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5.4 Electromotive Force & Internal Resistance

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

5.4 Electromotive Force & Internal Resistance

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5.4.1 Electromotive Force & Internal Resistance

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:

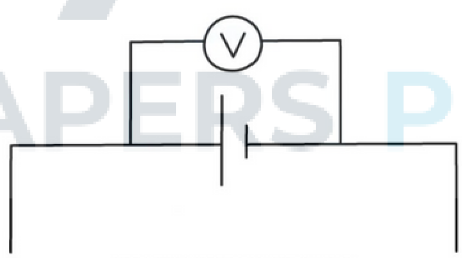
The amount of chemical energy converted to electrical energy per coulomb of charge (C) when passing through a power supply

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

- This can also be written as:

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

- E.m.f can be represented by the symbol ε (greek letter epsilon)
  - It is not actually a force, and is measured in **volts (V)**
- E.m.f is equal to 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, as so:



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

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

$$V = IR$$

- Where:
  - V = terminal p.d (V)
  - I = current (A)
  - R = resistance (Ω)

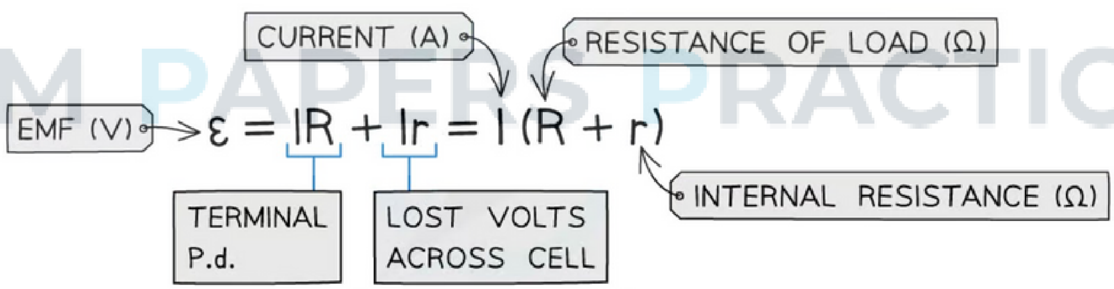
- Since a cell has internal resistance, the terminal p.d is always **lower** than the e.m.f
- In a closed circuit, current flows through a cell and a potential difference develops across the internal resistance
- Since resistance opposes current, this reduces the energy per unit charge (voltage) available to the rest of the external circuit
- This difference is called the 'lost volts'
  - **Lost volts** is usually represented by little *v*
  - It is defined as

    The work done per unit charge / coulomb to overcome the internal resistance / resistance inside the battery (when current flows)

  - In other words, this is the voltage lost in the cell due to internal resistance
  - So, from conservation of energy: v = e.m.f – terminal p.d

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

- Where:
  - v = lost volts (V)
  - I = current (A)
  - r = internal resistance of the battery (Ω)
  - ε = e.m.f (V)
  - V = terminal p.d (V)
- The e.m.f is the sum of these potential differences, giving the equation below:



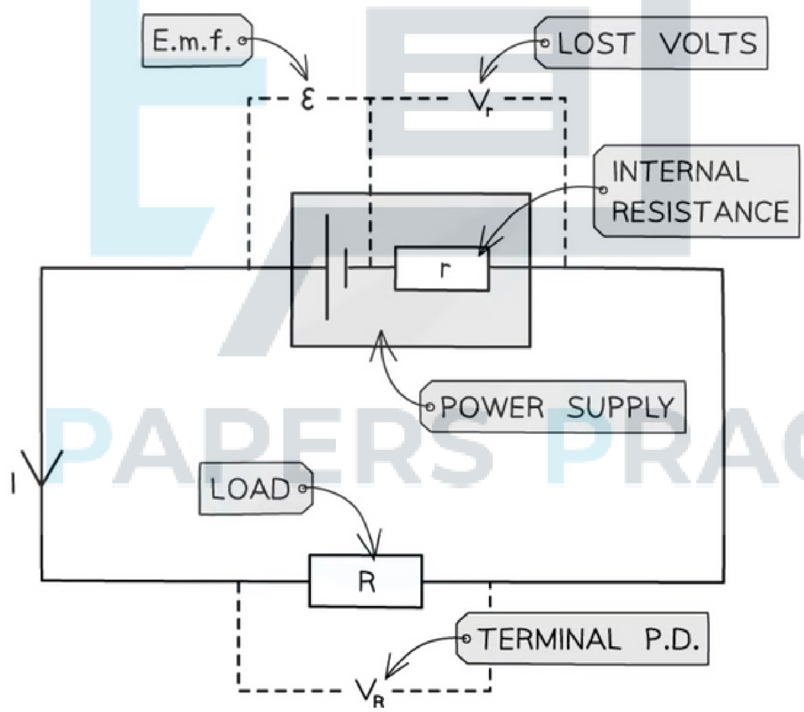
- E.m.f can therefore be defined as the **total**, or **maximum**, voltage available to the circuit

Internal Resistance

- All power supplies have some resistance between their terminals
  - This is called **internal resistance** (*r*)
- Internal resistance is defined as:

The resistance of the materials within the battery

- It is internal resistance that causes the charge circulating to dissipate some electrical energy from the power supply itself
  - This is why the cell becomes warm after a period of time
- Therefore, over time the internal resistance causes **loss of voltage** or energy loss in a power supply
- A cell can be thought of as a source of e.m.f with an internal resistance connected in series. This is shown in the circuit diagram below:

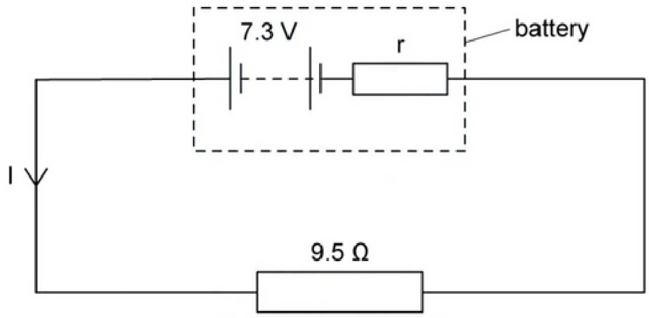


Circuit showing the e.m.f and internal resistance of a power supply

- Where:
  - Resistor *R* is the 'load resistor'
  - *r* is the internal resistance
  - ε is the e.m.f
  - V_r is the lost volts
  - V_R is the p.d across the load resistor, which is the same as the terminal p.d

Worked Example

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



Determine:

a) The current in the circuit

b) Lost volts from the battery

a.)

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

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

STEP 2 — REARRANGE FOR I

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

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

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

Exam Tip

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 (like that in the worked example), then the e.m.f equations must be used.

Required Practical: Investigating EMF & 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

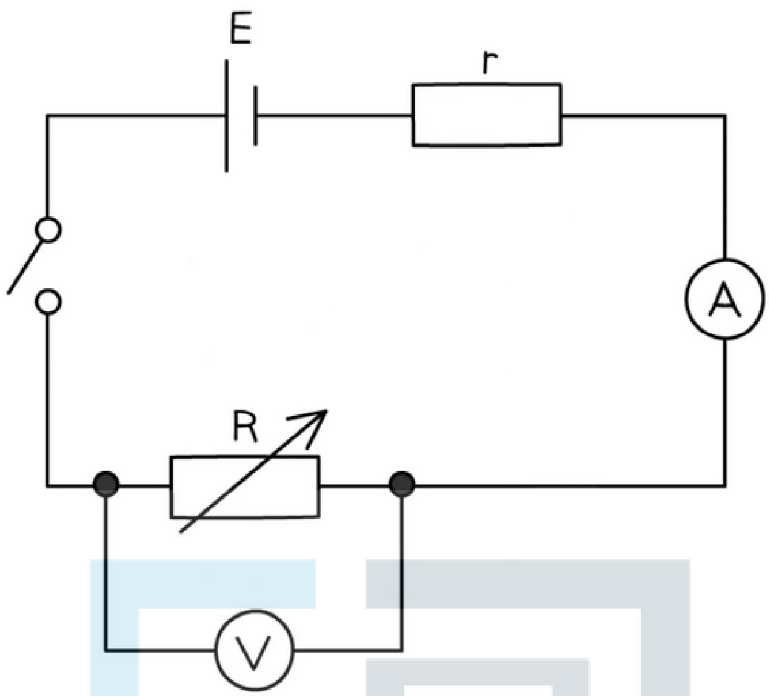
- Independent variable = voltage, *V* (V) & current, *I* (A)
- Dependent variable = resistance, *R* (Ω)
- Control variables:
  - E.m.f of the cell
  - Internal resistance of the cell

Equipment List

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

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

Method



1. The cell and the resistor, labelled *r*, should be connected in series and considered to be a single cell
2. With the switch open, record the reading *V* on the voltmeter
3. Set the variable resistor to its maximum value, close the switch and record *V* and the reading *I* on the ammeter - make sure to open the switch between readings
4. Vary the resistance of the variable resistor up to a minimum of 8–10 readings and record values for *V* and *I* for each resistance. Ensure to take readings for the whole range of the variable resistor

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

RESISTANCE OF VARIABLE RESISTOR — VOLTMETER READING — AMMETER READING

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								

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:

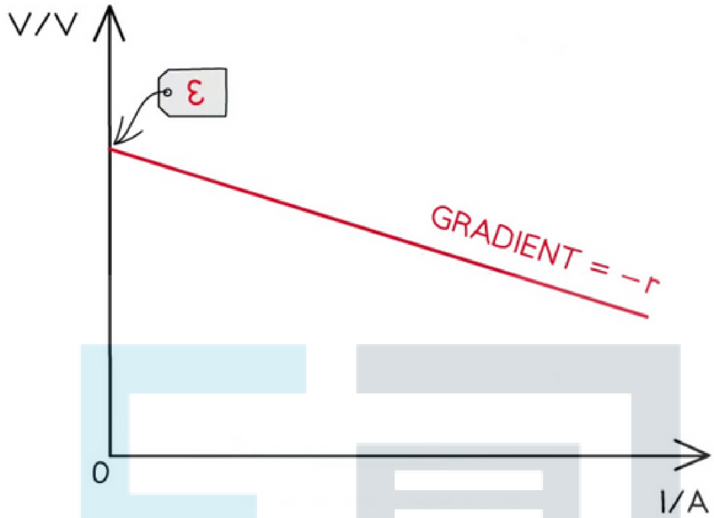
$$E = IR + Ir = V + Ir$$

- 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

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

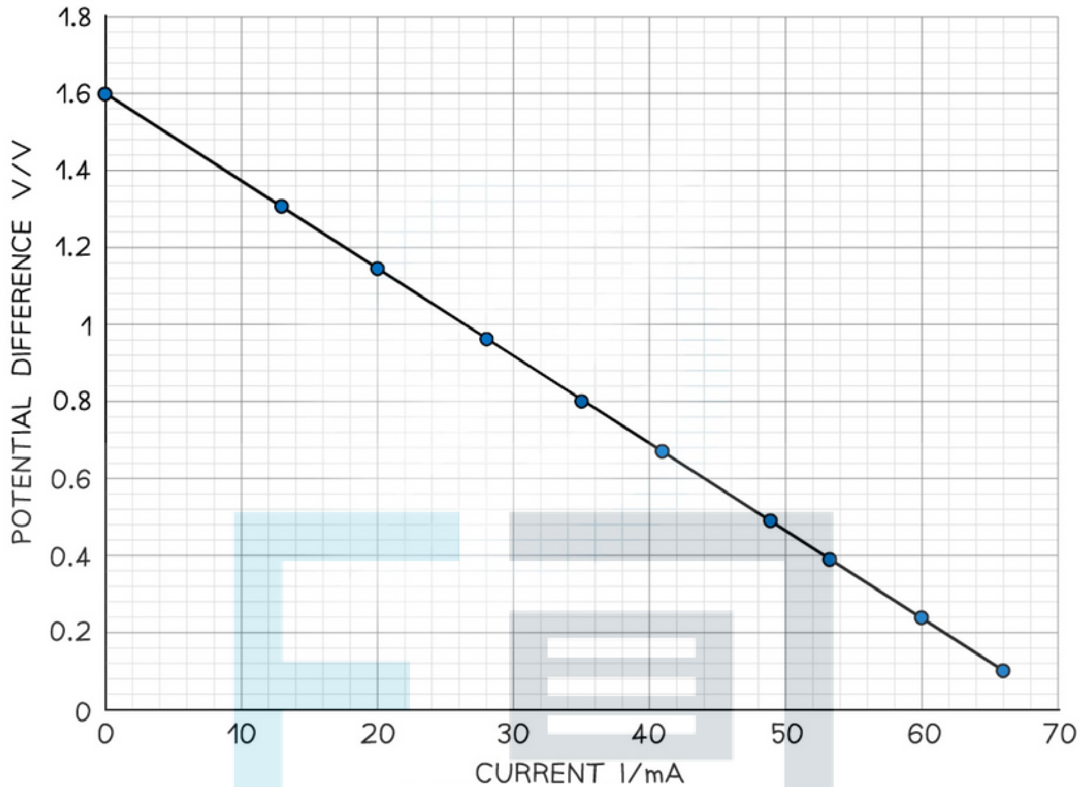
Worked Example

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

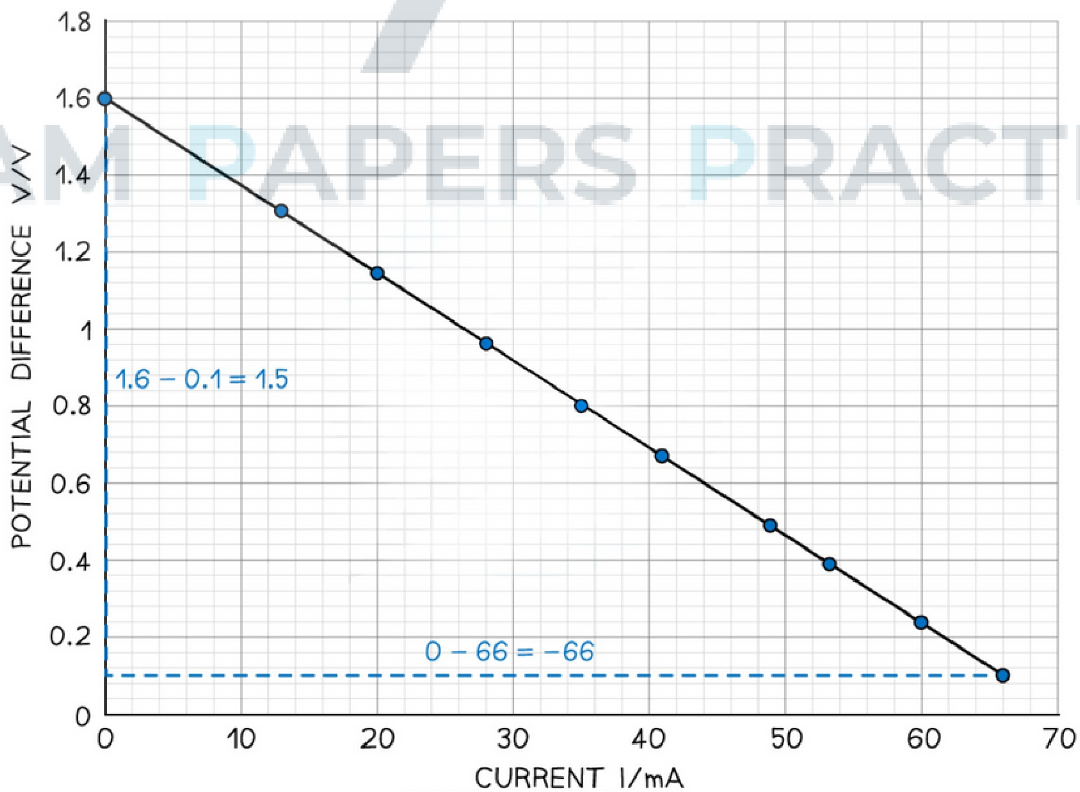
V / V	I / mA
1.60	0.0
1.30	13.1
1.14	20.0
0.96	28.2
0.80	35.2
0.65	41.5
0.49	48.8
0.38	53.4
0.23	60.3
0.10	66.0

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

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



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



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

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

$$V = -rI + E$$

- From this equation:
  - Gradient = $-r$ (Ω)
  - Y-intercept = E (V)

- Therefore:
  - Internal resistance, $r = 22.7\ \Omega$
  - E.m.f. $E = 1.60$ V