Edexcel International A Level (IAL) Physics

Your notes

E.M.F & Modelling Resistance

Contents

© 2026 Save My Exams, Ltd. Get more and ace your exams at savemyexams.com

Your notes

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)**

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

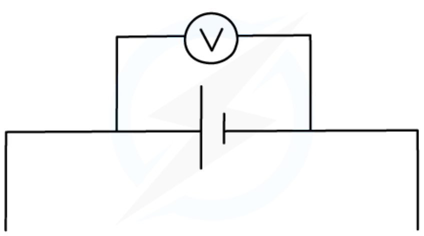
Copyright © Save My Exams. All Rights Reserved

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



Copyright © Save My Exams. All Rights Reserved

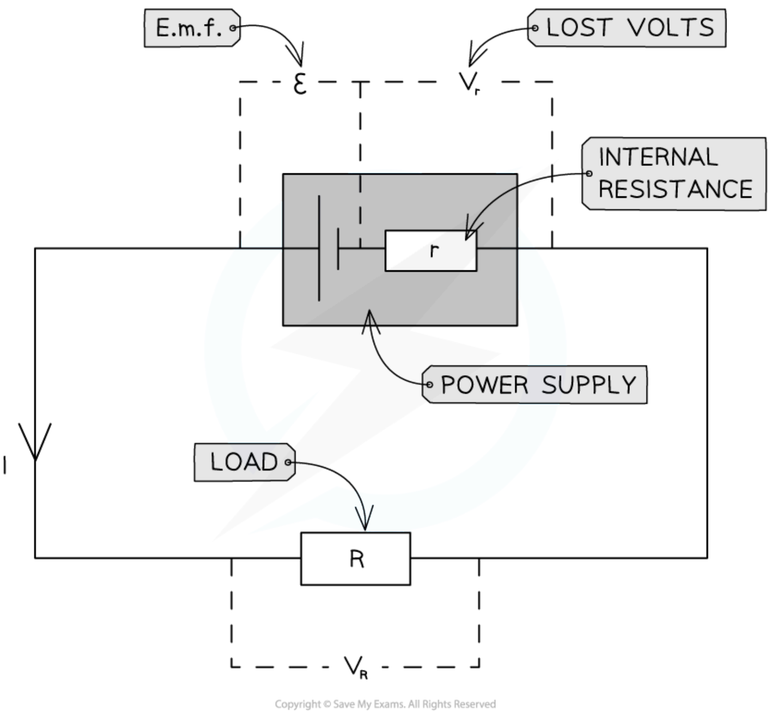
e.m.f. is measured using a voltmeter connected in parallel with the cell

Your notes

© 2026 Save My Exams, Ltd.
Get more and ace your exams at savemyexams.com

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

© 2026 Save My Exams, Ltd.

- ε = e.m.f.
- V_r = 'lost volts'
- V_R = voltage across the load (sometimes also called V_T, the terminal voltage)

Your notes

Examiner Tips and Tricks

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

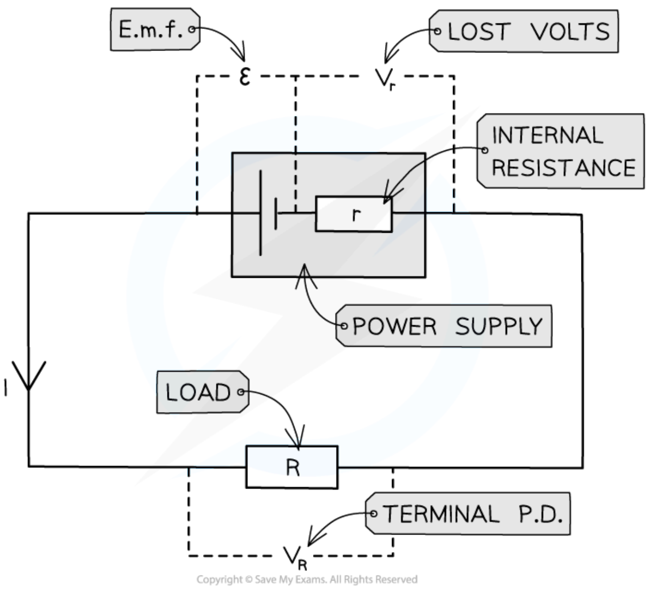
- Internal resistance of the cell can be treated as though it were a separate resistor - although it isn't!
- The load resistance is treated as another resistor in series
- Potential difference is measured across the load resistor
- The lost volts are calculated as though they were the potential difference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

© 2026 Save My Exams, Ltd. Get more and ace your exams at savemyexams.com

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

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

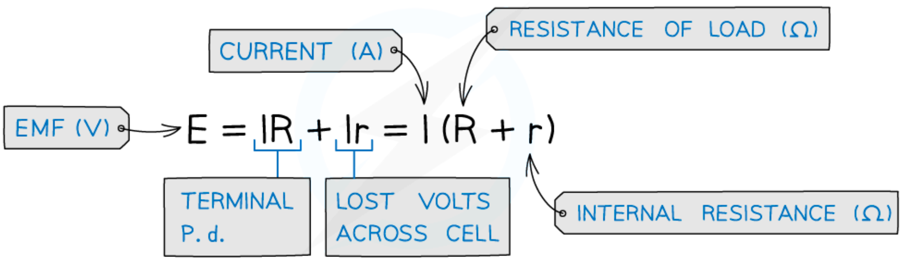
- Where:

- 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

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

- 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:



Copyright © Save My Exams. All Rights Reserved

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

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

Copyright © Save My Exams. All Rights Reserved

- 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

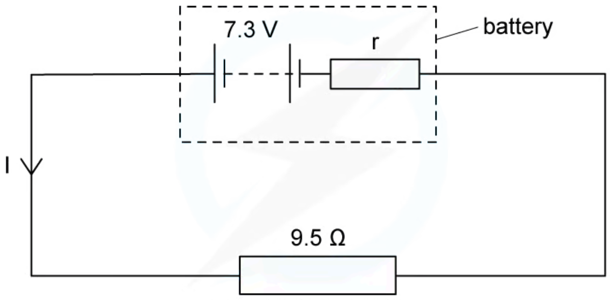
Your notes

- E.m.f. describes the **transfer of energy** from the **power supply** to **electrical charges** within the circuit

Your notes

Worked Example

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



Copyright © Save My Exams. All Rights Reserved

Determine:

a) The current in the circuit

b) Lost volts from the battery

Answer:

a.)

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

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

STEP 2: REARRANGE FOR I

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

STEP 3: SUBSTITUTE IN THE VALUES

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

b.)

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

$$\text{LOST VOLTS} = I \times r$$

STEP 2: SUBSTITUTE IN THE VALUES

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

Copyright © Save My Exams. All Rights Reserved

Examiner Tips and Tricks

If the exam question states 'a battery of negligible internal resistance', this assumes that e.m.f. of the battery is equal to its voltage. Internal resistance calculations will not be needed here. If the battery in the circuit diagram includes internal resistance, then the e.m.f. equations must be used.

Your notes

© 2026 Save My Exams, Ltd.

Core Practical 8: 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 = resistance, R (Ω)
- Dependent variable = voltage, V (V) & current, I (A)
- Control variables:
  - E.m.f of the cell
  - Internal resistance of the cell

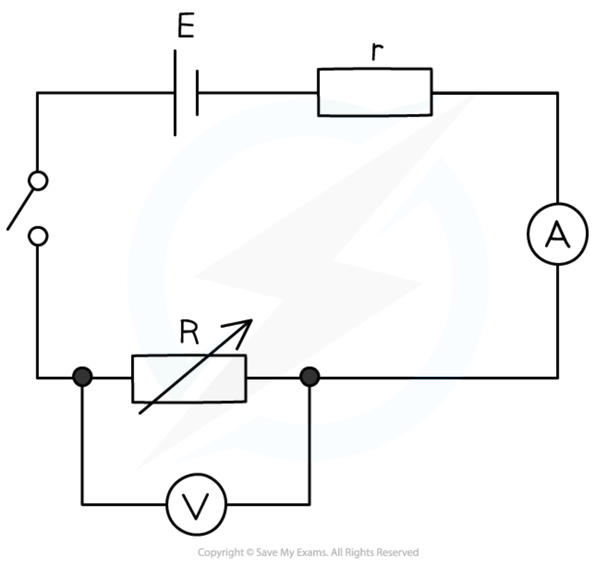
Equipment List

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

Copyright © Save My Exams. All Rights Reserved

- 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:

Your notes

RESISTANCE OF VARIABLE RESISTOR

VOLTMETER READING

AMMETER READING

R / Ω	1st READING		2nd READING		3rd READING		MEAN	
	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								

Copyright © Save My Exams. All Rights Reserved

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:

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

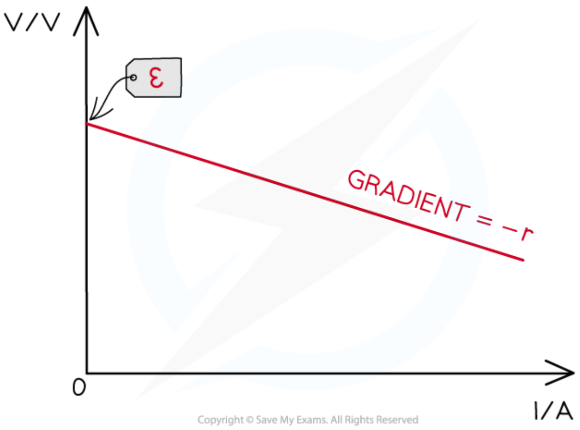
- Rearranging this equation for V:

$$V = -rI + E$$

- 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)

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



Evaluating the Experiment

Systematic Errors:

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

Random Errors:

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

Safety Considerations

- 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

Your notes

Worked Example

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

The data collected were as follows:

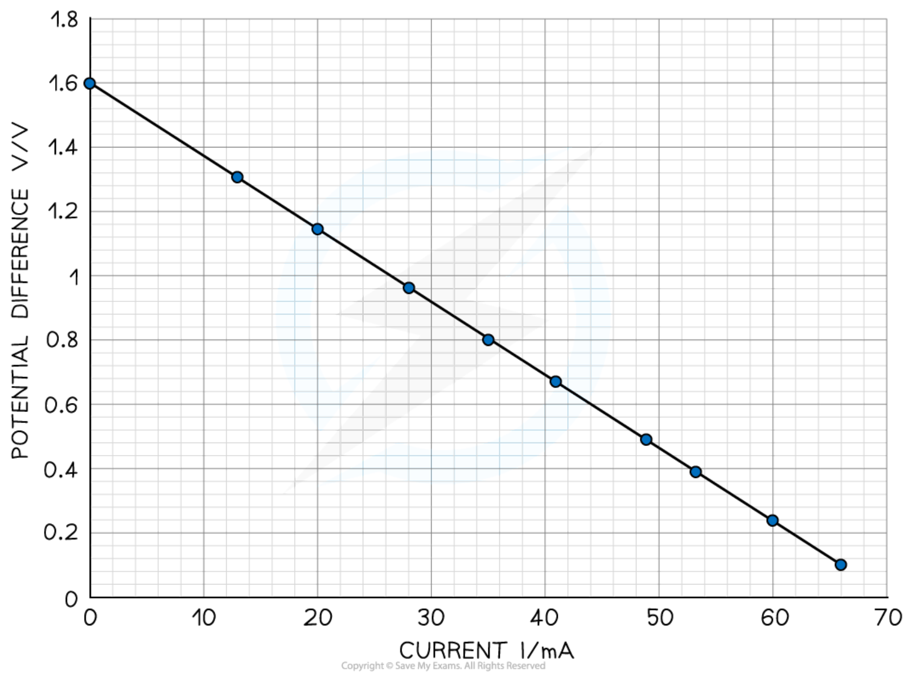
V / V	I / mA
1.60	0.0
1.30	13.1
1.14	20.0
0.96	28.2
0.80	35.2
0.65	41.5
0.49	48.8
0.38	53.4
0.23	60.3
0.10	66.0

Copyright © Save My Exams. All Rights Reserved

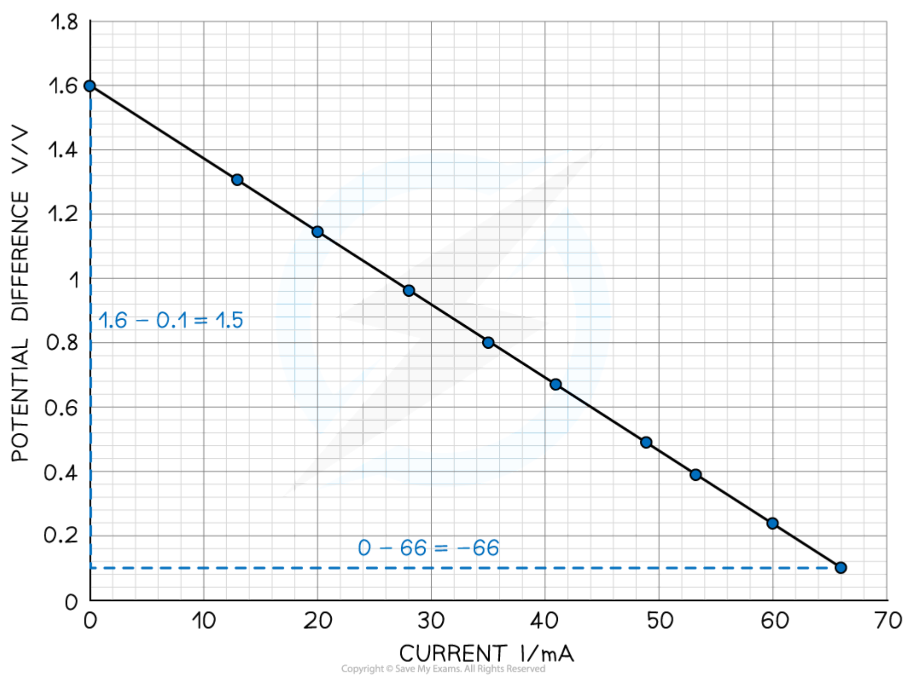
Plot a graph of these results and determine the e.m.f. and the internal resistance directly from the graph.

Answer:

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



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



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

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

$$V = -rI + E$$

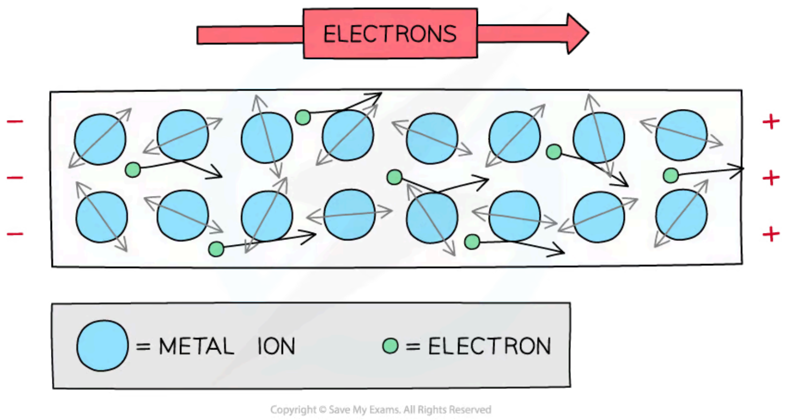
- From this equation:
  - Gradient = $-r$ (Ω)
  - Y-intercept = E (V)
- Therefore:
  - Internal resistance, r = 22.7 Ω
  - E.m.f. E = 1.60 V

Your notes

© 2026 Save My Exams, Ltd. Get more and ace your exams at savemyexams.com

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

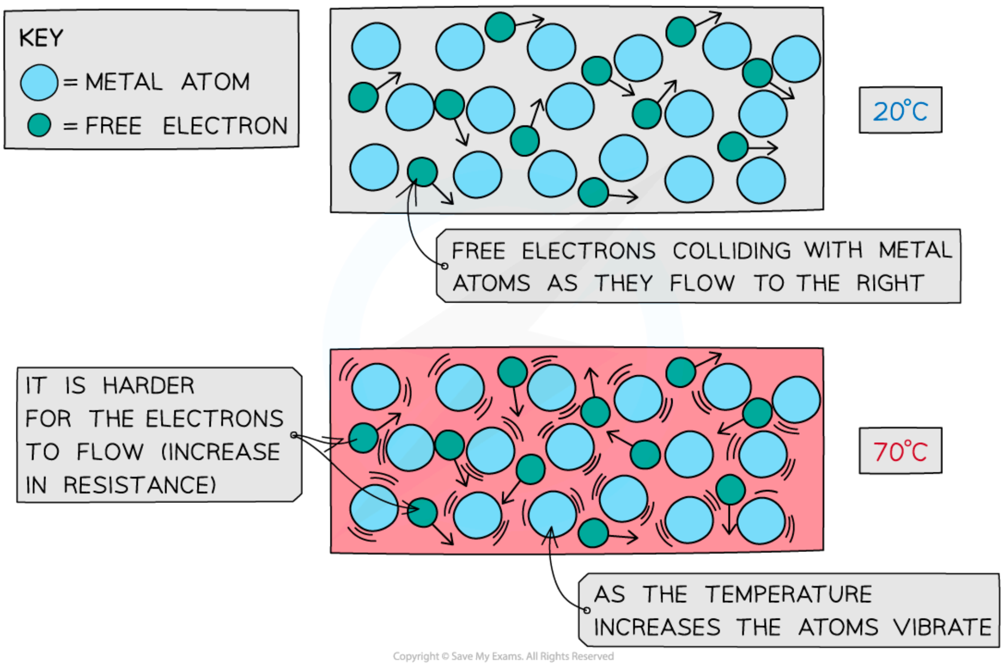
Resistance & Temperature for Metallic Conductors

- All solids are made up of vibrating atoms

Your notes

- This includes metal solids

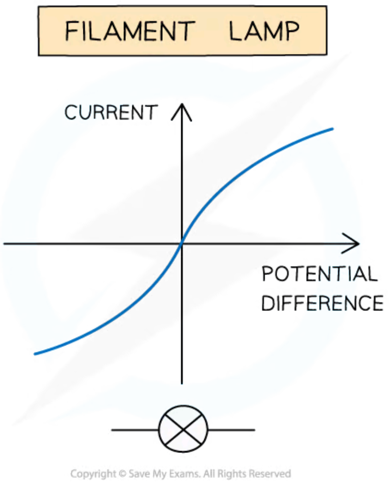
- As the temperature in a metal rises, the ions vibrate with a greater frequency and amplitude
  - The electrons collide with the vibrating atoms which impede their flow, hence the current **decreases**
  - electric current is the flow of free electrons in a material



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:
  - an **increase** in temperature leads to an **increase** in resistance and resistivity
  - a **decrease** in temperature leads to a **decrease** in resistance and resistivity
- The I-V graph for a filament lamp shows this effect

Your notes



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 leads to **increased vibrations** in the lattice of ions
  - As a result, the frequency of **collisions** between free electrons and the ions increases, which leads to an **increase** in resistance
- Resistance **opposes** the current, causing the current to increase at a slower rate
  - This is seen on the *I–V* graph as a curve with a **decreasing gradient**

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.

Answer:

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

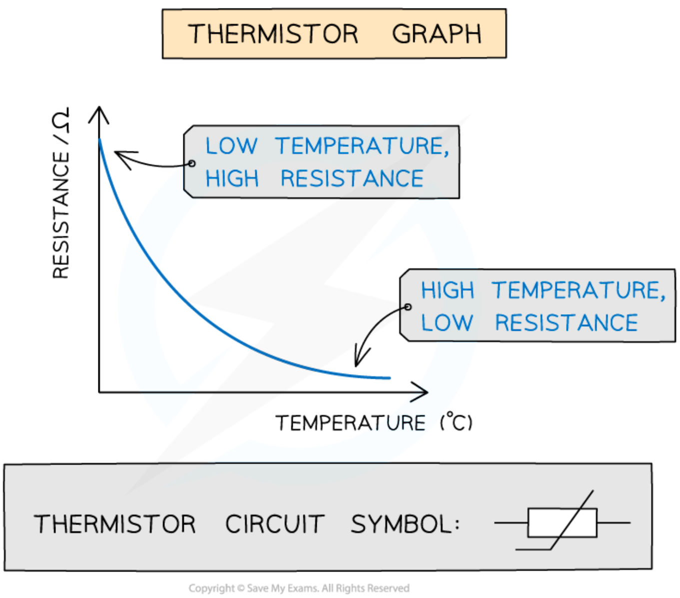
Step 3: Describe what happens to the vibrations of the lattice

- Therefore vibrations of the lattice ions increase

Resistance & Temperature for Thermistors

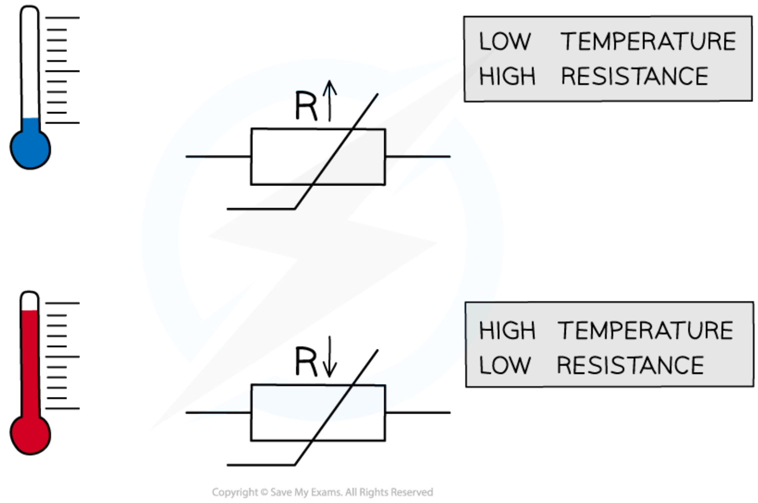
Your notes

- 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

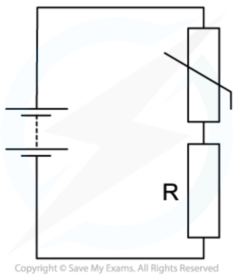
- As the thermistor gets **hotter**, its resistance **decreases**
- As the thermistor gets **cooler**, its resistance **increases**



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

Your notes

Your notes

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

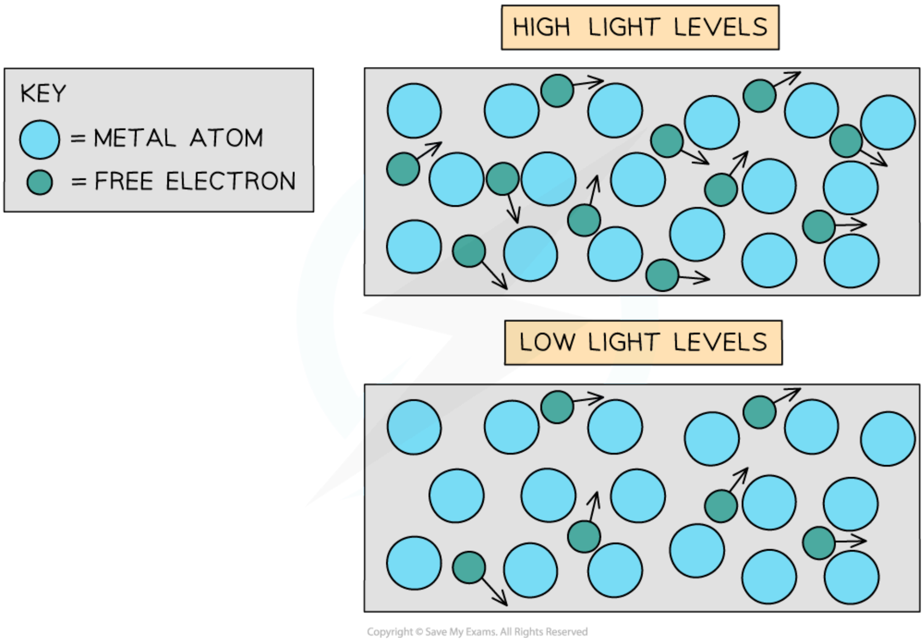
Step 4: State the conclusion

- Therefore, statement **A** is correct

© 2026 Save My Exams, Ltd. Get more and ace your exams at savemyexams.com

Modelling the Variation of Resistance with Illumination

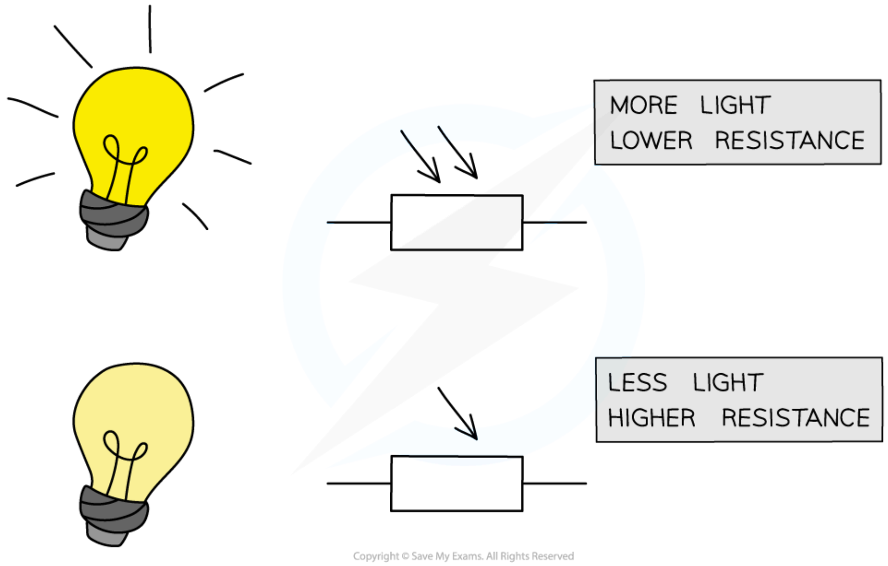
- Light can cause a change in conductivity of some semi-conductors
- When light is absorbed by the material it causes more electrons to be available for conduction



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

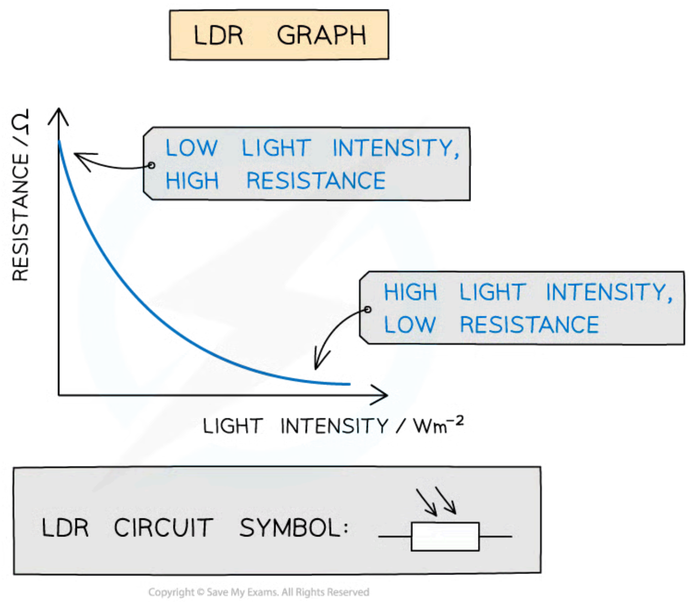
Resistance & Illumination for LDRs

- 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

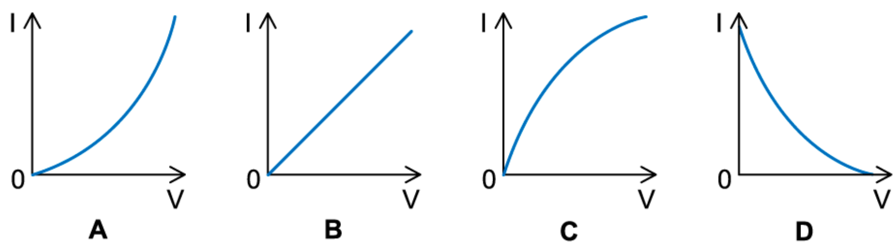
- LDRs can be used as light sensors, so, they are useful in circuits which automatically switch on lights when it gets dark, for example, street lighting and garden lights
  - In the dark, its resistance is very large (millions of ohms)
  - In bright light, its resistance is small (tens of ohms)

Your notes

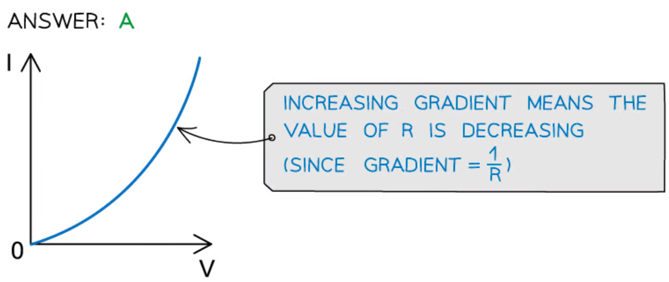
LDRs are used for automatic street lights

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?



Step 1: Consider the relationship between light intensity and resistance

Your notes

- 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**

Your notes