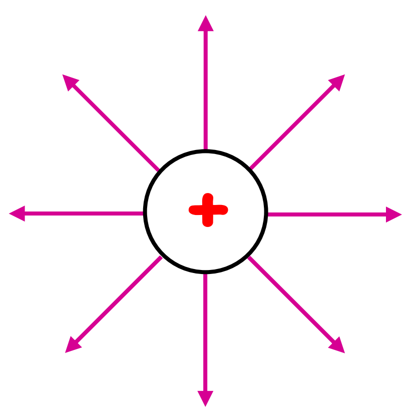
Higher Physics – Unit 2

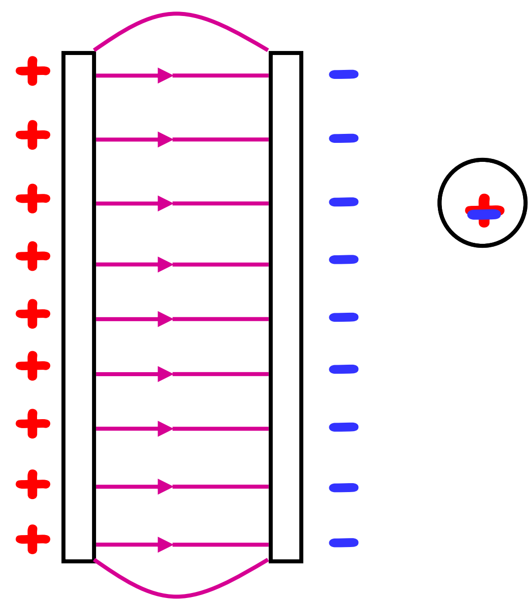
2.1 Electric fields and resistors in circuits

Electric Fields

Electric fields exist in the regions around electric charges.

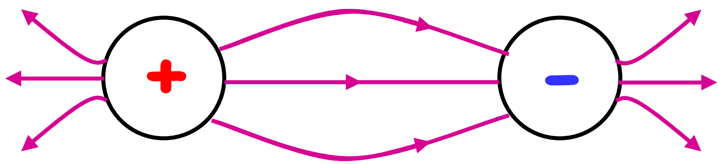
A charge experiences a force in an electric field.





The arrows show the direction a positive charge will be forced to move.

When two opposite charges are close, we see:



Electric Fields and Conductors

On applying an electric field to a conductor, the free electric charges (electrons) move.

These free electric charges moving, are called an electric current.

Worksheet – Electricity & Electronics Tutorial

Q1 & Q2

Charges in Electric Fields

For a charge to move through an electric field, work must be done:

$$W = Q\,V$$

work done (or energy gained by charge) (J, Joules)

charge (C, Coulombs)

potential difference (V, Volts)

The potential difference (V) between two points is a measure of the work done in moving one coulomb of charge between the points.

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

Example 1

60 J of work is done moving a charge through a p.d. of 2 kV.

Calculate the size of the charge.

$$W = 60\ J$$

$$V = 2\ kV = 2 \times 10^3\ V$$

$$Q = ?$$

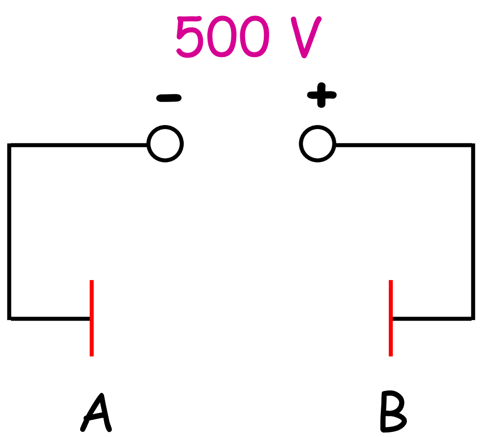
$$W = Q\,V$$

$$Q = \frac{W}{V} = \frac{60}{2 \times 10^3}$$

$$Q = 0.03\ C$$

Example 2

An electron is moved from plate A to plate B as shown.



Calculate the energy gained by the electron

$V = 500\ V$

$Q_{electron} = 1.60 \times 10^{-19}\ C$

** info from data sheet **

$W = ?$

$W = Q\,V$

$= (1.60 \times 10^{-19}) \times 500$

$W = 8 \times 10^{-17}\ J$

Example 3

An electron is moved between two metal plates with a potential difference of 5 kV.

Calculate the velocity of the electron as it reaches the positive plate.

$$V = 5\ kV$$
$$= 5 \times 10^{3}\ V$$

$$Q_{electron} = 1.60 \times 10^{-19}\ C$$

** info from data sheet **

$$W = ?$$

$$W = Q\ V$$
$$= \left(1.60 \times 10^{-19}\right) \times \left(5 \times 10^{3}\right)$$
$$W = 8 \times 10^{-16}\ J$$

Energy is conserved.

$$E_K = W$$
$$= 8 \times 10^{-16} \text{ J}$$

$$m_{electron} = 9.11 \times 10^{-31} \text{ kg}$$

** info from data sheet **

$$v = ?$$

$$E_K = \frac{1}{2} m v^2$$

$$8 \times 10^{-16} = \frac{1}{2} \times (9.11 \times 10^{-31}) \times v^2$$

$$8 \times 10^{-16} = (4.555 \times 10^{-31}) \times v^2$$

$$v^2 = \frac{8 \times 10^{-16}}{4.555 \times 10^{-31}}$$

$$v^2 = 1.756 \times 10^{15}$$

$$v = \sqrt{1.756 \times 10^{15}}$$

$$v = 41.9 \times 10^{6} \text{ ms}^{-1}$$

Worksheet - Electricity & Electronics Tutorial

Q3 - Q7

Definition of a Volt

Consider the equation $W = Q\,V$.

Rearrange to give $V = \frac{W}{Q}$.

This means then that $1\,\text{Volt} = \frac{1\,\text{Joule}}{1\,\text{Coulomb}}$

This is written as: $1\,V = 1\,J\,C^{-1}$

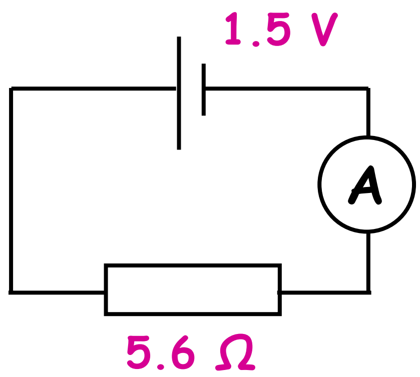
Definition of 1 Volt

The potential difference between two points is **1 volt** when **1 Joule** of energy is required to **move 1 Coulomb** of charge between the two points.

Circuits with Batteries or Cells

Experiment

Set up the circuit shown.



Calculation of Current in Circuit

$V = 1.5\ V$

$R = 5\ \Omega$

$I = ?$

$V = I R$

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

$= \frac{1.5}{5}$

$I = 0.3\ A$

Measurement of Current in Circuit

The reading on the ammeter is _______ A.

Why are the two results different?

Answer

The results are different because the battery has a resistance inside it, which we have not taken into consideration previously.

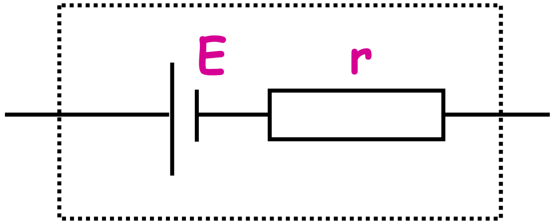
This resistance is called the **INTERNAL RESISTANCE** of the battery and has the symbol **r**.

Internal Resistance

Every **electrical source** can be thought of as a **source of emf** with a **resistor in series**.

The resistance from within a cell or battery is known as INTERNAL RESISTANCE.

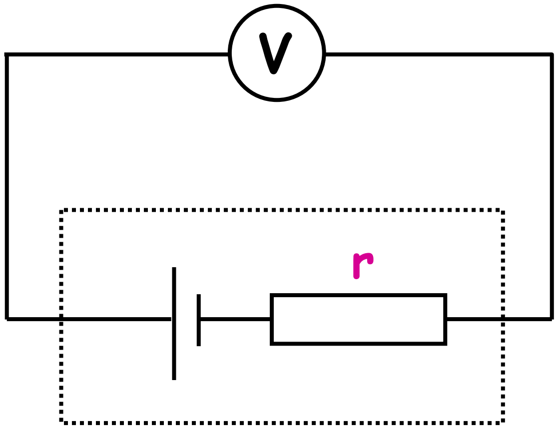
Batteries or cells with internal resistance should be drawn as shown.



Measuring emf of a Battery

Experiment

Connect a voltmeter across the terminals of a battery as shown.



Reading on (V) = emf.

The nominal emf of a battery is usually written on it.

(e.g. an AA battery has an emf of 1.5 V, however checking this with a voltmeter may give about 1.54 V)

Electromotive Force (emf)

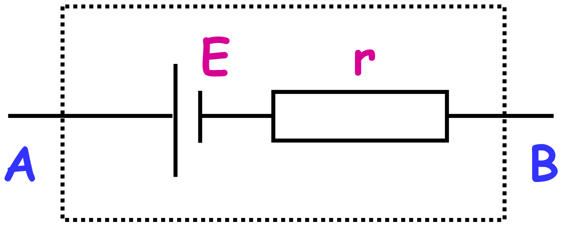
The maximum voltage of a battery is called the electromotive force (emf) and has the symbol E.

The emf of an electrical supply is:

the number of Joules of energy given to each Coulomb of charge passing through the supply.

Remember: $1\,V = 1\,J\,C^{-1}$

The voltage measured across the cell is measured between terminals A and B.



This is called the TERMINAL POTENTIAL DIFFERENCE (tpd).

When the circuit is open, no current is being taken from the source, and so no energy is lost in overcoming the internal resistance.

This means:

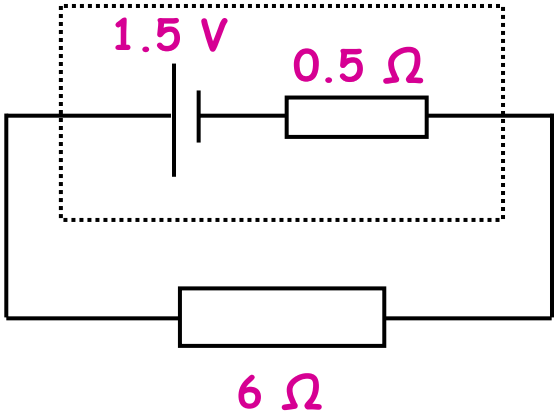
e.m.f. of a source = open circuit t.p.d.

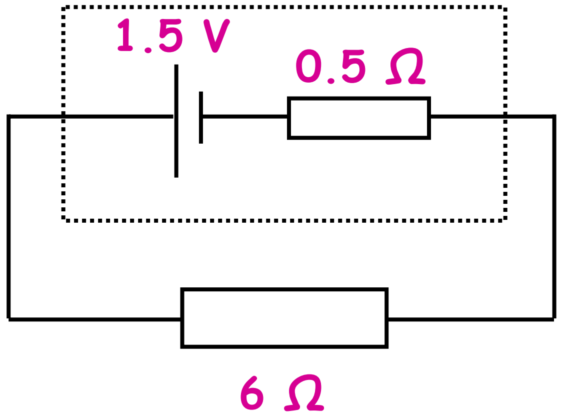
Example 1

A battery of emf 1.5 V and internal resistance 0.5 Ω, is connected to a 6 Ω resistor.

(a) Calculate the current in the circuit.

Draw diagram and insert values given.





$$V = 1.5\ V$$

$$r = 0.5\ \Omega$$

$$R = 6\ \Omega$$

$$R_{tot} = 6.5\ \Omega$$

$$I = ?$$

$$V = I\,R_{tot}$$

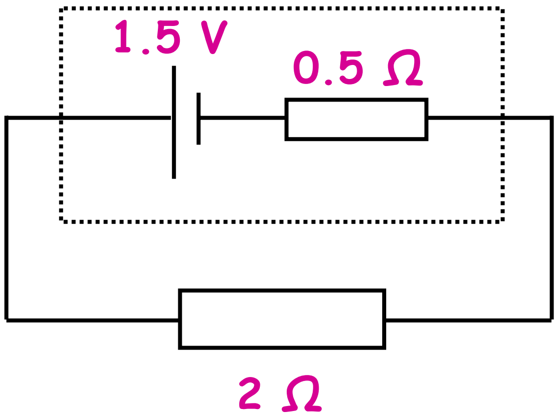
$$I = \frac{V}{R_{tot}}$$

$$= \frac{1.5}{6.5}$$

$$I = 0.23\ A$$

(b) The 6 Ω resistor is replaced by a 2 Ω resistor.

Calculate the new current in the circuit.



$$V = 1.5\ V$$

$$r = 0.5\ \Omega$$

$$R = 2\ \Omega$$

$$R_{tot} = 2.5\ \Omega$$

$$I = ?$$

$$V = I R_{tot}$$

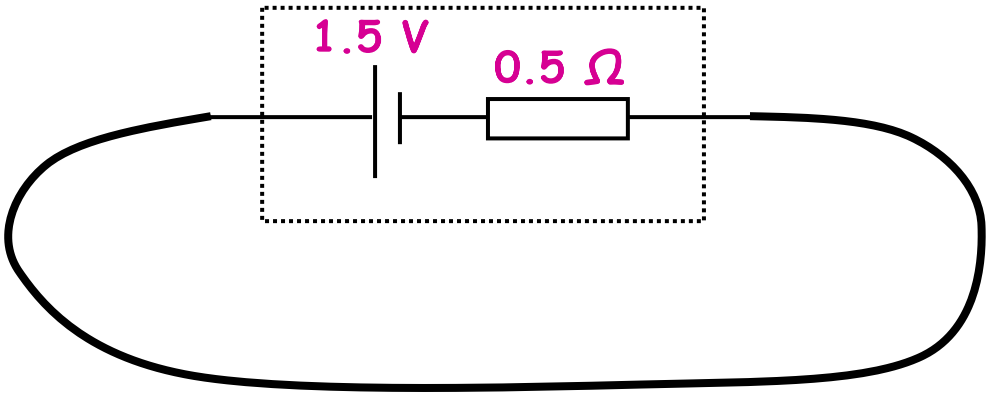
$$I = \frac{V}{R_{tot}}$$

$$= \frac{1.5}{2.5}$$

$$I = 0.6\ A$$

(c) The battery is short circuited using thick copper wire, which has negligible resistance.

Calculate the short circuit current.

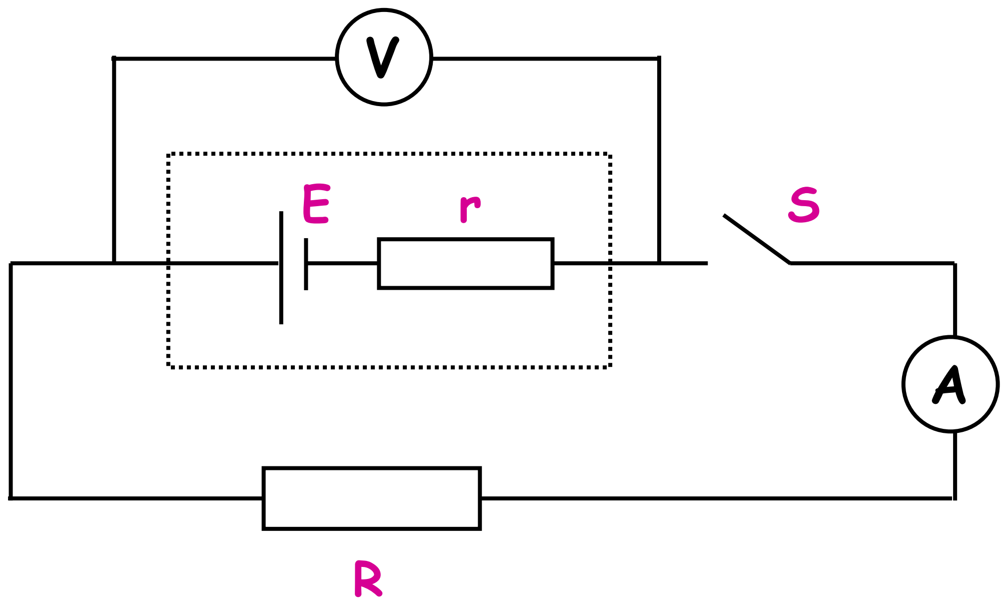


$$V = 1.5\ V$$
$$R_{tot} = 0.5\ \Omega$$
$$I = ?$$

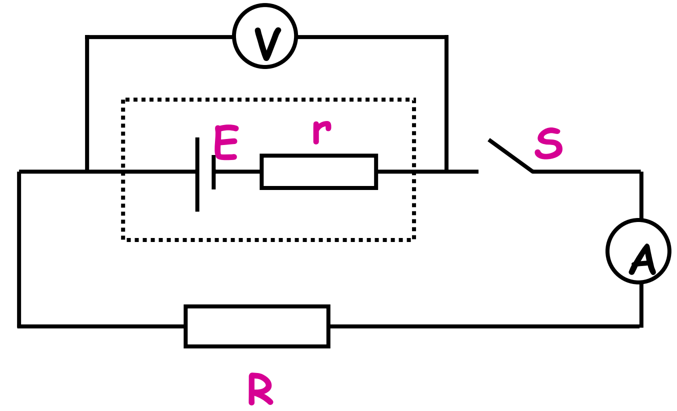
$$I = \frac{V}{R_{tot}}$$
$$= \frac{1.5}{0.5}$$
$$I = 3\ A$$

emf and Internal Resistance

The following circuit is used to find the emf and internal resistance of a cell.



Switch S Open



- reading on (V) = emf
- reading on (A) = 0 A

Switch S Closed

- reading on (V) falls to a value less than emf.
- the reading now on (V) is called the **TERMINAL POTENTIAL DIFFERENCE**.
- the tpd is the voltage across the external resistor R.
- voltage across internal resistance of the battery = emf - tpd.
- this voltage is called **LOST VOLTS** (voltage used up overcoming internal resistance).

The 'lost volts' increase with current.

This gives us the following relationship:

$$\text{emf} = \text{tpd} + \text{lost volts}$$

$$E = IR + Ir$$

emf (V)

tpd (V)

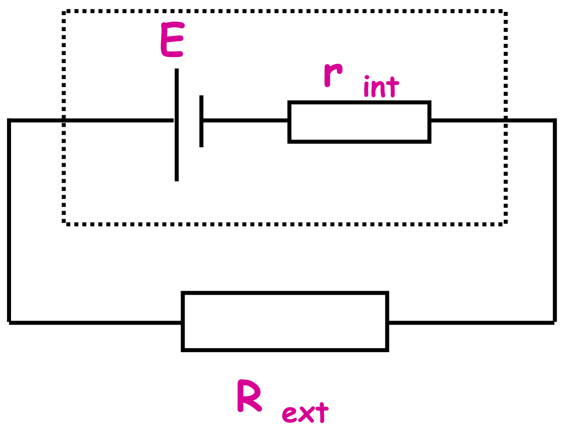
lost volts (V)

In the SQA data book, the equation is given as:

$$E = V + Ir$$

Internal Resistance Problems

Ohm's Law, $V = IR$ applies to ALL circuits, as does the fact that voltages in a series circuit add up to give the supply voltage.



emf = total voltage

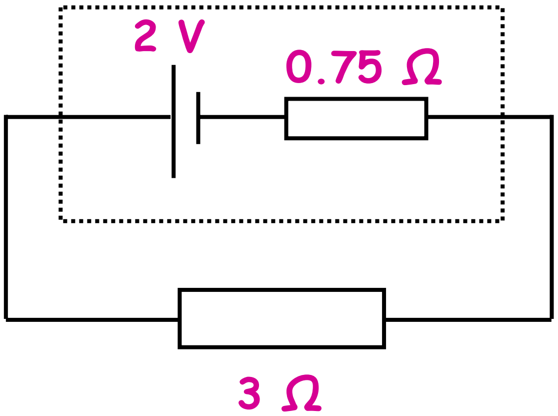
tpd = voltage across R_{ext}

lost volts = voltage across r_{int}

Example 1

A cell with emf 2 V and internal resistance 0.75 Ω is connected to an external resistor of 3 Ω.

(a) Draw a circuit diagram.



(b) Calculate the current in the circuit.

$E = 2\ V$

$R = 3\ \Omega$

$r = 0.75\ \Omega$

$I = ?$

$E = IR + Ir$

$E = I(R + r)$

$2 = I(3 + 0.75)$

$3.75\,I = 2$

$\underline{\underline{I = 0.53\ A}}$

(c) Calculate the lost volts.

**** Lost volts is due to the internal resistance, so use r. ****

$I = 0.53\ A$

$r = 0.75\ \Omega$

$\text{lost volts} = ?$

$\text{lost volts} = Ir$

$= 0.53 \times 0.75$

$\underline{\underline{\text{lost volts} = 0.4\ V}}$

(d) Calculate the terminal potential difference.

**** tpd is voltage across the external resistor, so use R. ****

$$I = 0.53\ A$$
$$R = 3\ \Omega$$
$$tpd = ?$$

$$tpd = I\,R$$
$$= 0.53 \times 3$$
$$\underline{\underline{tpd = 1.6\ V}}$$

An alternate method:

$$emf = tpd + \text{lost volts}$$
$$tpd = emf - \text{lost volts}$$
$$= 2 - 0.4$$
$$\underline{\underline{tpd = 1.6\ V}}$$

Worksheet – Electricity & Electronics Tutorial

Q15, Q16, Q17, Q18, Q19*, Q20, Q21*, Q22 – Q24.

Worksheet – Internal Resistance

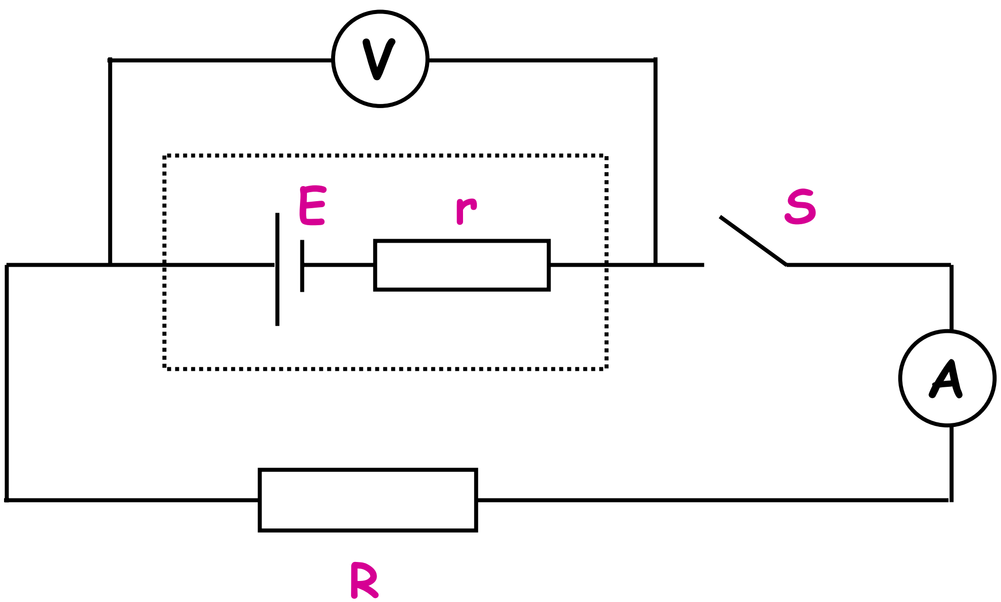
Q1 – Q6.

Measuring emf & Internal Resistance

Experiment (Method 1)

The circuit shown is used to measure the emf and tpd

The lost volts and internal resistance can then be calculated.



Switch S Open

voltmeter reading = _____ V

∴ emf = _____ V

Switch S Closed

voltmeter reading = _____ V

∴ tpd = _____ V

Calculation of Lost Volts

lost volts = emf - tpd

=

lost volts = _____ V

Calculation of Internal Resistance

$I = \_\_\_\_\_ \ A$

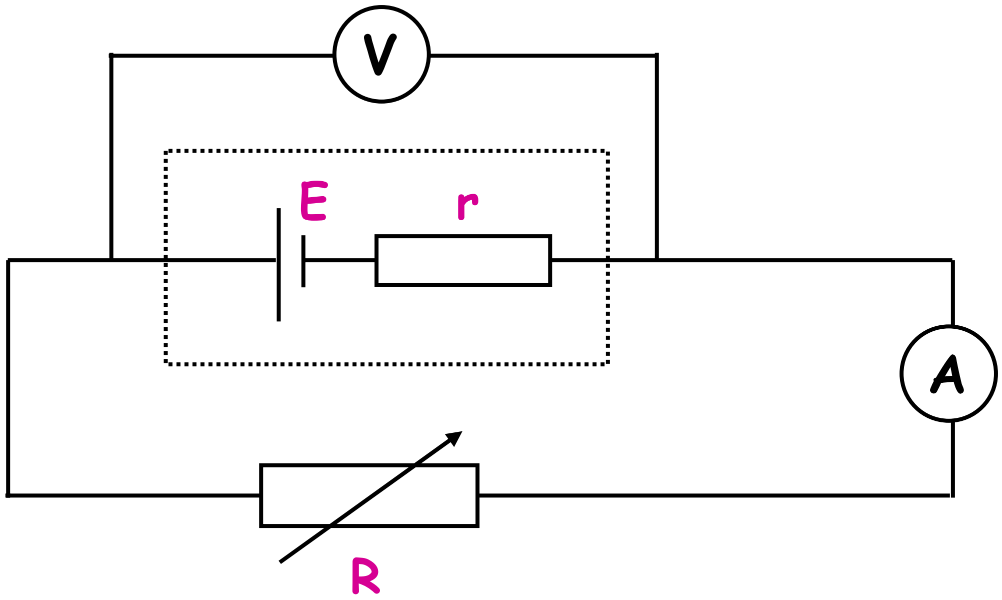
$$r = \frac{\text{lost volts}}{I}$$

$$= \frac{\text{emf - tpd}}{I}$$

$$r = \_\_\_\_\_ \ \Omega$$

Experiment (Method 2)

The following circuit is used to measure internal resistance of a cell.



Ⓥ measures the tpd V.

Ⓐ measures the current I.

Record these values in a table of results.

Change the setting on the variable resistor and note the new values of V and I each time.

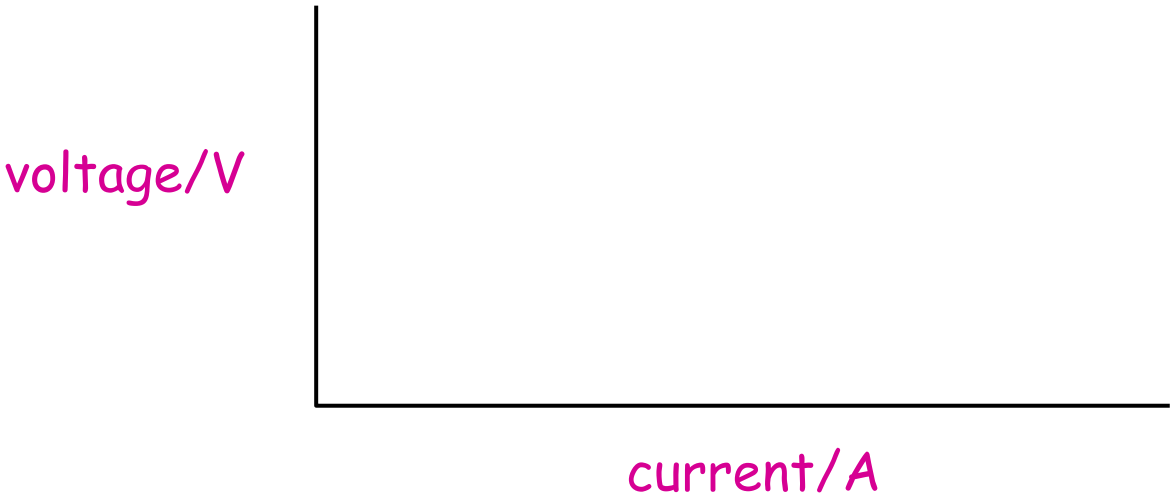
Repeat this several times.

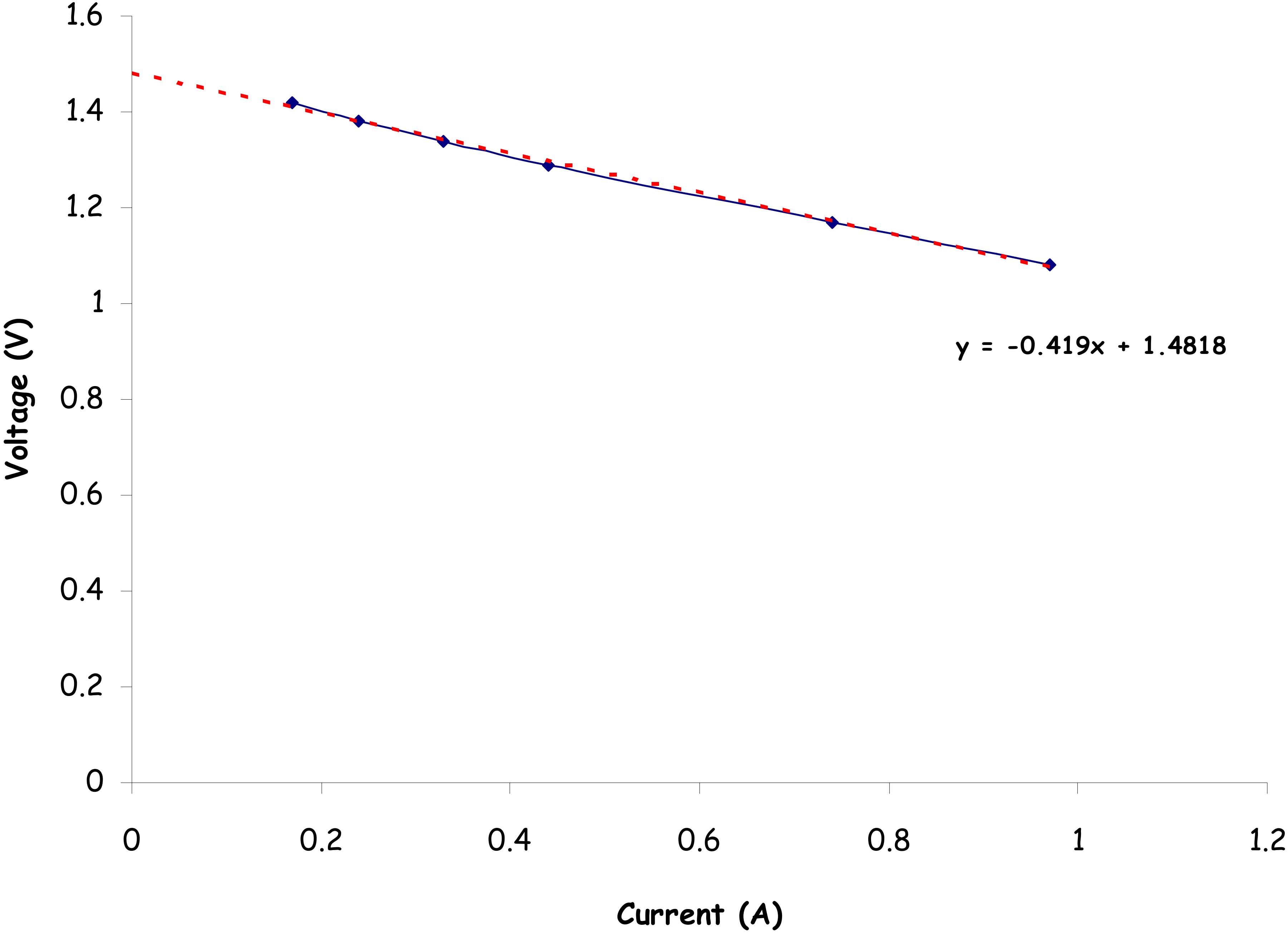
Results

V (volts)	**I (amps)**

Graph

Plot a graph of V against I.





y = -0.419x + 1.4818
Voltage (V)
Current (A)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
1.2

Theory

$$\text{emf} = \text{tpd} + \text{lost volts}$$

$$E = V + I\,r$$

$$V = E - I\,r$$

$$V = -r\,I + E$$

Compare this with the equation of a straight line: $y = m\,x + c$

$$r = |\text{gradient of graph}|$$

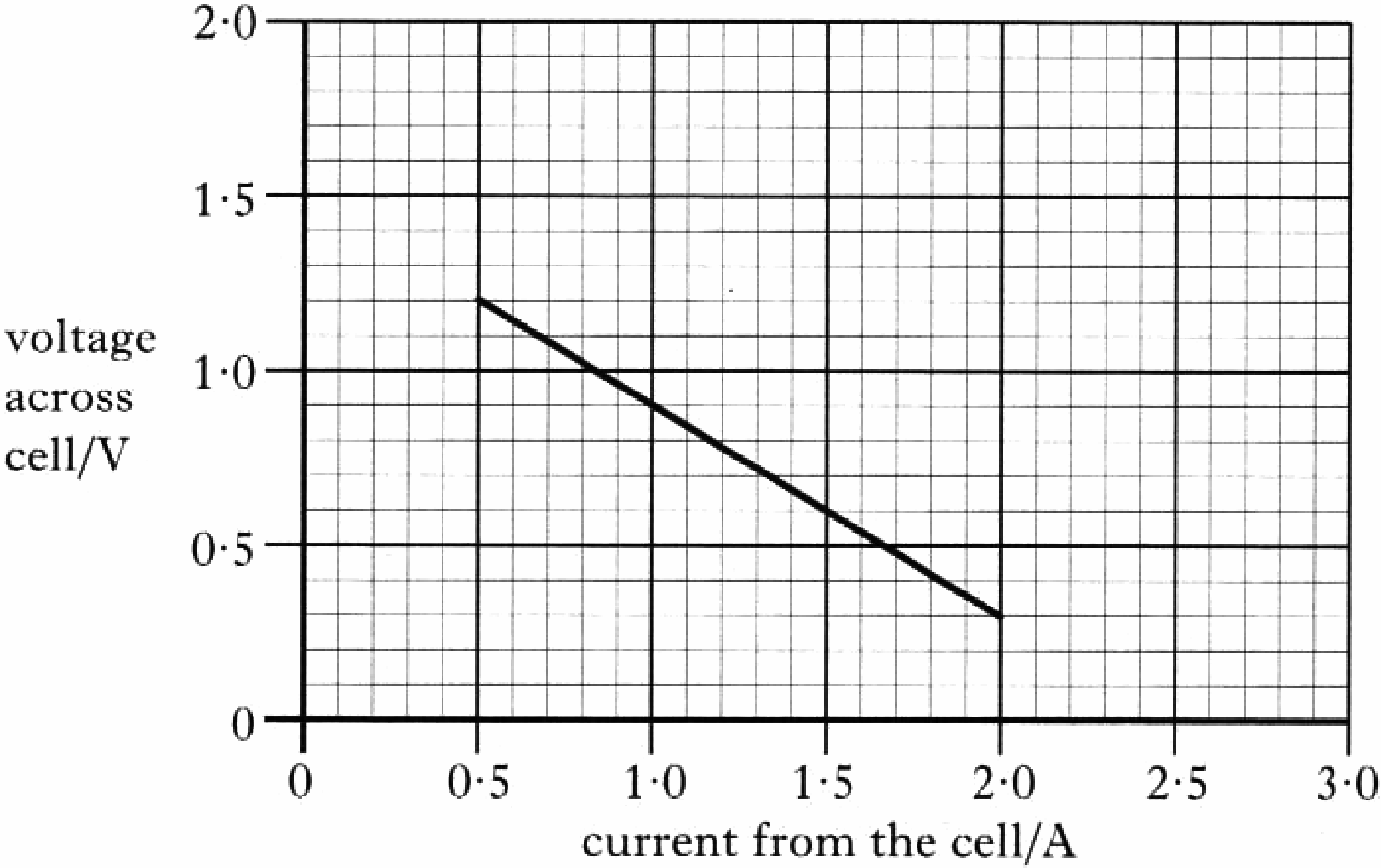
$$E = \text{intercept on V axis}$$

To calculate the gradient of the graph: $\text{gradient} = \dfrac{V_2 - V_1}{I_2 - I_1}$

The internal resistance of the battery is ______ Ω.

Q1. *Adapted from Higher Physics SQP [X069/301]*

During an experiment to measure the e.m.f. and internal resistance of a cell, the following graph is obtained.



(a) Draw a circuit which could be used to obtain the data for this graph. (2)

(b) (i) What is the value of the e.m.f of the cell?

(ii) Calculate the internal resistance of the cell. (3)

Worksheet - Electricity & Electronics Tutorial

Q23, Q24

Conservation of Energy

Electromotive Force

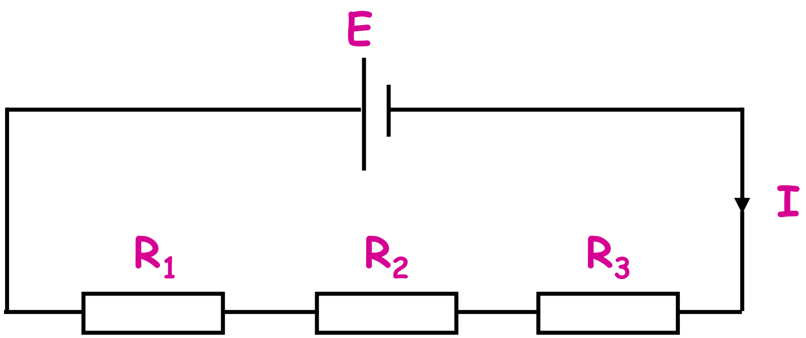
When a circuit is open (no current flowing) the pd across the terminals is in fact the emf.

When a current flows through components, the sum of the energies produced in each component equals the total energy provided by the source.

emf of closed circuit = sum of pd's across components

Resistors in Series

The energy lost from the electrical source E, is gained by each of the resistors in series.



$$\text{energy lost} = \text{energy gained}$$

$$E = V_1 + V_2 + V_3$$

$$I R_T = I R_1 + I R_2 + I R_3$$

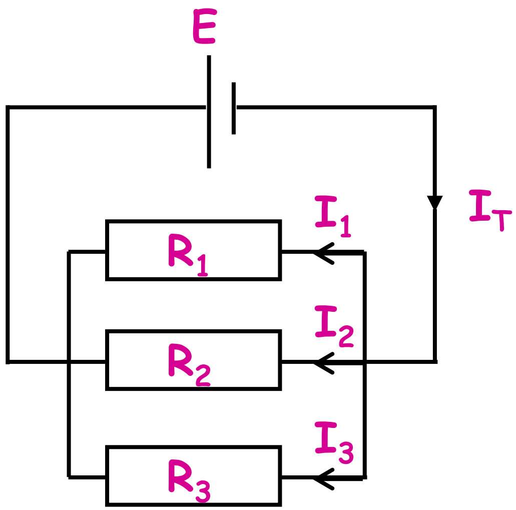
since current same at all points in a series circuit

$$R_T = R_1 + R_2 + R_3$$

Conservation of Charge

Resistors in Parallel

The current (charge per second) splits up in a parallel circuit.



$$I_T = I_1 + I_2 + I_3$$

$$\frac{E}{R_T} = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

since voltage across each resistor constant and equal to supply

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Resistance Calculations

Calculations involving resistors will require you to add resistors, some in parallel and some in series.

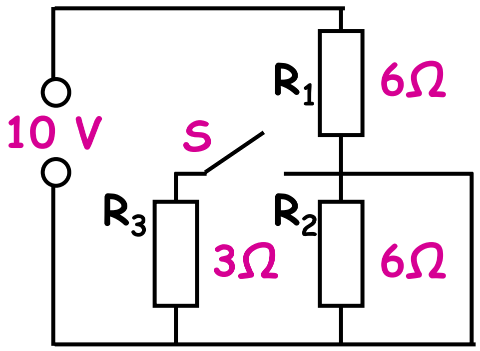
Example 1

The circuit shows resistors connected as a potential divider.

Calculate the voltmeter reading:

(a) when the switch S is open

(b) when the switch S is closed.



(a)

**** Switch S open, so have a series circuit with two resistors ****

$$R_1 = 6\ \Omega$$
$$R_2 = 6\ \Omega$$
$$V_T = 10\ V$$

$$R_T = R_1 + R_2$$
$$= 6 + 6$$
$$R_T = 12\ \Omega$$

Know total voltage, and total resistance, so can calculate total current.

$$I_T = \frac{V_T}{R_T}$$
$$= \frac{10}{12}$$
$$I_T = 0.83\ A$$

**** Series circuit, ∴ total current must flow through each resistor. ****

$$I_T = 0.83\,A$$
$$R = 6\,\Omega$$
$$V = ?$$

$$V = IR$$
$$= 0.83 \times 6$$
$$V = 5\,V$$

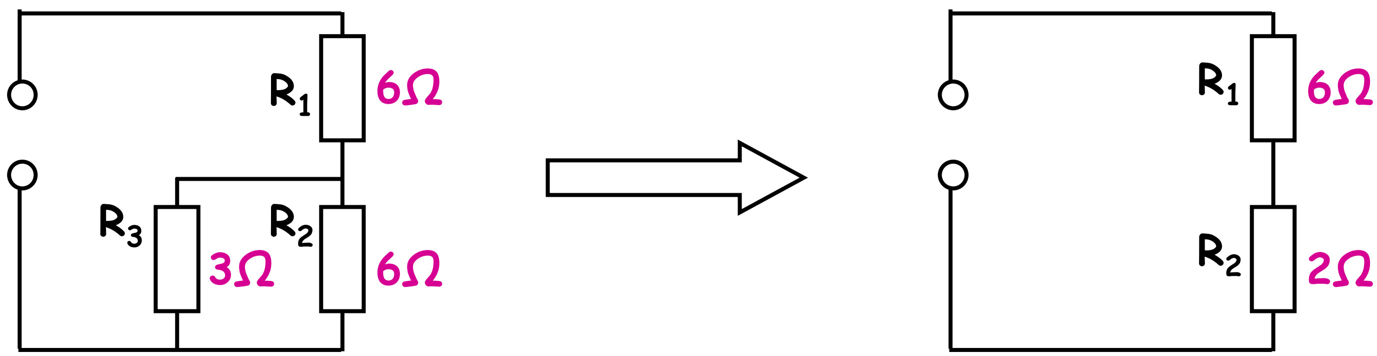
(b)

**** Switch closed, two resistors in parallel now. ****

$$R_2 = 6\,\Omega$$
$$R_3 = 3\,\Omega$$
$$R_P = ?$$

$$\frac{1}{R_P} = \frac{1}{R_2} + \frac{1}{R_3}$$
$$= \frac{1}{6} + \frac{1}{3}$$
$$\frac{1}{R_P} = 0.5$$
$$R_P = \frac{1}{0.5}$$
$$R_P = 2\,\Omega$$

** Now have two resistors in series. **



Combined R_2 and R_3.

Now need to combine these resistors to find total resistance.

$$R_1 = 6\ \Omega$$
$$R_2 = 2\ \Omega$$
$$V_T = 10\ V$$

$$R_T = R_1 + R_2$$
$$= 6 + 2$$
$$R_T = 8\ \Omega$$

Know total voltage, and total resistance, so can calculate total current.

$$I_T = \frac{V_T}{R_T}$$

$$= \frac{10}{8}$$

$$I_T = 1.25\ A$$

So can now calculate the size of voltage across R_1.

$R_1 = 6\ \Omega$

$I = 1.25\ A$

$V_1 = ?$

$$V_1 = I\,R_1$$

$$= 1.25 \times 6$$

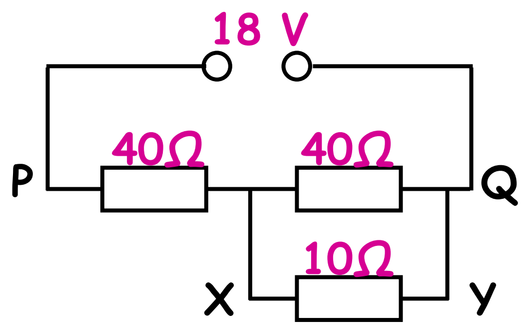
$$V_1 = 7.5\ V$$

The voltage across R_2 is given by: $10 - 7.5 = 2.5\ V$

Voltage across R_3 is also 2.5 V (voltage across components in parallel are same).

Example 2

A potential divider, PQ is set up as shown.



Calculate the potential difference across XY.

** Add the two resistors in parallel. **

$R_1 = 40\ \Omega$
$R_2 = 10\ \Omega$
$R_P = ?$

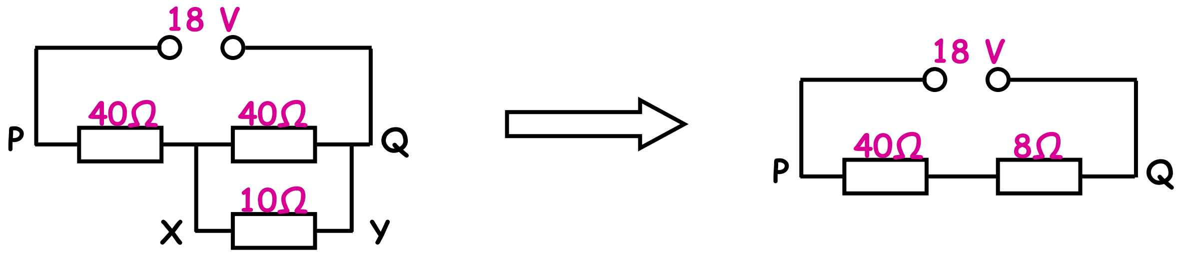
$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{40} + \frac{1}{10}$$

$$\frac{1}{R_P} = 0.125$$

$$R_P = 8\ \Omega$$

** Now have two resistors in series, 8Ω and 40Ω . **



$$R_T = 8 + 40$$

$$R_T = 48\ \Omega$$

Know total voltage, and total resistance, so can calculate total current.

$$I_T = \frac{V_T}{R_T}$$

$$= \frac{18}{48}$$

$$I_T = 0.375\,A$$

So the voltage across 40 Ω is:

$$R = 40\,\Omega$$

$$I = 0.375\,A$$

$$V = ?$$

$$V = I\,R$$

$$= 0.375 \times 40$$

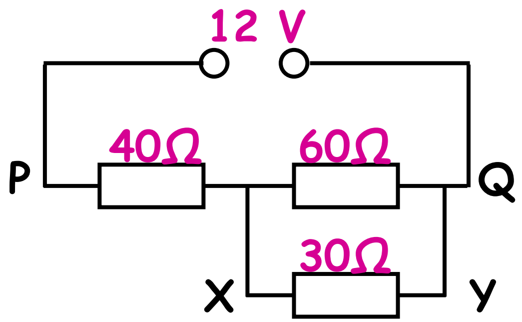
$$V = 15\,V$$

So the voltage across each of the resistors in parallel is:

$$18 - 15 = 3\,V$$

Question

Calculate the potential difference across XY for the circuit shown.



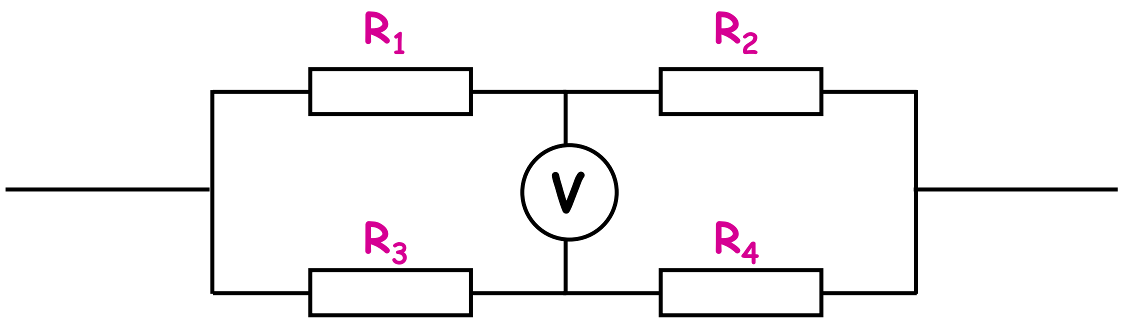
potential difference across XY = 4 V

Worksheet – Electricity & Electronics Tutorial

Q11, Q12, Q13, Q14

Wheatstone Bridge

A Wheatstone bridge contains four resistors as shown.

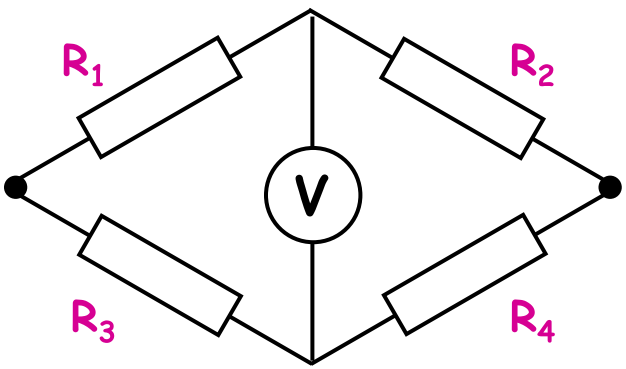


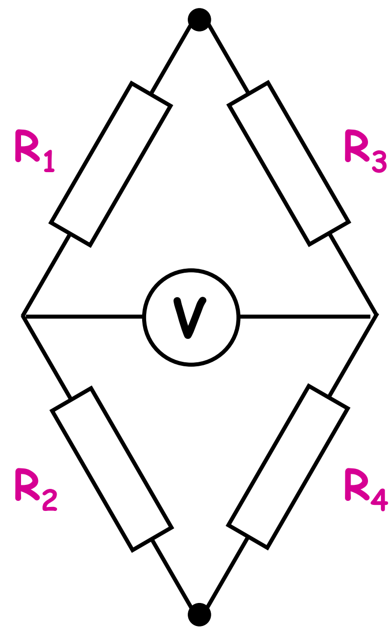
The bridge is said to be balanced when the reading on (V) = 0 V.

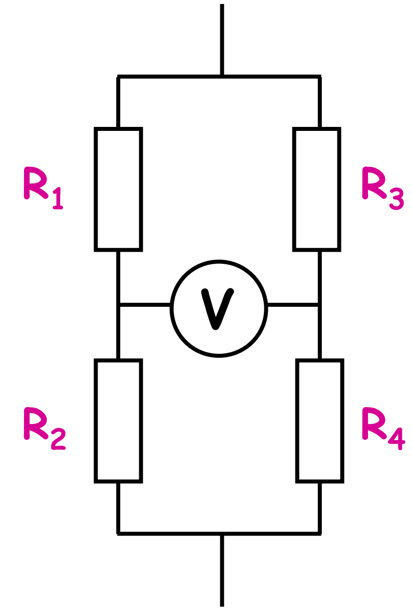
When this is the case:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Wheatstone bridge circuits are sometimes drawn:





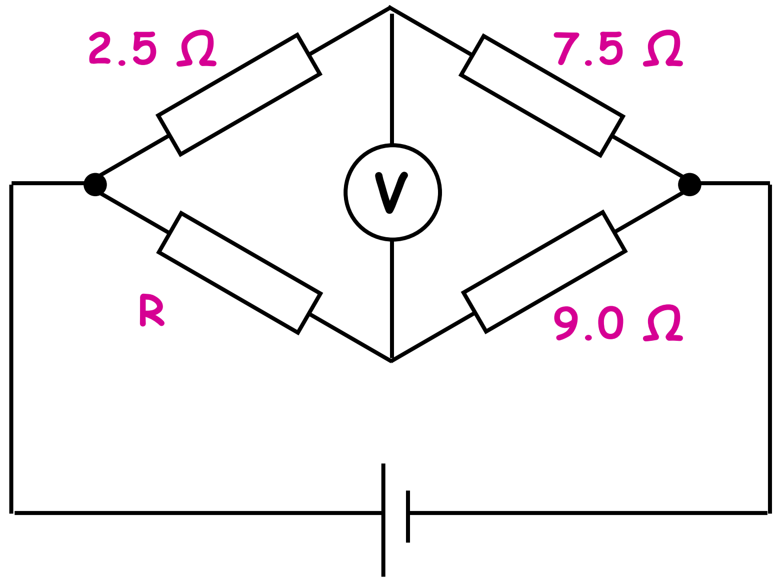


Take care in numbering the resistors.

Resistors in series are numbered consecutively.

Example 1 (Higher 2000 – A – Q9)

In the following circuit the reading on the voltmeter is zero.



The resistance of resistor R is

A 0.33 Ω

B 0.48 Ω

C 2.1 Ω

D 3.0 Ω

E 27 Ω

Balanced Wheatstone bridge => $\frac{R_1}{R_2} = \frac{R_3}{R_4}$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

$R_1 = 2.5\ \Omega$

$R_2 = 7.5\ \Omega$

$R_3 = ?$

$R_4 = 9.0\ \Omega$

$$\frac{2.5}{7.5} = \frac{R}{9.0}$$

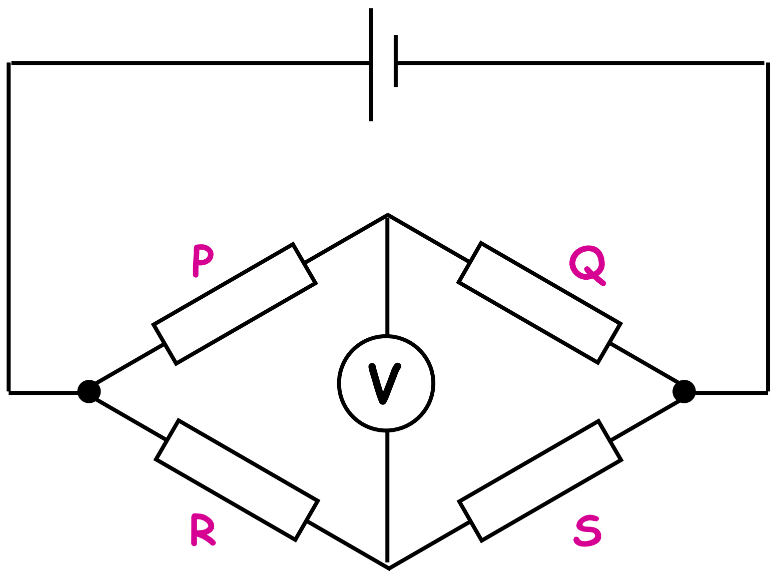
$$7.5 \times R = 2.5 \times 9.0$$

$$R = \frac{22.5}{7.5}$$

$$R = 3.0\ \Omega$$

Question (Higher 2002 – A – Q9)

The diagram below shows a balanced Wheatstone bridge where all the resistors have different values.



Which change(s) would make the bridge unbalanced?

I. Interchange resistors P and S.
II. Interchange resistors P and Q
III. Change the e.m.f. of the battery.

A. I only
B. II only
C. III only
D. II and III only
E. I and III only

Consider

$$R_1 = 3\ \Omega$$
$$R_2 = 5\ \Omega$$
$$R_3 = 6\ \Omega$$
$$R_4 = 10\ \Omega$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

$$\frac{P}{Q} = \frac{R}{S}$$

$$\frac{3}{5} = \frac{6}{10}$$

both sides = 0.6

$\therefore$ balanced

I – interchange P and S

$$\frac{10}{5} = \frac{6}{3}$$

both sides = 2

$\therefore$ balanced

II – interchange P and Q

$$\frac{5}{3} = \frac{6}{10}$$

both sides ≠ same

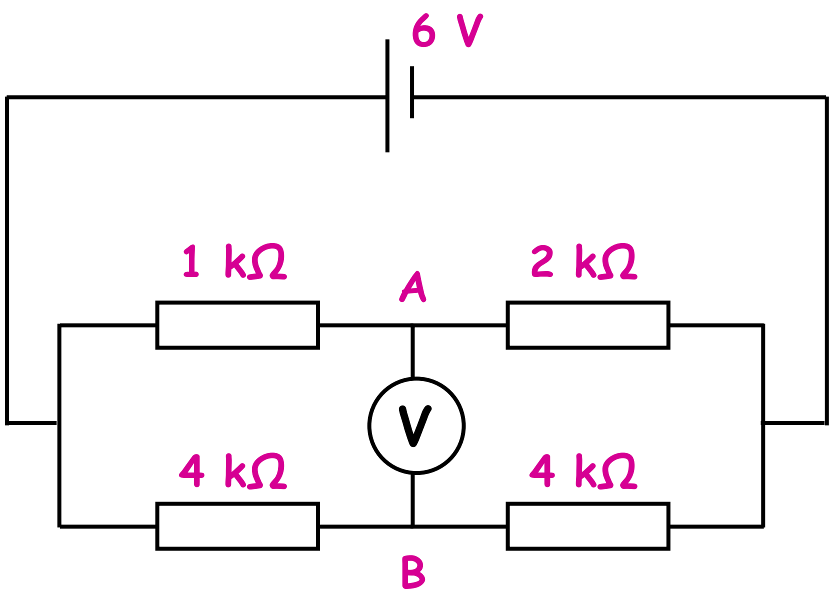
$\therefore$ unbalanced

Unbalanced Wheatstone Bridge

The voltmeter reading is non-zero when the Wheatstone Bridge is unbalanced.

To calculate voltmeter reading, use:

$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right) \times V_S$$



Calculate the reading on the voltmeter (potential difference between A and B).

Potential Across R_1

$R_1 = 1\,k\Omega$

$R_2 = 2\,k\Omega$

$V_s = 6\,V$

$V_2 = ?$

$$V_2 = \left(\frac{R_2}{R_1 + R_2}\right) \times V_S$$

$$= \left(\frac{2}{2+1}\right) \times 6$$

$$V_2 = 4\,V$$

Potential Across R_2

$R_3 = 4\,k\Omega$

$R_4 = 4\,k\Omega$

$V_s = 6\,V$

$V_4 = ?$

$$V_4 = \left(\frac{R_4}{R_3 + R_4}\right) \times V_S$$

$$= \left(\frac{4}{4+4}\right) \times 6$$

$$V_2 = 3\,V$$

potential difference between A and B = 4 - 3

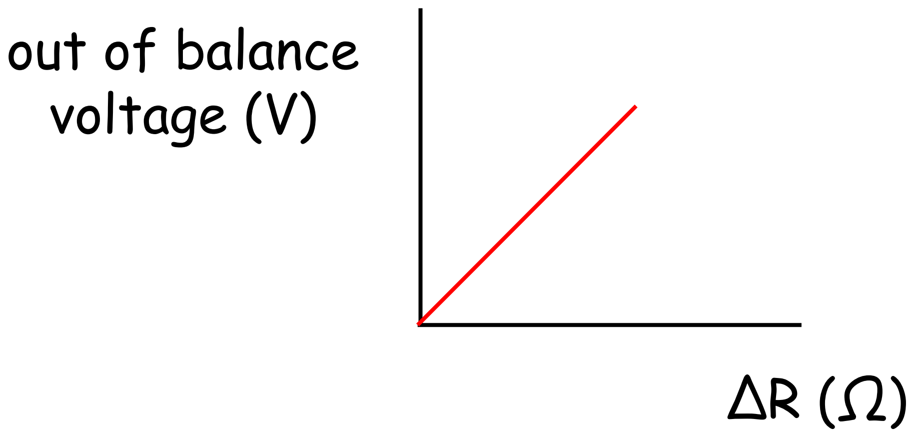
= 1 V

Relationship

In a balanced Wheatstone bridge circuit, (V) = 0 V.

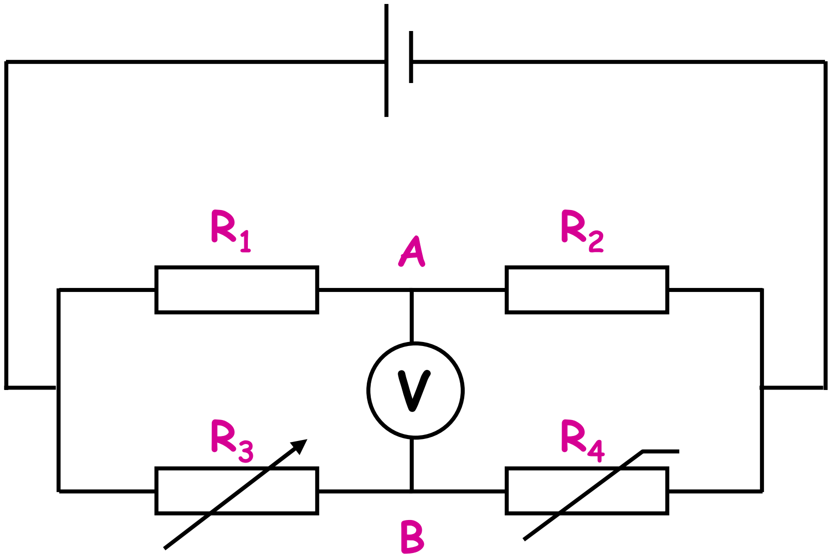
If any resistor is changed by ΔR, the bridge becomes unbalanced, meaning (V) $\neq$ 0 V.

We find that: **out of balance voltage $\propto \Delta R$**



Thermometer

A thermometer can be made using a Wheatstone Bridge circuit.



R_3 is a variable resistor.

R_4 is a thermistor (its resistance changes with temperature).

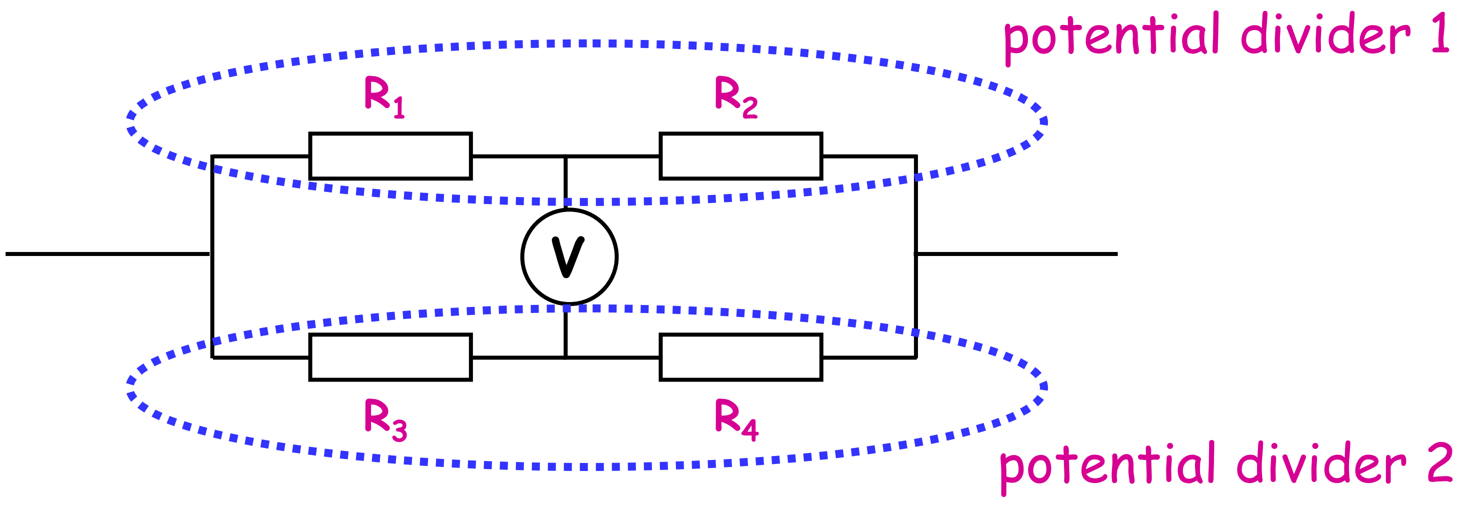
The bridge is balanced by adjusting the variable resistor.

When the bridge is balanced, (V) = 0 V.

The scale is calibrated to read °C rather than volts.

As the thermistor is heated or cooled, the bridge becomes unbalanced.

This causes the temperature reading to change accordingly.



potential divider 1
R1
R2
V
R3
R4
potential divider 2