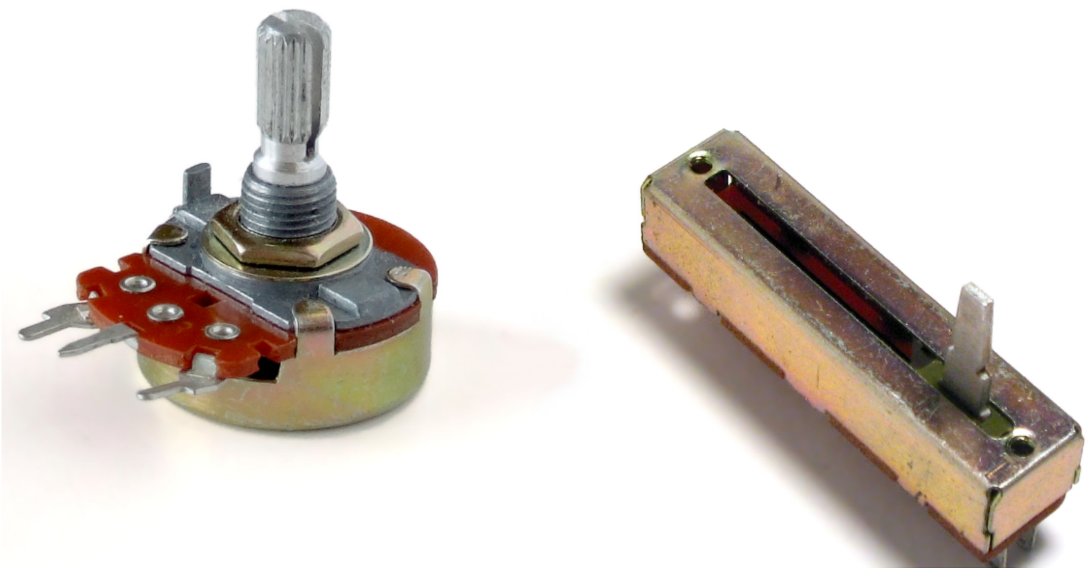
- Where:
  - V_1 = potential difference of R_1 (V)
  - V_2 = potential difference or R_2 (V)
- Using Ohm's Law, with a constant current, I, these can also be written as:
  - $V_1 = IR_1$
  - $V_2 = IR_2$

YOUR NOTES
↓

Potential Dividers & Variable Resistance

The Potentiometer

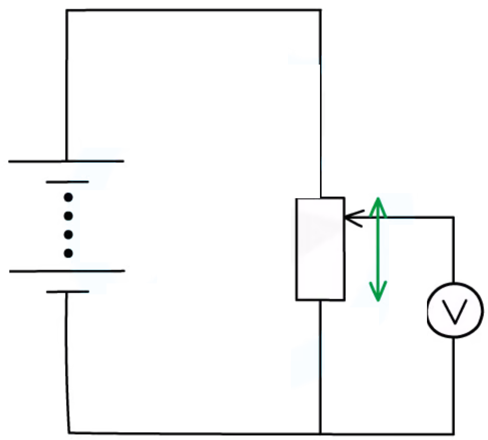
- A potentiometer is a single component which can act as a potential divider.
  - It consists of a coil of wire with a sliding contact
  - A variable output voltage can be varied by moving a slider along the component



A potentiometer is a type of variable resistor

- The circuit symbol is drawn as an arrow next to the resistor, to represent the sliding contact

- The sliding contact has the effect of separating the potentiometer into two parts
  - Each part will have different resistances
  - Therefore output voltage will change

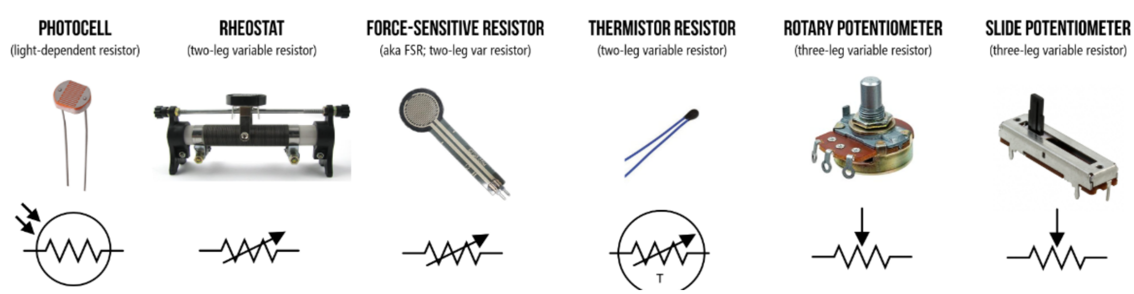


Moving the slider (the arrow in the diagram) changes the resistance (and hence potential difference) of the two parts of the potentiometer

- If the slider in the above diagram is moved upwards, the resistance of the lower part will increase and so the potential difference across it will also increase
- Therefore, the variable resistor obtains a maximum or minimum value for the output voltage
- If the resistance is 3 Ω:
  - Maximum voltage is when the resistance is 3 Ω
  - Minimum voltage is when the resistance is 0 Ω

Thermistors & Light Dependent Resistors (LDRs)

- Sensory resistors are used in potential dividers to vary the output voltage
  - This could cause an external component to switch on or off
  - For example, a heater switches off automatically when its surroundings are at room temperature
- Examples of the variable sensory resistors used are **thermistors** and **light-dependent resistors (LDRs)**



LDR and thermistor in a potential divider circuit with a fixed resistor R

- The voltmeter in both circuits is measuring V_{out}
- From Ohm's law ***V = IR***, the potential difference V_{out} from a sensory resistor in a potential divider circuit is **proportional** to its resistance
  - If an LDR or thermistor's resistance **decreases**, the potential difference through it also **decreases**
  - If an LDR or thermistor's resistance **increases**, the potential difference through it also **increases**
- Since the total potential difference of the components must be equal to $V_{in:}$
  - If the potential difference of the sensory resistor **decreases** then the potential difference across the other resistor in the circuit must **increase**
  - If the potential difference of the sensory resistor **increases** then the potential difference across the other resistor in the circuit must **decrease**

The resistance of an LDR…

- Varies with **light intensity**
  - The higher the light intensity, the lower the resistance
  - The lower the light intensity, the higher the resistance
- Therefore:
  - If light intensity increases, V_{out} across the LDR will **decrease** because resistance has decreased
  - If light intensity decreases, V_{out} across the LDR will **increase** because resistance has increased
- An LDR circuit is often used for street and security lights
  - When light intensity falls, V_{out} increases and so this can provide the voltage required to turn on a lamp

The resistance of a thermistor…

- Varies with **temperature**
  - The hotter the thermistor, the lower the resistance
  - The cooler the thermistor, the higher the resistance
- Therefore:
  - If temperature increases, V_{out} across the thermistor will **decrease** because resistance has decreased
  - If temperature decreases, V_{out} across the thermistor will **increase** because resistance has increased
- A thermistor circuit is used in fire alarms, ovens and digital thermometers
  - When temperature falls, V_{out} increases and so this can provide the voltage required to turn on a heater

E.M.F & Modelling Resistance

3.15 Electromotive Force

Electromotive Force

- When charge passes through a power supply such as a battery, it **gains** electrical energy
- The **electromotive force (e.m.f.)** is defined as:

  The amount of chemical energy converted to electrical energy per unit charge when charge passes through a power supply

- e.m.f. is measured in **Volts (V)**

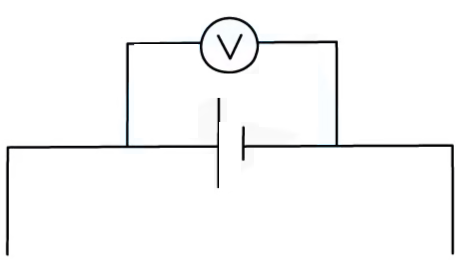
$$\text{E.M.F.} = \frac{\text{ENERGY TRANSFORMED FROM OTHER FORMS TO ELECTRICAL}}{\text{CHARGE}}$$

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

- This can also be written as:

$$\varepsilon = \frac{E}{Q}$$

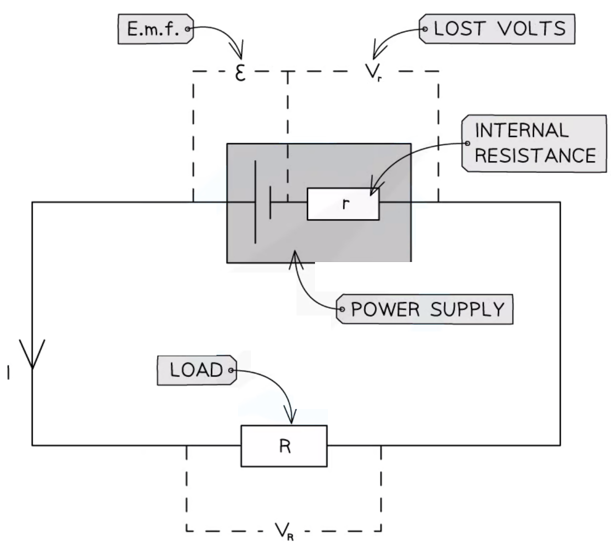
- E.m.f. is:
  - represented by the symbol ε (greek letter epsilon)
  - not actually a force, but a measure of energy transferred per coulomb of charge
  - is measured in **volts (V)**, which is $J\ C^{-1}$ in S.I. units
- e.m.f. is also the potential difference across the cell when no current is flowing
- 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

Internal Resistance

- All power supplies have some resistance between their terminals
  - This is called **internal resistance** (*r*)
- Internal resistance causes some electrical energy to be transformed to heat energy in the power supply itself
  - This is why the cell becomes warm after a period of time
- Therefore, the internal resistance causes 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
- The amount of voltage lost is known as the 'lost volts'
  - A higher internal resistance will result in a higher value for lost volts



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

- Where:
  - R = resistance of the circuit (the 'load resistor')
  - r = internal resistance
  - ε = e.m.f.
  - V_r = 'lost volts'
  - V_R = voltage across the load (sometimes also called V_T, the terminal voltage)

Exam Tip

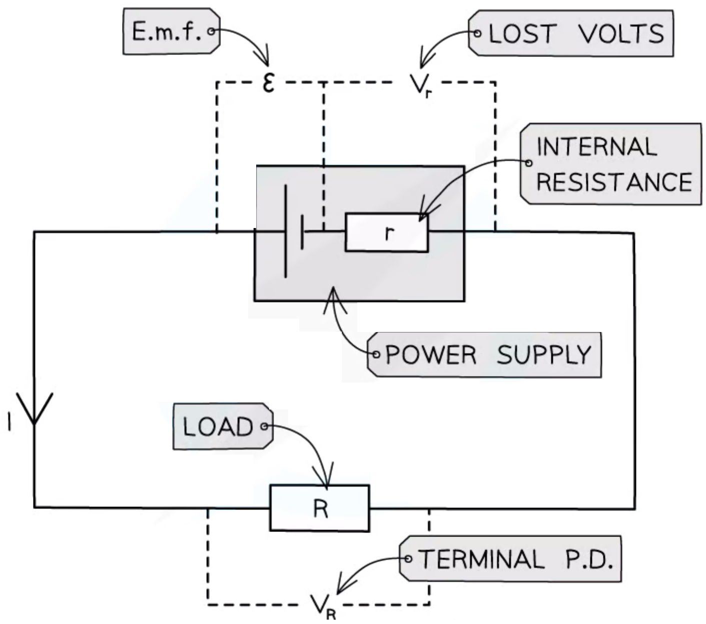
The internal resistance concept catches many students out. Make sure you fully understand the circuit diagram;

- Internal resistance of the cell can be treated as though it were a separate resistor - although it isn't!
- The load resistance is treated as another resistor in series
- Potential difference is measured across the load resistor
- The lost volts are calculated as though they were the potential difference across the 'internal resistor'

E.M.F. vs. Terminal Potential Difference

Terminal Potential Difference

- **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.
  - If a cell has internal resistance, 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. is **also** the potential difference across the load resistor



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.

- Terminal potential difference is the voltage available to the rest of the circuit

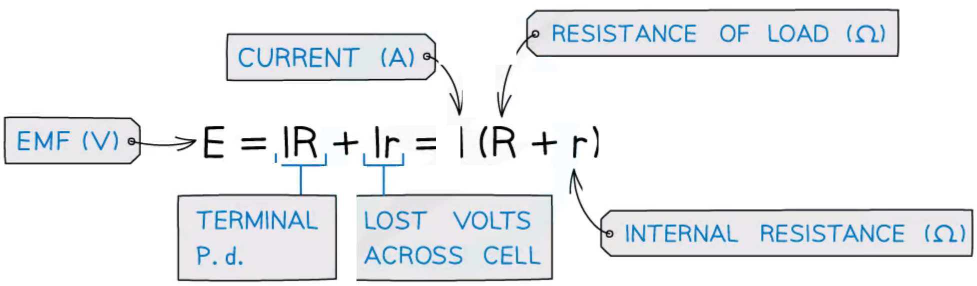
$$V_R = I \times R \text{ (from Ohm's law)}$$

- Where:
  - R = load resistance (Ω)
  - I = current in the circuit (A)
  - V_R = Terminal p.d. (V)

- When a load resistor is connected, current flows through the cell and a potential difference develops across the internal resistance.
  - This voltage is not available to the rest of the circuit so is called the 'lost volts'
- V_r is the **lost volts**
  - This is the voltage lost in the cell due to internal resistance

$$V_r = I \times r \text{ (from Ohm's law)}$$

- Where:
  - r = internal resistance (Ω)
  - I = current in the circuit (A)
  - V_r = Lost volts (V)
- The e.m.f. is the sum of the terminal p.d. and the lost volts:



The Difference Between Potential Difference and E.M.F

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

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

- 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

Core Practical 3: Investigating E.M.F. & 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

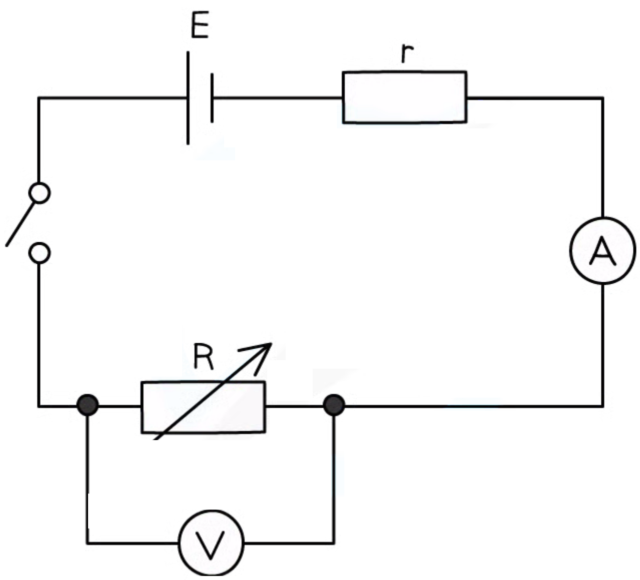
- Independent variable = voltage, *V* (V) & current, *I* (A)
- Dependent variable = resistance, *R* (Ω)
- Control variables:
  - E.m.f. of the cell
  - Internal resistance of the cell

Equipment List

Apparatus	Purpose
1.5 V Cell	To provide an e.m.f. to the circuit
Resistor	Uknown resistance – to act as internal resistance
100Ω Variable Resistor	To change the values of current and voltage in the circuit
Voltmeter	0-2B 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
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 → R/Ω

VOLTMETER READING → V/V

AMMETER READING → I/mA

	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

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

- Where:
  - E = 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:

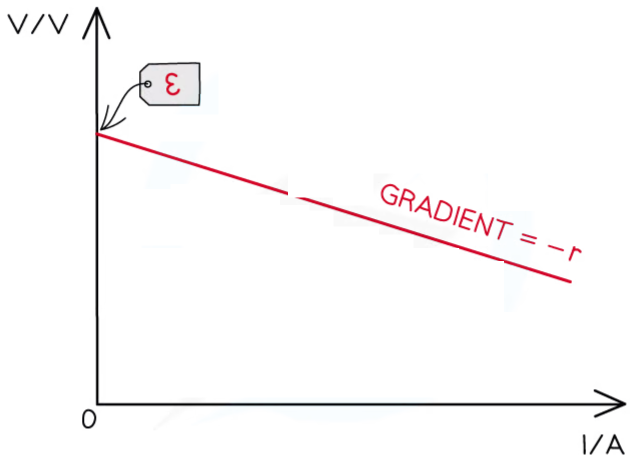
$$E = IR + Ir = V + Ir$$

- Rearranging this equation for V:

$$V = -rI + E$$

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

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:

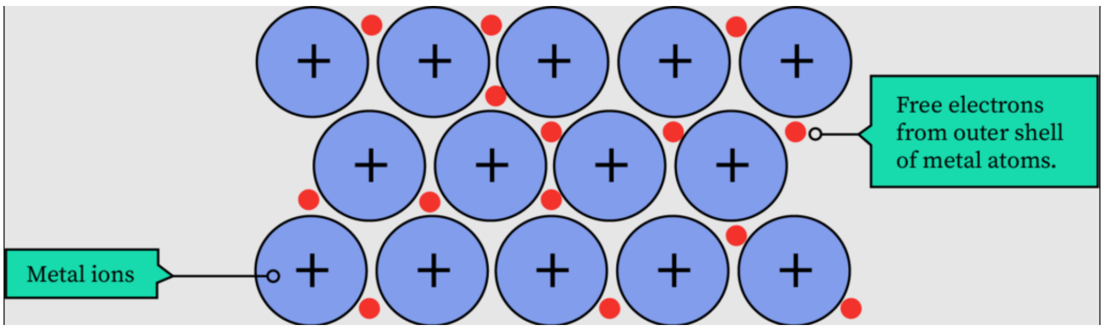
- Only use fairly new cells otherwise the e.m.f. and internal resistance of run-down batteries can vary during the experiment
- Wait for the reading on the voltmeter and ammeter to stabilise (stop fluctuating) before recording the values
- Take multiple repeat readings (at least 3) for each voltage and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

Safety Considerations

- Electrical components can get hot when used for a long period
- Switch off the power supply right away if there is a burning smell
- Make sure there are no liquids close to the equipment

Modelling the Variation of Resistance with Temperature

- All materials have some **resistance** to the flow of charge
- As **free electrons move** through a metal wire, they collide with ions which get in their way
- As a result, they **transfer** some, or all, of their **kinetic energy** on **collision**, which causes electrical **heating**

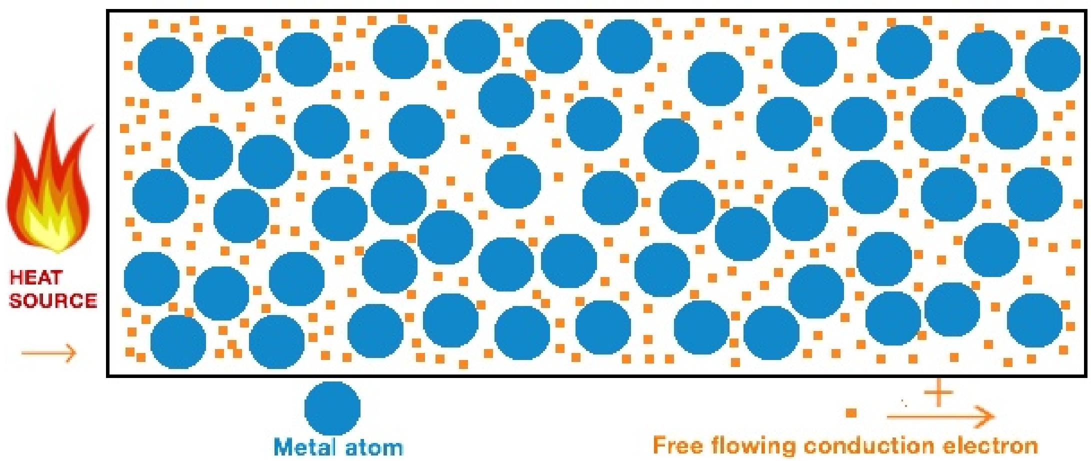


Free electrons collide with ions which resist their flow

- As temperature increases, the vibrations of the ions in the lattice also increase
  - This increases the chance of collisions between the conduction electrons and the ions
- Since **current** is the **flow** of **charge**, the ions resisting the flow of electrons cause **resistance**
- Therefore as temperature increases so does resistance
  - At small increases of temperature this increase is linear
- A higher current will cause temperature to rise
  - This is due to more collisions between free electrons and ions
  - The collisions cause the ions to vibrate more

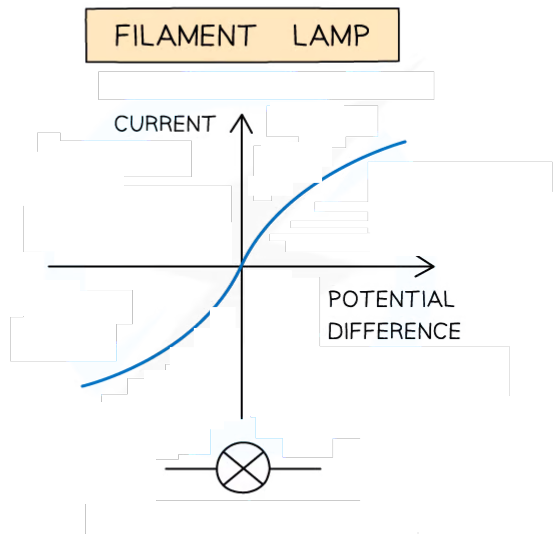
Resistance & Temperature for Metallic Conductors

- All solids are made up of vibrating atoms
  - This includes metal solids
- As the temperature in a metal rises, the ions vibrate with a greater frequency and amplitude
  - The electrons collide with the vibrating atoms which impede their flow, hence the current **decreases**
  - electric current is the flow of free electrons in a material



Metal atoms and free electrons at low and high temperatures

- Current decreases because the resistance has increased (from $V = IR$)
  - This is because resistivity has increased
  - This is from $\rho \propto R$ (if the area A and length L is constant)
- For a metallic conductor which obeys Ohm's law:
  - An **increase** in temperature causes an **increase** in resistance and resistivity
  - A **decrease** in temperature causes a **decrease** in resistance and resistivity
- The I-V graph for a filament lamp shows this effect



I–V characteristics for a filament lamp

- As the current increases, the number of collisions between free electrons and the lattice of ions increases
    - This increases the temperature of the filament in the lamp
- An increase in temperature:
    - Causes greater vibrations in the lattice of ions
    - Therefore increased collisions between free electrons and the ions
    - And so an increased resistance
- Resistance opposes the current, causing the current to increase at a slower rate
    - This is seen as a curve in the graph

Worked Example

The temperature of a non-ohmic resistor increases as the current through it increases.

Explain this is terms of the structure of a metal.

Step 1: Consider the effect on rate of electron flow:

- Rate of flow of electrons increases

Step 2: Consider the effect on number of collisions of conduction electrons with the lattice

- This increases the number of collisions of conduction electrons with the ions in the lattice

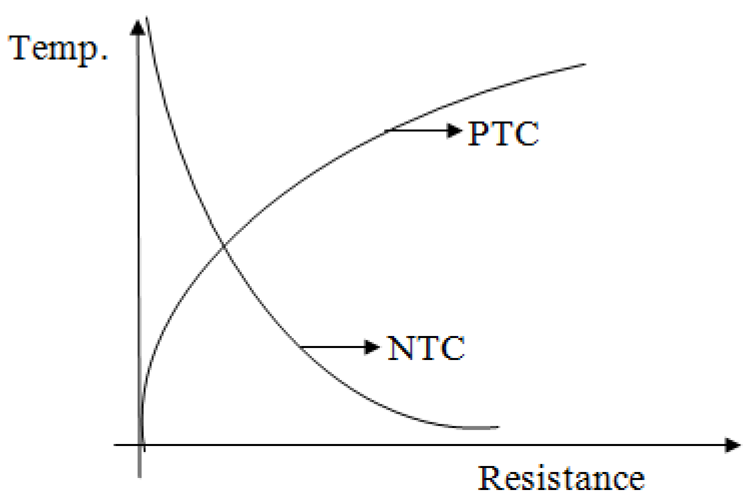
Step 3: Describe what happens to the vibrations of the lattice

- Therefore vibrations of the lattice ions increase

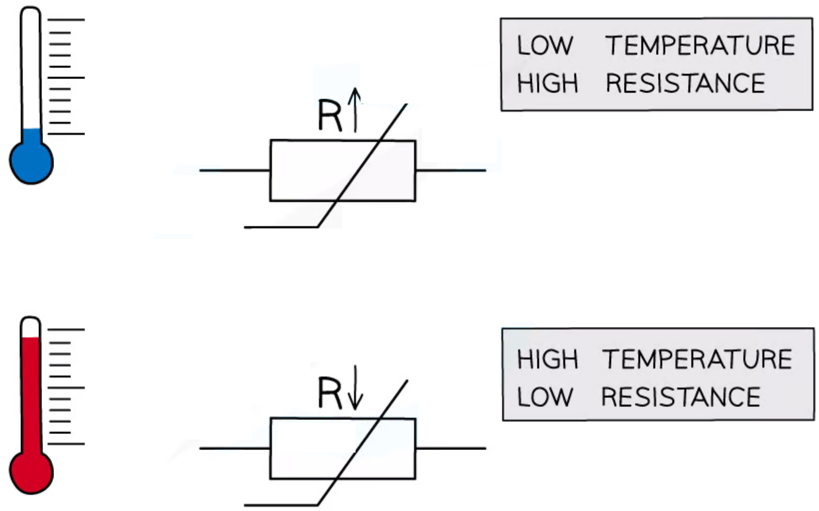
Resistance & Temperature for Thermistors

- The resistivity of a thermistor behaves in the **opposite** way to metals
  - This is because it is a type of semiconductor
  - Semiconductors behave in a different way to metals
- The number density of charge carriers (such as electrons) **increases** with **increasing** temperature
- Therefore, for a thermistor:
  - An **increase** in temperature causes a **decrease** in resistance and resistivity
  - A **decrease** in temperature causes an **increase** in resistance and resistivity

- Thermistors are often used in temperature sensing circuits such as thermometers and thermostats
- A thermistor is a non-ohmic conductor and sensory resistor whose resistance varies with temperature
  - Most thermistors are negative temperature coefficient ntc) components.
  - This means that if the temperature **increases,** the resistance of the thermistor **decreases** (and vice versa)
- The temperature-resistance graph for a thermistor is shown below



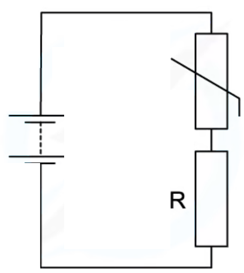
- Thermistors are temperature sensors and are used in circuits in ovens, fire alarms and digital thermometers
  - As the thermistor gets **hotter**, its resistance **decreases**
  - As the thermistor gets **cooler**, its resistance **increases**



The resistance through a thermistor is dependent on the temperature of it

Worked Example

A thermistor is connected in series with a resistor *R* and a battery.



The resistance of the thermistor is equal to the resistance of *R* at room temperature.

Which statement describes the effect when the temperature of the thermistor decreases?

A. The p.d across the thermistor increases

B. The current in *R* increases

C. The current through the thermistor decreases

D. The p.d across *R* increases

ANSWER: A

Step 1: Outline the nature of a thermistor

- The resistance of the thermistor increases as the temperature decreases

Step 2: Consider the properties of current in a series circuit

- Since the thermistor and resistor *R* are connected in series, the current *I* in both of them is the same

Step 3: Consider a relevant equation

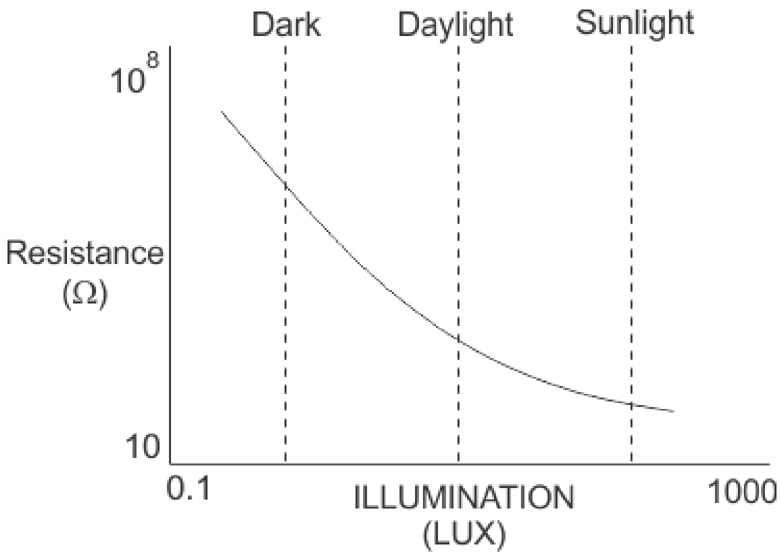
- Ohm's law states that $\boldsymbol{V = IR}$
- Since the resistance of the thermistor increases, and *I* is the same, the potential difference *V* across it increases

Step 4: State the conclusion

- Therefore, statement **A** is correct

Modelling the Variation of Resistance with Illumination

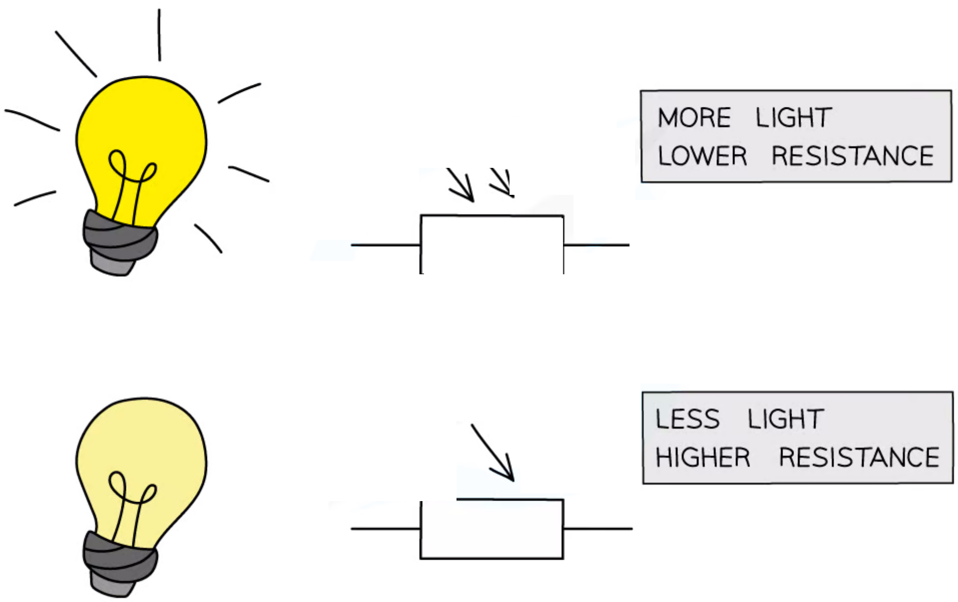
- Light can cause a change in conductivity of some semi-conductors
- When light is absorbed by the material it causes more electrons to be available for conduction



- An increase in the number of conduction electrons reduces the resistance

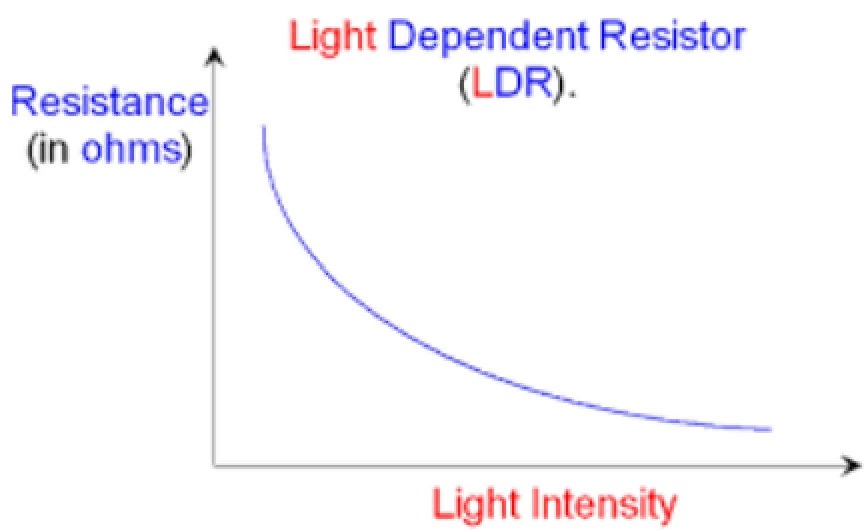
Resistance & Illumination for LDRs

- A light-dependent resistor (LDR) is a non-ohmic conductor and sensory resistor
- Its resistance automatically changes depending on the light energy falling onto it (illumination)
- As the **light intensity increases**, the **resistance** of an LDR **decreases**



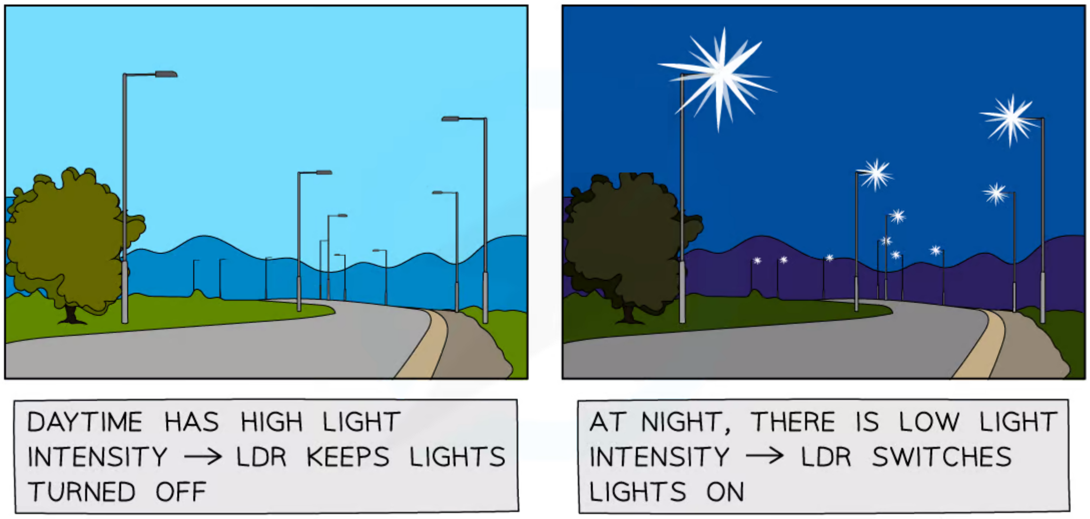
Resistance of an LDR depends on the light intensity falling on it

- This is shown by the following graph:



Graph of light intensity and resistance for an LDR

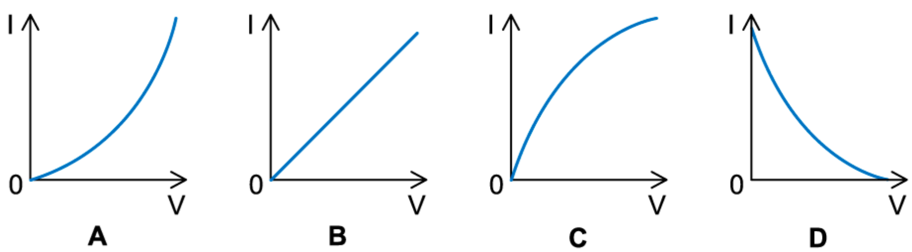
- LDRs can be used as light sensors, so, they are useful in circuits which automatically switch on lights when it gets dark, for example, street lighting and garden lights
  - In the dark, its resistance is very large (millions of ohms)
  - In bright light, its resistance is small (tens of ohms)



LDRs are used for automatic street lights

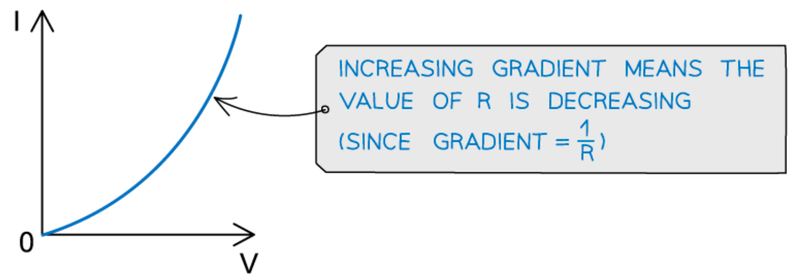
Worked Example

The graphs show various possible relationships between current and voltage through a component.



Which graph best represents the relationship between the current and voltage of an LDR?

ANSWER: A



Step 1: Consider the relationship between light intensity and resistance

- As light intensity increases, resistance decreases in an LDR
- If the resistance decreases then the potential difference will increase

Step 2: Consider a relevant equation

- Ohm's law states that ***V = IR***
- The resistance is equal to V/I or 1/R = I/V = gradient of the graph
  - Since *R* decreases, the value of 1/R increases, so the gradient must increase

Step 3: State the conclusion

- Therefore, *I* increases with changing *V* with an increasing gradient
- This is seen in graph **A**