5.2 Resistance & Resistivity

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

5.2 Resistance & Resistivity

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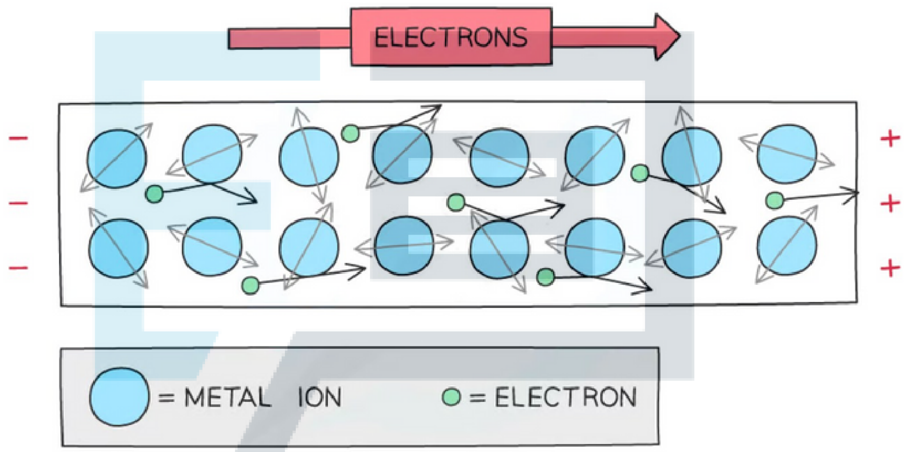
5.2.1 Resistivity

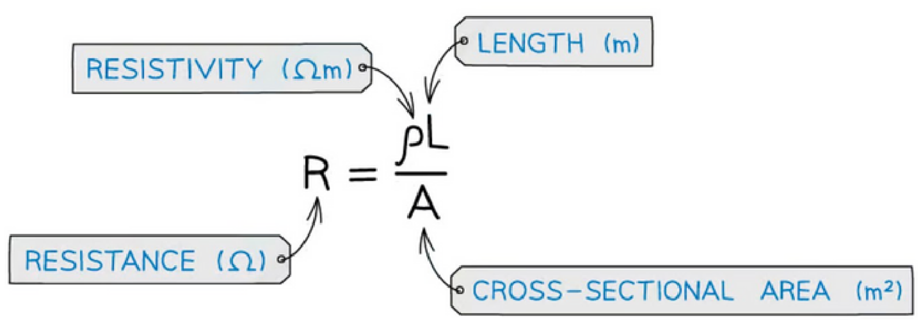
Resistivity

- 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**



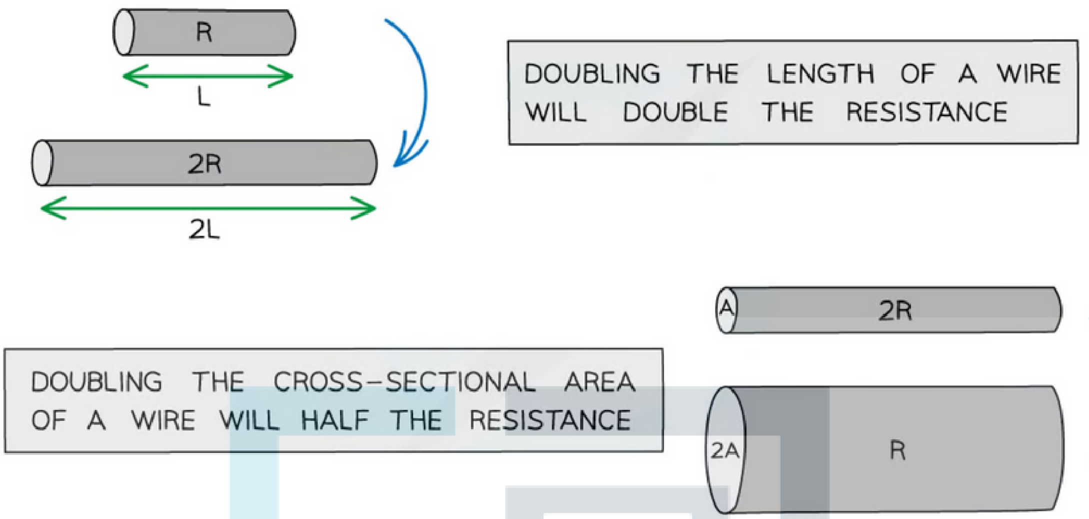
Free electrons collide with ions which resist their flow

- Since **current** is the **flow** of **charge**, the ions resisting their flow causes **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 c electric current through it
- It is a property of the material, and is dependent on temperature
- Resistivity is measured in **Ωm**

Resistivity of some materials at room temperature

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

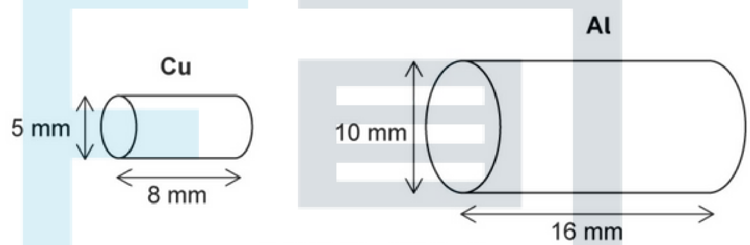
  - The higher the resistivity of a material, the higher its resistance

- This is why copper, with its relatively low resistivity at room temperature, is used for electrical wires — current flows through it very easily
- Insulators have such a high resistivity that virtually no current will flow through them

Worked Example

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

Their dimensions are shown below.



Copper resistivity = 1.7×10^{-8} Ω m

Aluminium resistivity = 2.6×10^{-8} Ω mWhich cylinder is the better conductor?

STEP 1

THE BETTER CONDUCTOR WILL HAVE LOWER RESISTANCE

STEP 2

RESISTANCE IS CALCULATED FROM

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

STEP 3

RESISTANCE OF THE COPPER CYLINDER

THE CROSS-SECTIONAL AREA OF A CYLINDER IS A CIRCLE

mm → m

$$A = \pi \times r^2 = \pi \times \left(\frac{d}{2}\right)^2 = \pi \times \left(\frac{5 \times 10^{-3}}{2}\right)^2 = 2.0 \times 10^{-5}\ m^2$$

$$R = \frac{1.7 \times 10^{-8} \times 8 \times 10^{-3}}{2.0 \times 10^{-5}\ m^2} = 6.8 \times 10^{-6}\ \Omega$$

SUBSTITUTE VALUES INTO THE EQUATION

STEP 4

RESISTANCE OF THE ALUMINIUM CYLINDER

$$A = \pi \times r^2 = \pi \times \left(\frac{d}{2}\right)^2 = \pi \times \left(\frac{10 \times 10^{-3}}{2}\right)^2 = 7.9 \times 10^{-5}\ m^2$$

$$R = \frac{2.6 \times 10^{-8} \times 16 \times 10^{-3}}{7.9 \times 10^{-5}\ m^2} = 5.3 \times 10^{-6}\ \Omega$$

STEP 5

RESISTANCE OF ALUMINIUM CYLINDER < RESISTANCE OF COPPER CYLINDER

THE ALUMINIUM CYLINDER IS THE BETTER CONDUCTOR

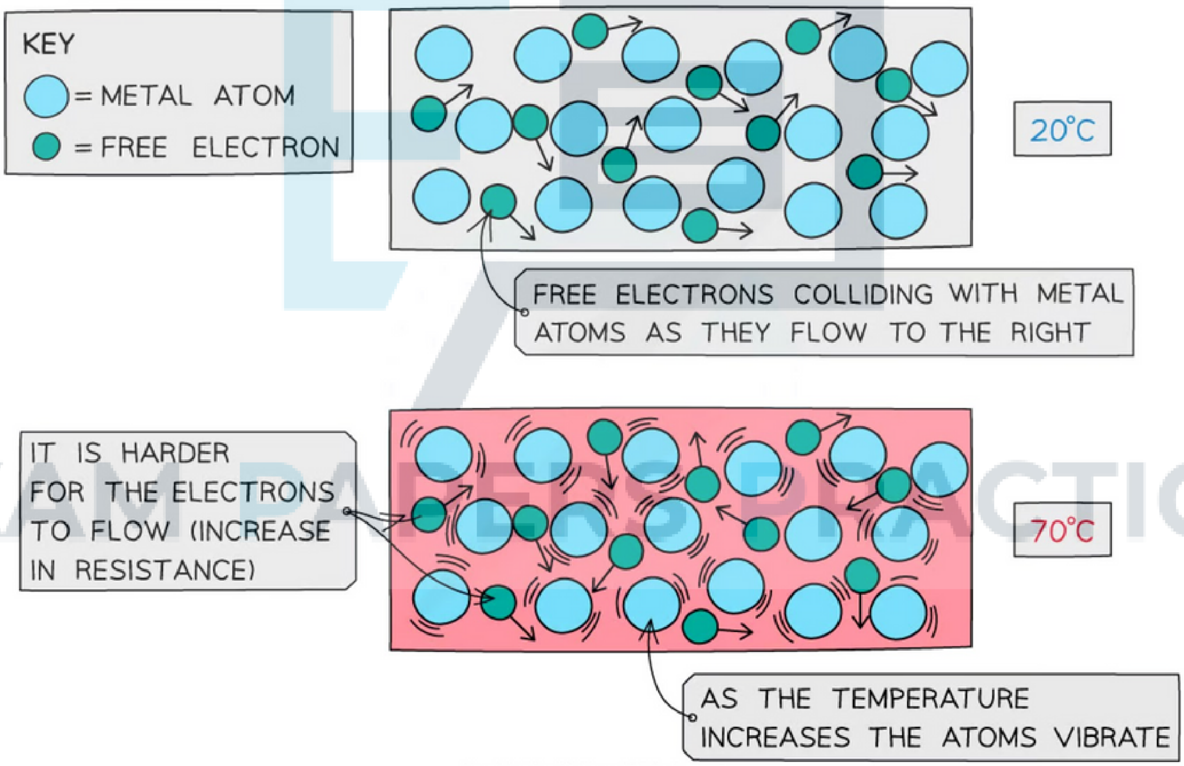
Exam Tip

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

5.2.2 Resistance in a Thermistor

Temperature & Resistance

- All solids are made up of vibrating atoms
  - The higher the temperature, the faster these atoms vibrate
- Electric current is the flow of free electrons in a material
  - The electrons collide with the vibrating atoms which impede their flow, hence the current **decreases**

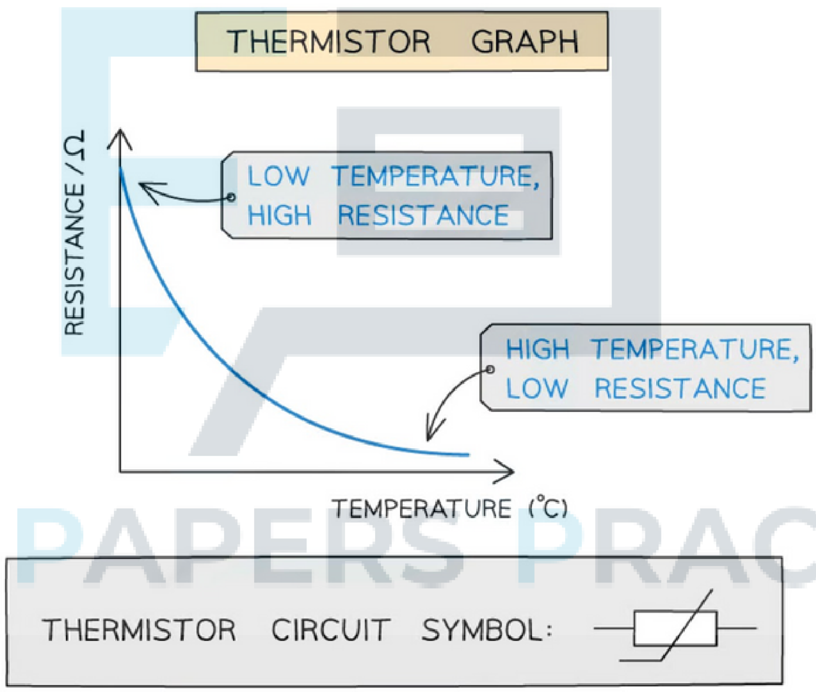


Metal atoms and free electrons at low and high temperatures

- So, if the current decreases, then the resistance will increase (from $V = IR$)
- Therefore, for a metallic conductor which obeys Ohm's law:
  - An **increase** in temperature causes an **increase** in resistance
  - A **decrease** in temperature causes a **decrease** in resistance
- This is **not** the case for components such as a thermistor
  - For a thermistor, an **increase** in temperature causes a **decrease** in resistance

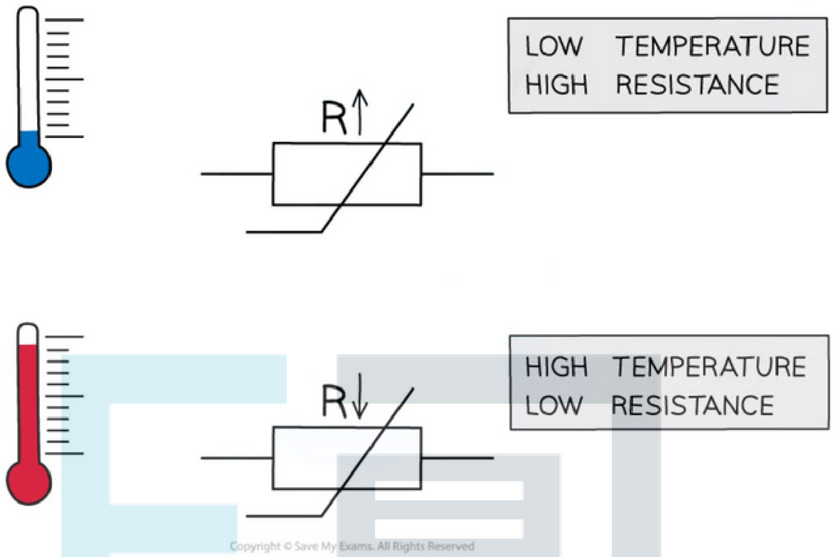
Applications of a Thermistor

- 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



Graph of temperature against resistance for a thermistor

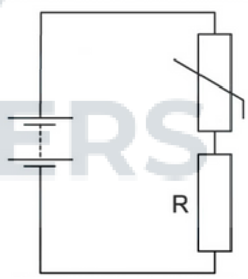
- Thermistors are temperature sensors and are used in circuits in ovens, fire alarms and digital thermometers
    - As the thermistor gets **hotter**, its resistance **decreases**
    - As the thermistor gets **cooler**, its resistance **increases**



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. When the temperature of the thermistor decreases, which statement is correct?

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

- The resistance of the thermistor increases as the temperature decreases
- Since the thermistor and resistor *R* are connected in series, the current *I* in both of them is the same
- Ohm's law states that ***V = IR***
- Since the resistance of the thermistor increases, and *I* is the same, the potential difference *V* across it increases
- Therefore, statement **A** is correct

5.2.3 Superconductivity

Superconductivity

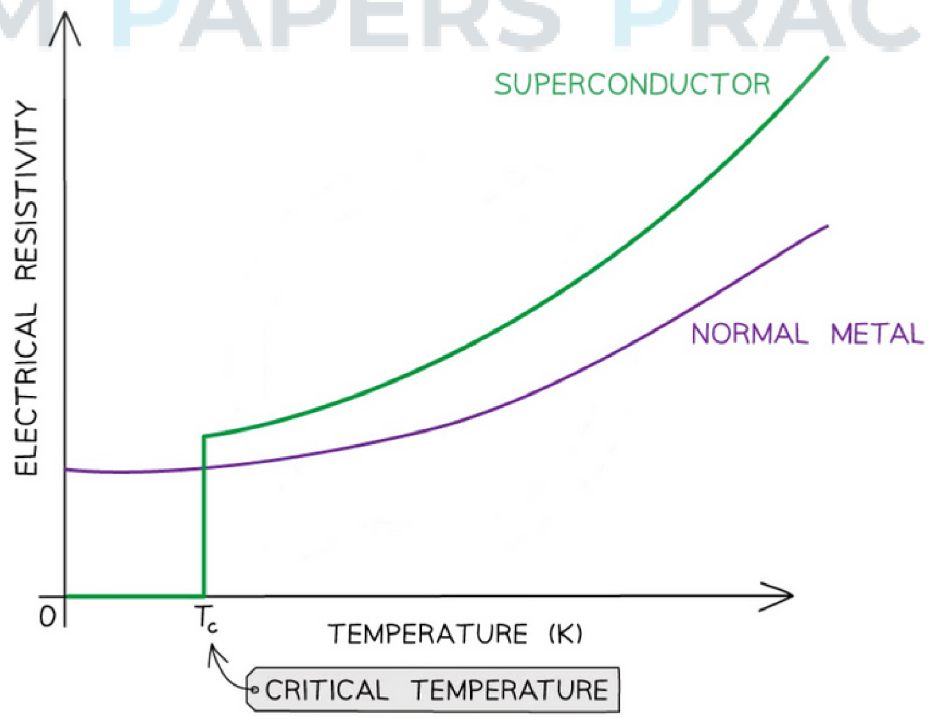
- All materials have some resistivity - even good electrical conductors such as copper and silver
- Resistance means that when electricity flows through a material, it heats up and the electrical energy is wasted as thermal energy
  - The resistivity of a material can be lowered by lowering its temperature
- If a material is cooled below a temperature called the critical temperature, its resistivity disappears entirely. It is now a **superconductor**
- Therefore, a superconductor (or superconducting material) is defined as

A material with no resistance below a critical temperature

- The critical temperature is defined as

The temperature at which a material becomes superconducting

- A common superconducting material is mercury
  - Mercury has a critical temperature of 4.2 K
- The electrical resistivity against temperature for a normal metal compared to a superconductor can be shown on the following graph:



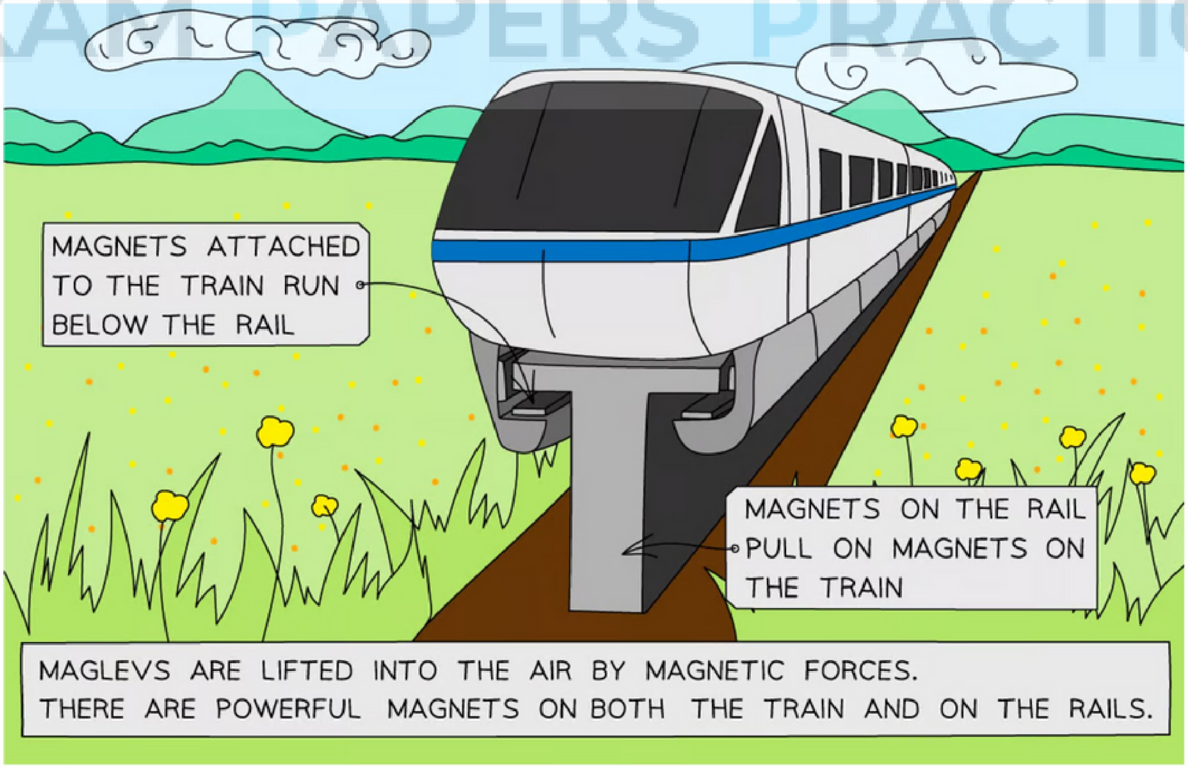
Resistivity against Temperature graph for a superconductor vs. a normal metal

- Superconductivity is a property of only certain materials that have the characteristics above
- This temperature threshold is sometimes referred to as the **transition temperature**

> **Exam Tip**
>
> Superconductivity occurs when there is **no** resistance. Avoid writing that there is a 'little' resistance or 'thermal' conductivity, which are not entirely correct

Applications of Superconductors

- Superconductors are useful for applications that require large electric currents
- Therefore, they are useful for:
  - The production of strong magnetic fields
  - The reduction of energy loss / dissipation in the transmission of electric power
- Such applications which require these could be:
  - MRI scanners
  - Transformers & generators - for fewer fire risks
  - Motors
  - Monorail trains
  - Maglev (magnetic levitation) trains
  - Particle accelerators - need large magnetic fields to accelerate particles
  - Fusion reactors
  - Electromagnets
  - Power / electrical cables
  - Microchips
- Maglev trains require extremely strong electromagnets to levitate the train due to such a large mass
  - This means they can travel at extremely high speeds up to 603 km / h
  - Maglev train systems currently only exist in Japan, South Korea and China



Maglev trains use strong electromagnets attached to the train and rails to levitate

5.2.4 Required Practical: Investigating Resistivity

Required Practical: Investigating Resistivity

Aims of the Experiment

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

Variables:

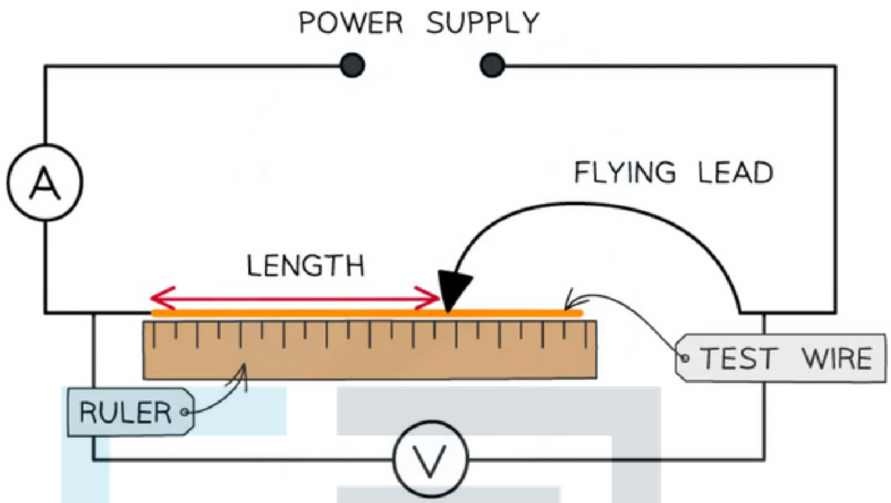
- Independent variable = Length, *L*, of the wire (m)
- Dependent variable = The current, *I*, through the wire (A)
- Control variables:
  - Voltage through the wire
  - The material the wire is made from

Equipment List

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

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

Method



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

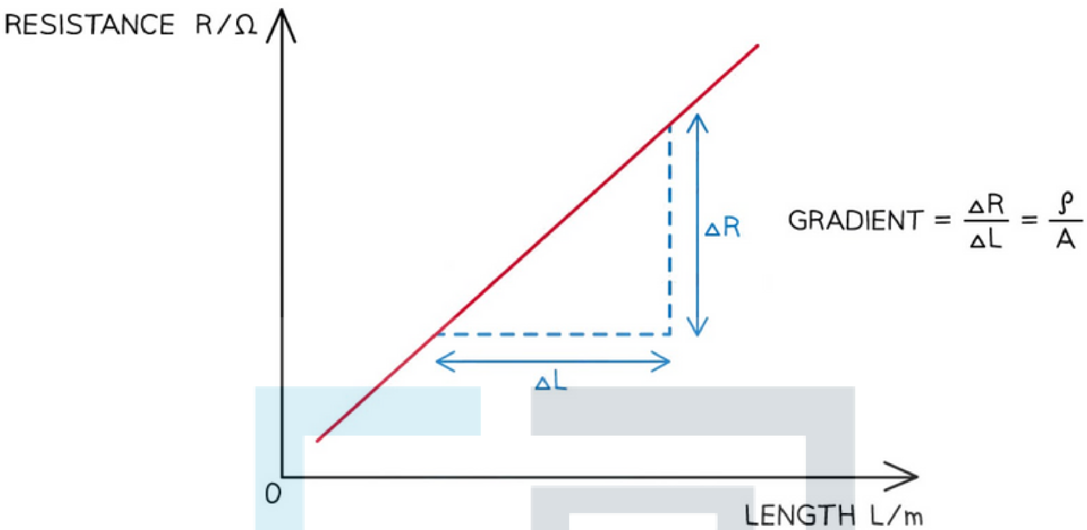
- Rearranging for the resistance, R, gives:

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

- 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

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



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

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

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

Safety Considerations

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

Worked Example

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

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

The following additional data for the wire is:

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

Calculate the resistivity of the wire

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

- The resistance is calculated using the equation

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

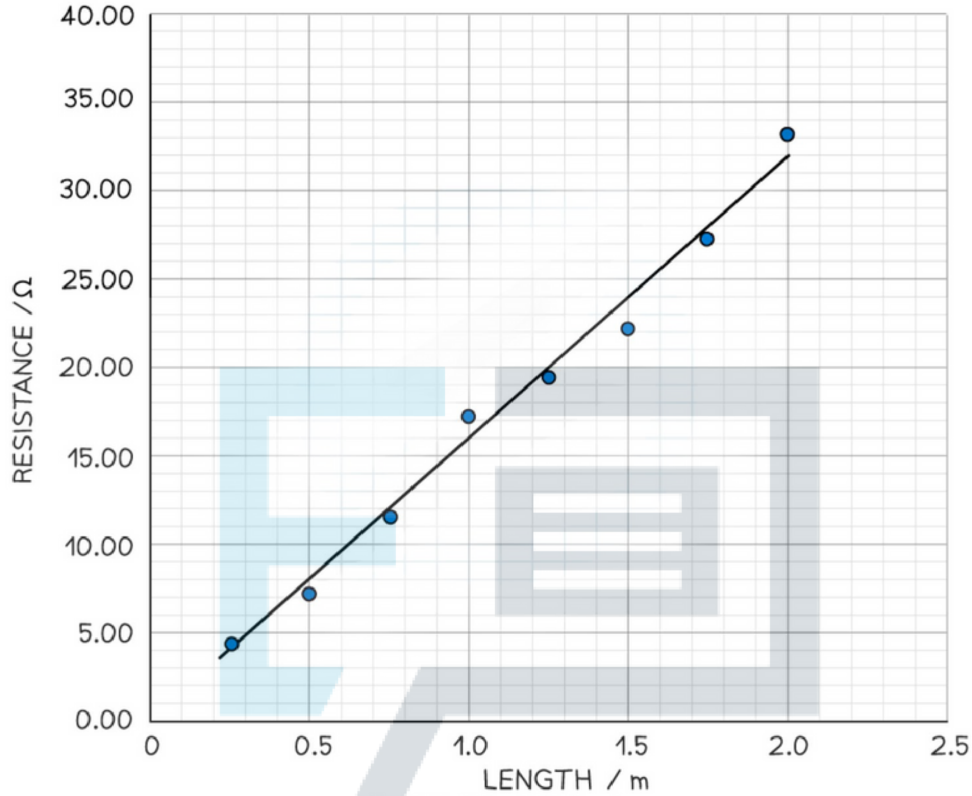
Length of wire L / m	Current I_1 / A	Current I_2 / A	Current I_3 / A	Average Current I / A	Resistance R / Ω
0.25	1.34	1.34	1.35	1.34	4.48
0.50	0.85	0.85	0.83	0.84	7.14
0.75	0.51	0.51	0.50	0.51	11.76
1.00	0.35	0.36	0.35	0.35	17.14
1.25	0.30	0.31	0.31	0.31	19.35
1.50	0.27	0.27	0.27	0.27	22.22
1.75	0.23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

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

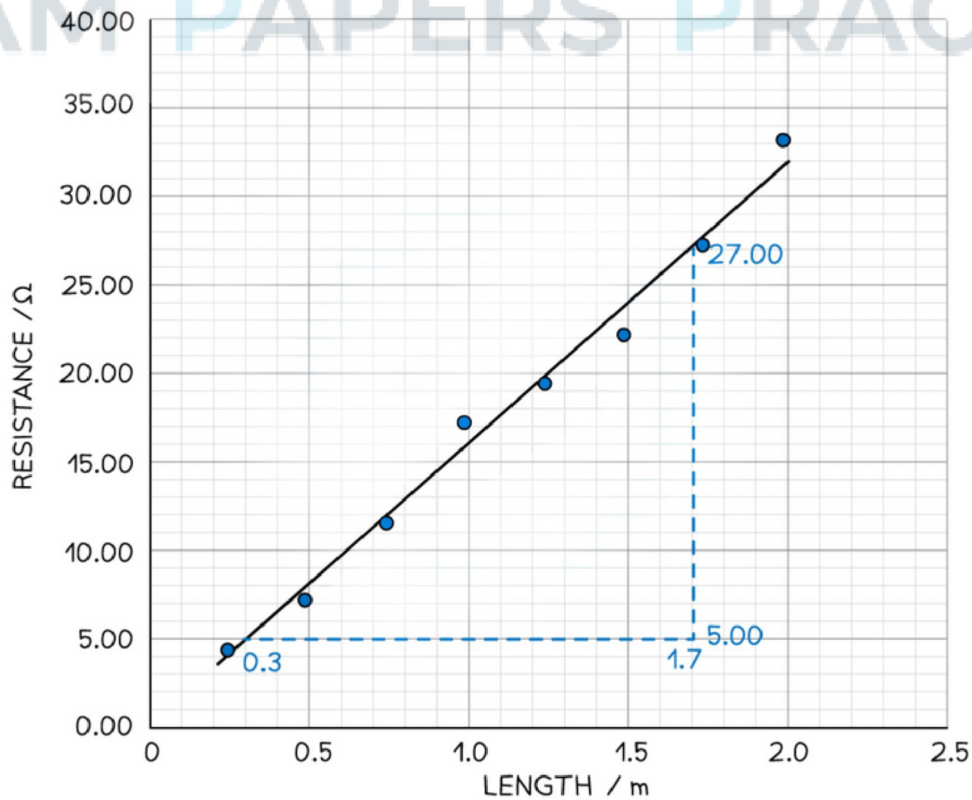
- The average diameter is 0.191 mm = 0.191×10^{-3} m
- The cross-sectional area is equal to

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

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



Step 4: Calculate the gradient of the graph



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

Step 5: Calculate the resistivity of the wire

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