St Ninian's HS

Higher Physics

Electricity

Pupil Notes

SQA Course Specification Higher

Monitoring and measuring AC

- Knowledge that AC is a current that changes direction and instantaneous value with time.

- Use of appropriate relationships to solve problems involving root mean squared (rms) and peak values.

- Determination of frequency, peak and rms values from graphical data.

Electrical Current

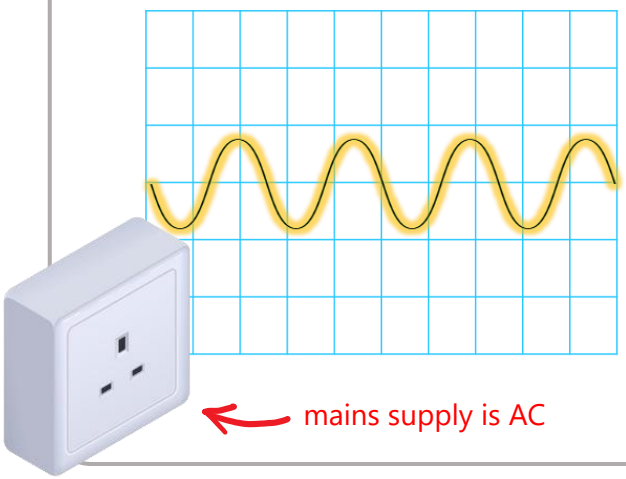
*Electr*ic current is the flow of *electr*ic charge – usually *electr*ons – through an electrical conductor.

In N5, we learned about two different types of electrical supply – a.c. and d.c. (or AC and DC).

Alternating current (AC):

AC is an oscillation (back-and-forth cycles) of electrons in a circuit.

The current changes direction and value over time.

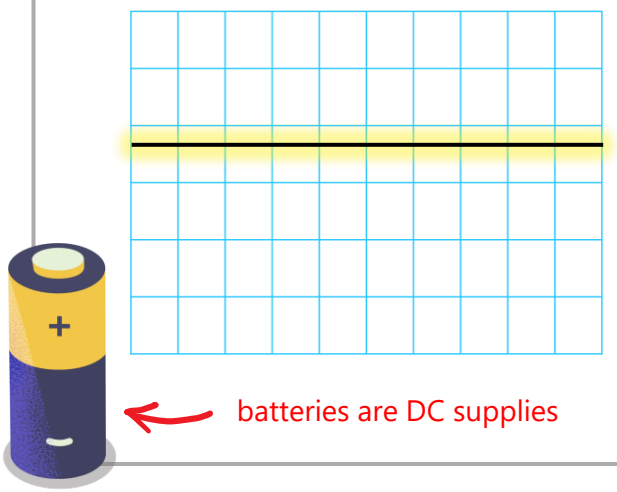


mains supply is AC

Direct current (DC):

DC is a one-way flow of electrons, from the negative to positive terminals of a power supply.

The value of current remains constant.

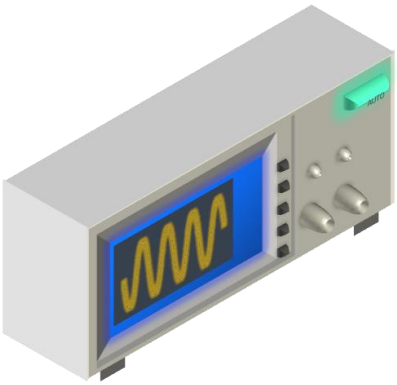


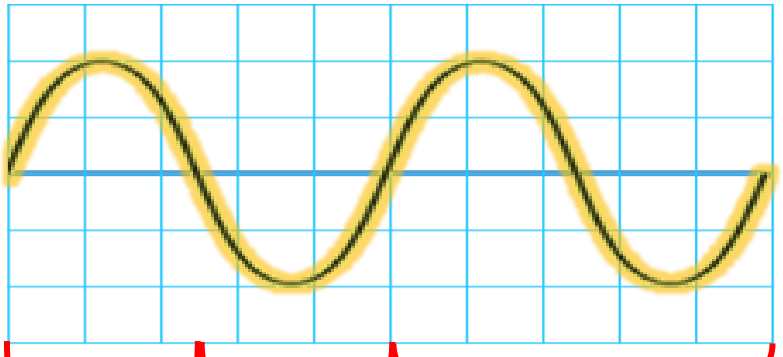
batteries are DC supplies

Alternating Current

AC is a current that changes direction and instantaneous value with time.

An oscilloscope is a device which measures and displays a voltage signal over time. An oscilloscope trace of an AC supply is shown:





The cycle is repeated

Magnitude of voltage increases, peaks, then decreases.

Magnitude of voltage increases, peaks, then decreases.
Negative values indicate that this is in the opposite direction to previous measurements.

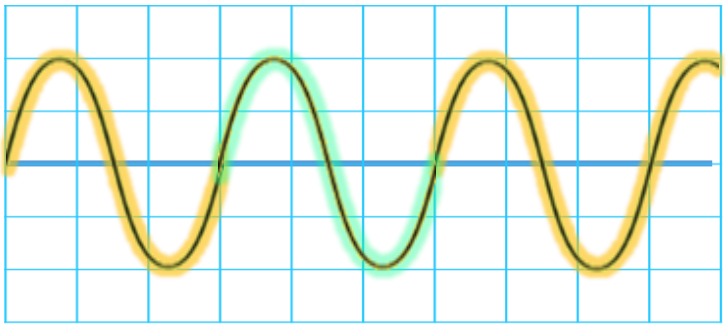
There are two important measurements we can make directly, using the oscilloscope trace above:

- The period – the time taken for one complete cycle.
- The peak voltage – the greatest magnitude of voltage reached (regardless of direction).

AC – Period & Frequency

The **period** of an AC is the **time taken** for **one complete cycle**.

We can determine the period of the waveform directly from an oscilloscope – the x-axis on the oscilloscope displays time, so if we count how many divisions/boxes make up a single cycle and we know the value of time represented by each division (known as the *"timebase setting"*), then we know the period, T.



One complete cycle is highlighted on the oscilloscope trace in green – it is 4 divisions wide.



If the timebase setting is 5 ms per division, then:

period, $T = 4 \times 5\ ms = 20\ ms$

If we know the period of an AC signal, we can determine its frequency.

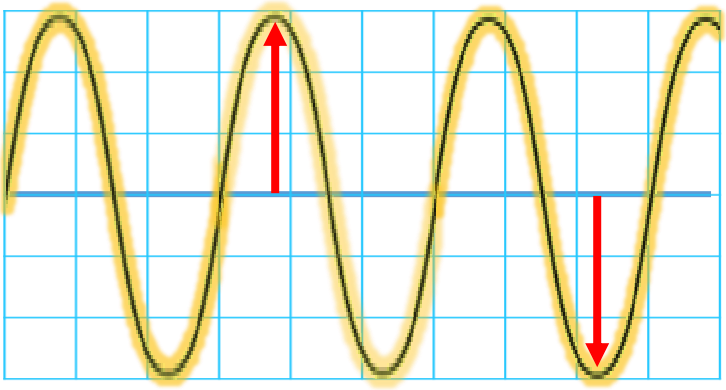
The **frequency** of an AC is the **number of cycles** per **second**.

We can determine frequency of an AC using:

frequency (Hz) → $f = \frac{1}{T}$ ← period (s)

AC – Peak Voltage vs RMS Voltage

We can determine the peak voltage of the AC directly from an oscilloscope – the y-axis on the oscilloscope displays voltage, so if we count how many divisions/boxes make up the maximum vertical deviation from the centre line and we know the value of voltage represented by each division (known as the *"y-gain"*), then we know the peak voltage, V_{Peak}.



The maximum vertical deviation from the centre line is highlighted on the oscilloscope trace in red – it is 3 divisions up/down.



If the y-gain is $2\,V$ per division, then:

peak voltage, $V_{peak} = 3 \times 2\ V = 6\ V$

Knowing the peak voltage of an AC supply is useful because this value is the absolute maximum voltage the connected components will have to withstand. However, the peak voltage is not consistently what we would *get out* of an AC supply – the average magnitude of voltage will be less.

To find the average output voltage from an AC supply (considered an effective DC equivalent) we calculate V_{rms}. RMS stands for "root mean squared" and is a way of finding an average that allows us to ignore negative values (otherwise the average would just be 0).

We can determine V_{rms} of an AC supply using:

r.m.s. voltage (V) → $V_{rms} = \dfrac{V_{peak}}{\sqrt{2}}$ ← peak voltage (V)

Using RMS vs Peak Values

Current in the circuit changes alonside voltage. Consider Ohm's Law ($V = IR$): if the resistance in a circuit is constant, then voltage and current are directly proportional.

This means that when voltage peaks, current peaks. When using Ohm's Law or any other circuit relationship, then peak voltage must be used with peak current, and r.m.s. voltage with r.m.s. current.

Peak current and r.m.s. current are related similarly:

r.m.s. current (A) → $I_{rms} = \frac{I_{peak}}{\sqrt{2}}$ ← peak current (A)

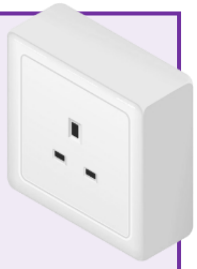
Remember: you cannot mix and match with peak and rms values:

$V = IR$ can be used as $V_{peak} = I_{peak} \times R$ or $V_{rms} = I_{rms} \times R$

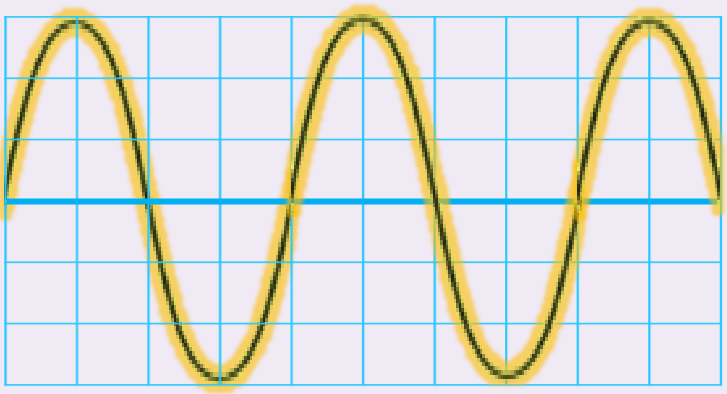
Unless specified otherwise, a given value of power will match with RMS values:

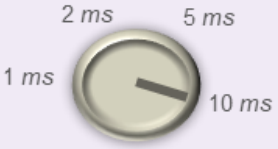
$P = IV$ is generally only used as $P = I_{rms} \times V_{rms}$

Worked Example: The Mains Supply



An electrical engineer uses an oscilloscope to monitor the voltage of the mains supply over time. The oscilloscope trace, timebase setting, and y-gain are shown below.







a) Mains is an AC supply.

State what is meant by the term *alternating current (AC)*.

An alternating current changes direction and instantaneous value over time.

b) **Calculate** the frequency of the mains supply.

To determine frequency we need the period of the AC supply:

Period, T = number of divisions for 1 cycle × timebase setting

$$T = 4 \times 10\ ms = 40\ ms$$

Then to find frequency:

$$f = \frac{1}{T} \qquad f = \frac{1}{40 \times 10^{-3}} \qquad f = 25\ Hz$$

c) **Show that** the r.m.s. voltage of the mains supply is 6.4 V.

To determine rms voltage we need the peak voltage of the AC supply:

Peak voltage, V_{peak} = number of divisions to peak from centreline × y-gain

$$V_{peak} = 3 \times 3\ V = 9\ V$$

Then to find rms voltage:

$$V_{rms} = \frac{V_{peak}}{\sqrt{2}} \qquad V_{rms} = \frac{9}{\sqrt{2}} \qquad V_{rms} = 6.4\ V \text{ as required}$$

SQA Course Specification Higher

Current, potential difference, power, and resistance

- Use of appropriate relationships to solve problems involving potential difference, current, power, and resistance. Solutions may involve several steps.

- Use of appropriate relationships to solve problems involving potential divider circuits.

Note: this section is largely a recap of National 5 Circuits! Essential quantities will be defined again here but reviewing the basics of series/parallel circuits, circuit components, etc. from the SNHS N5 Physics Energy & Electricity Notes may prove useful!

Essential Quantities – Current, Voltage, Resistance, Power

Electrical Current

In the section above, we defined *electr*ic current is the flow of *electr*ic charge – usually *electr*ons – through an electrical conductor. Mathematically:

Current is the **charge** passing a point **per second**.

Charge itself is a fundamental property of matter (similar to mass). An particle/object can be uncharged (AKA "neutral"), positively charged, or negatively charged. Electrons are negatively charged particles (the magnitude of charge on an electron can be found on the Higher Physics data sheet).

$$Q = It$$

charge (C) — time (s) — current (A)

The current *through* a component in an electric circuit can be measured by placing an *ammeter* in *series* with the component – if two components are *in series* then the current must flow through both, with no other paths to take.



The ammeter above is placed *in series* with the resistor, and is correctly placed to measure the *current through* the resistor.

Resistance

All components and materials have some resistance to electrical current – even wires and electrical supplies/sources themselves, though we often assume this is a negligible amount.

Resistance is the **opposition** to the flow of electrical **current**.

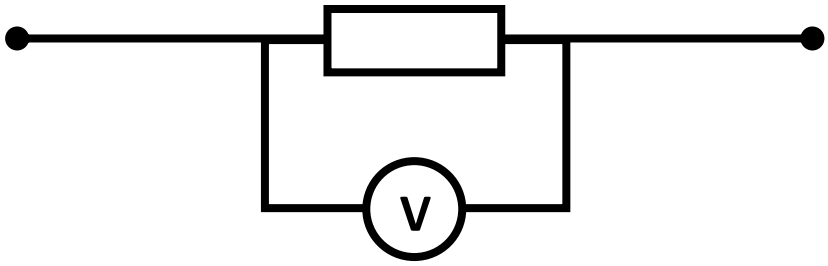
Resistance is measured in ohms (Ω).

Potential Difference/Voltage

Similar to how a particle/object with *mass* in a *gravitational field* possesses *gravitational potential energy*, a *charged particle* in an *electric field* possesses *electrical potential energy* – so "potential difference" or "p.d." refers to the energy stored by charged particles, or the energy charged particles have given away to components between two points on a circuit. This may also be referred to as voltage.

Potential difference (AKA voltage) is the **energy** stored/transferred **per unit of charge**.

The p.d. *across* a component in an electric circuit can be measured by placing a *voltmeter* in *parallel* with the component – if two components are *in parallel* then the current cannot flow through both without splitting. There will be more than one path available.



The voltmeter above is placed *in parallel* with the resistor, and is correctly placed to measure the *voltage across* the resistor. It might be useful to imagine the voltmeter taking a little sample of the *energy per charge* at either side of the resistor.

Ohm's Law

Ohm's Law is a relationship that links the p.d. (AKA voltage) across a component, the current through the component, and the resistance of the component.

$$V = IR$$

potential difference (AKA voltage) (V)

current (A)

resistance (Ω)

Remember: Ohm's Law can be applied to a single component. Values cannot be mixed and matched from several different components.

Electrical Power

Electrical power is the rate at which energy is transferred/transformed within a circuit/component. Power is affected by a circuit/component's current, resistance, and voltage.

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

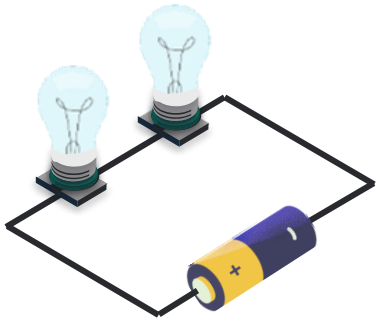
where:

P is the power (W)
I is the current (A)
V is the voltage (V)
R is the resistance (Ω)

Similarly to Ohm's Law, a power relationship can only be applied to a single component at a time – no mixing and matching of values between different components!

Components in Series

If two components are *in series* then the current must flow through both, with no other paths to take. There are different rules for current through, voltage across, and combined resistance of components in series:

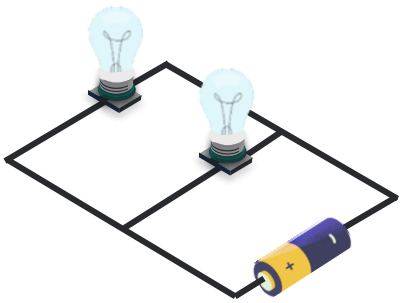


Bulb 1 and bulb 2 above are connected *in series*. The battery provides a supply voltage, which pushes electrons round the circuit. All electrons must flow through both bulbs.

Quantity	***Rule for Components in Series***
Current	Current is the same at all points *in series*. E.g. $I_{battery} = I_{bulb\ 1} = I_{bulb\ 2}$
Voltage	Voltage splits between components *in series*. E.g. $V_{battery} = V_{bulb\ 1} + V_{bulb\ 2}$
Resistance	Connecting components *in series increases* the total resistance between two points. E.g. $R_T = R_1 + R_2$

Components in Parallel

If two components are *in parallel* then the current cannot flow through both without splitting– there will be more than one path available. There are different rules for current through, voltage across, and combined resistance of components in parallel:



Bulb 1 and bulb 2 above are connected *in parallel*. The battery provides a supply voltage, which pushes electrons round the circuit. A single electron cannot pass through both bulbs.

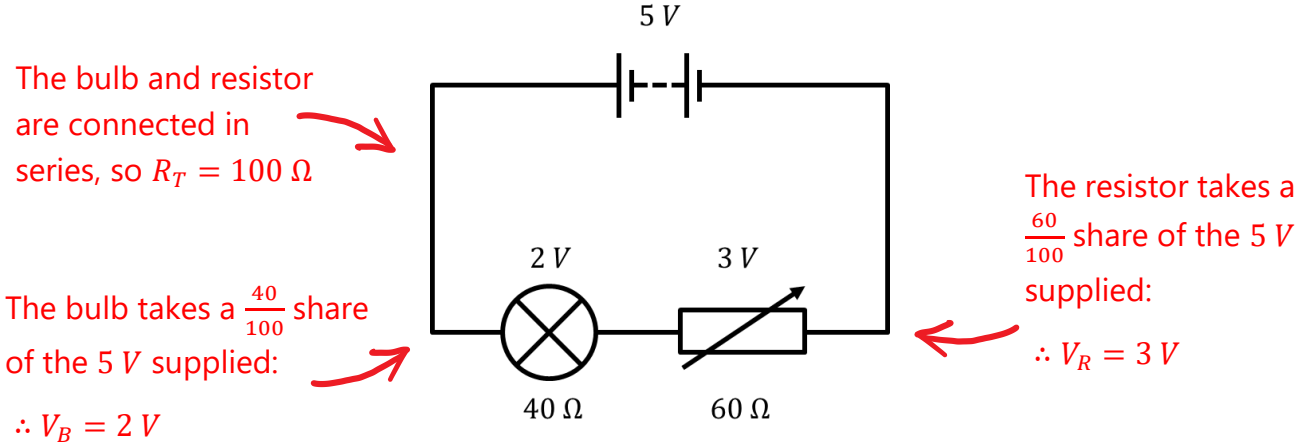
Quantity	***Rule for Components in Series***
Current	Current splits between parallel branches. E.g. $I_{battery} = I_1 + I_2$
Voltage	Voltage is equal across each parallel branch. E.g. $V_{battery} = V_1 = V_2$
Resistance	Connecting components *in parallel* *decreases* the total resistance between two points. E.g. $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$

Potential Divider Circuits

A potential divider (AKA "voltage divider") is a circuit that splits a supplied voltage into smaller voltages. At its most simple, a potential divider can be just a series circuit with two components.

The greater the resistance of a component, the larger the share of the supplied voltage that it takes.

For example, consider we had a bulb that was rated for a maximum of $2\ V$ and a battery that supplied $6\ V$. Connecting the bulb directly to the battery could damage it, but if we put the bulb in series with another component (e.g. a variable resistor) we can control how much of the $6\ V$ is given to the bulb.



There are two relationships that we can use to determine how the supplied voltage is divided:

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right) V_S$$

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

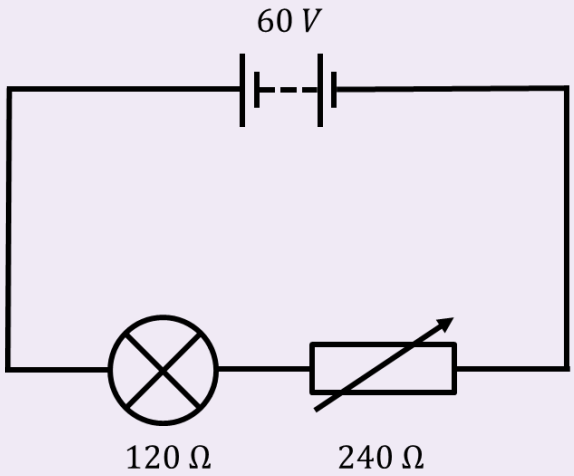
where:

V_1 is the p.d. across one component (V)
V_2 is the p.d. across the other component (V)
V_S is the supplied voltage (V)
R_1 is the resistance of one component (Ω)
R_2 is the resistance of the other component (Ω)

It doesn't matter which component is "one" and which is "the other", as long as the labels 1 and 2 are applied consistently.

Worked Example: The Dimmer Switch

A potential divider circuit is set up to allow a light bulb's brightness to be adjusted.



a) **Calculate** the potential difference across the variable resistor when its resistance is set to 240 Ω.

Labelling the variable resistor as component 1 and the bulb as component 2:

$V_1 = ?$ $R_1 = 120\ \Omega$
$V_S = 60\ V$ $R_2 = 240\ \Omega$

Since we know the supply voltage but not V_2:

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right) V_S \qquad V_1 = \left(\frac{120}{120 + 240}\right) 60 \qquad V_1 = 20\ \Omega$$

b) **State** the potential difference across the bulb when the variable resistor is set to 240 Ω.

The rule for voltage for components in series is $V_S = V_1 + V_2$, $\therefore V_2 = 40\ V$.

c) **State** whether increasing the resistance of the variable resistor would increase, decrease, or have no effect on the voltage across the bulb. **Justify** your answer.

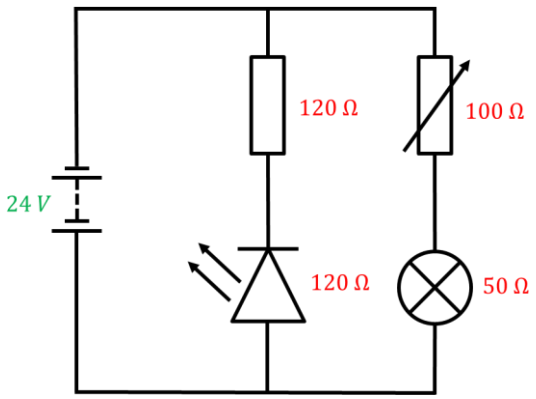
Increasing R_{VR} would cause V_{BULB} to <u>decrease</u>...

... because the variable resistor takes a greater share of the supplied voltage.

These relatively simple potential divider circuits can be stacked on top of one another – each on a parallel branch. Following our parallel circuit rules, each branch will have the same voltage available across it.

For example, for the circuit here with a supply voltage of 24 V:

- In the first branch, the resistor and the LED will share 24 V between them.
- Using our potential divider relationships:
  - 12 V across the resistor.
  - 12 V across the LED.
- In the second branch, the variable resistor and the bulb will share 24 V between them.
- Using our potential divider relationships:
  - 16 V across the variable resistor.
  - 8 V across the bulb.



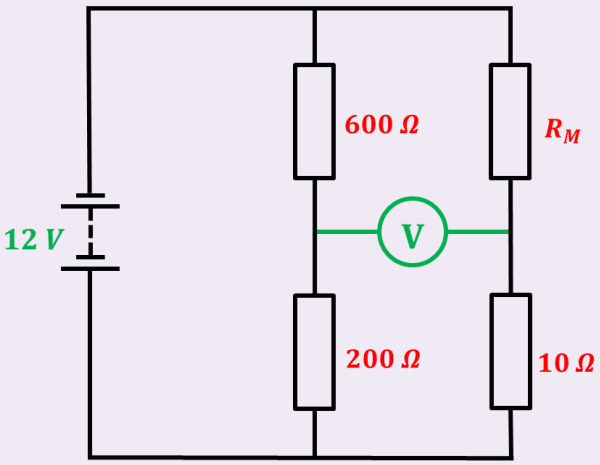
Worked Example: The Mystery Resistor

A careless electrical engineer has mislabelled a resistor, and needs to determine its value. They have a battery, a voltmeter, and 3 resistors of known value.

They set up the circuit shown:

The voltmeter reads $0\ V$.

Determine the value of the mystery resistor, R_M.



Since the voltmeter reading is 0 V, the potential difference between the two points of the circuit the voltmeter touches must be 0 V.

This means that the 200 Ω and 10 Ω resistors must take the same share of 12 V. The 600 Ω resistor and mystery resistor must also take the same share of 12 V. Therefore, if we know what share of 12 V the 600 Ω resistor takes, we know that the mystery resistor takes the same share. If we know its share of voltage we can find its resistance.

Using our voltage divider equations (or otherwise) to find what share of 12 V the 600 Ω resistor takes:

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right) V_S \qquad V_1 = \left(\frac{600}{600 + 200}\right) 12 \qquad V_1 = 9\ \text{V} \qquad \therefore V_M = 9\ \text{V}$$

Then another voltage divider equation (or otherwise) to find the value of resistance:

$$\frac{V_1}{V_2} = \frac{R_1}{R_2} \qquad \frac{9}{(12 - 9)} = \frac{R_M}{10} \qquad R_M = 30\ \Omega$$

SQA Course Specification Higher

Electrical sources and internal resistance

- Knowledge of the terms "electromotive force" (EMF), "internal resistance", "lost volts", "terminal potential difference" (t.p.d.), "ideal supplies", "short circuit" and "open circuit".

- Use of appropriate relationships to solve problems involving EMF, lost volts, t.p.d., current, external resistance and internal resistance.

- Description of an experiment to measure the EMF and internal resistance of a cell.

- Determination of EMF, internal resistance, and short circuit current using graphical analysis.

Internal Resistance

In the last section we noted that "*all components and materials have some resistance to electrical current - even wires and electrical supplies/sources themselves*".

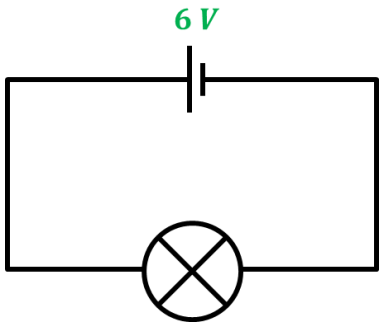
In this section we will take a closer look at electrical supplies (e.g. a cell), and consider the impact of the resistance of the supply itself on the circuit it is in.

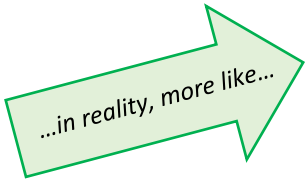
Internal resistance is the **resistance** of the electrical **supply** itself.

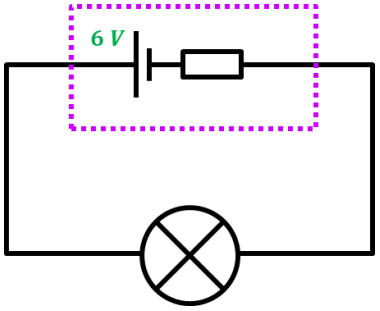
Unless explicitly dealing with the topic of *Internal Resistance,* we generally treat the cell/battery in our circuits is an "ideal supply" – meaning the *internal resistance* is 0 Ω. This is theoretical – all supplies will have *some* internal resistance, even if it is a negligible amount.

An **ideal supply** is an electrical **supply** with **zero internal resistance**.

Consider a simple circuit – a bulb connected directly to a single 6 *V* cell:







The 6 *V* cell alongside the resistor in the pink dotted box represent the *real* cell, factoring in its internal resistance.

This means that entire $6\ V$ doesn't make it *out* of the cell – the p.d. across the cell will be *less than* $6\ V$.

Electromotive Force (EMF)

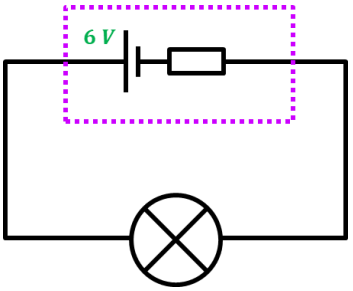
In the circuit on the left above, we would have previously referred to the $6\ V$ as the "supply voltage". When considering internal resistance, we instead refer to this as the "electromotive force", or "EMF".

EMF is the **energy** provided by an electrical source, **per colomb of charge**.

The name is misleading – EMF isn't truly a *force*, and is not measured in Newtons. It is measured in volts (*V*). Think of it as the electrical *push* that drives the current around a circuit.

EMF can be shorted to the symbol "E" (or sometimes "$\mathcal{E}$"). Context is key here – don't mix it up with energy!

Consider the same simple circuit – a bulb connected directly to a single $6\ V$ cell – this time taking into account the internal resistance of the cell.



The EMF, $E = 6\ V$, must be shared between the *internal resistance* and the bulb.

Applying the rule for voltage for components in series:

$$V_S = V_1 + V_2 \qquad \Longrightarrow \qquad E = V_{ir} + V_{bulb}$$

The voltage dropped across the internal resistance never makes it *out* of the cell – it is *lost*. The remaining voltage is available for the rest of the circuit.

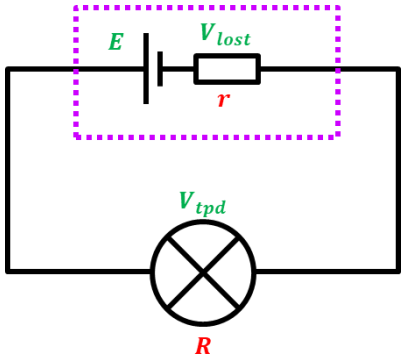
We have specific terms for share of the EMF lost to internal resistance, and the share of EMF that remains for the rest of the circuit.

The **lost volts** is the **potential difference** lost to a cells **internal resistance**.

The **terminal potential difference** is the **potential difference** available to the **rest of the circuit**.

Here, "terminal" refers to the terminals (the positive and negative sides) of the source – the potential difference measured between terminals of the source its what's left after the lost volts have been *lost*.

Consider the same circuit again:



- The EMF is split between the two components in series (the external resistance (AKA "*load resistance*") and the internal resistance).
  → $E = V_{tpd} + V_{lost}$
- We can use Ohm's Law ($V = IR$) to write this in different ways:
  → $E = IR + Ir$ → $E = I(R + r)$
  → $E = V_{tpd} + Ir$
  → $E = IR + V_{lost}$

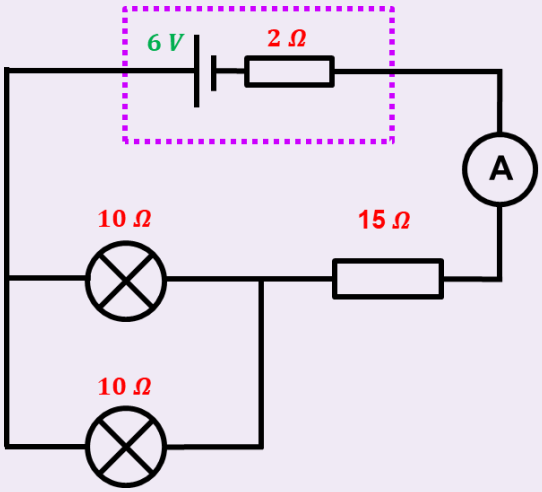
The version given on the data sheet is:

EMF (V) → $E = V + Ir$ ← internal resistance (Ω)

terminal p.d. (V) ↑ ↑ current drawn from supply (A)

Worked Example: The 6 *V* Cell

A cell with an EMF of 6 *V* and internal resistance 2 Ω is connected in a circuit as shown.



a) **Describe** what is meant by an EMF of 6 *V*.

The cell supplies 6 J of energy to each coulomb of charge.

b) **Calculate** the load resistance.

First find the equivalent resistance of the parallel section:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} \qquad \frac{1}{R_P} = \frac{1}{10} + \frac{1}{10} \qquad R_P = 5\ \Omega$$

Then add this to the value of the resistor in series to find the total external resistance:

$R_T = 5 + 15 = 20\ \Omega$ AKA the load resistance

c) **Determine** the reading on the ammeter.

To find the reading on the battery, use:

$$E = V + Ir$$

but in the form $E = I(R + r)$, where R is the load resistance.

$$E = I(R + r) \qquad 6 = I(20 + 2) \qquad I = 0.27\ A$$

d) **Calculate** the lost volts in the cell.

Apply Ohm's Law to the internal resistor:

$$V = IR \qquad V_{lost} = Ir \qquad V_{lost} = 0.27 \times 2 \qquad V_{lost} = 0.54\ V$$

e) The resistor is removed from the circuit.
State whether this increases, decreases, or has no effect on the value of lost volts.
Justify your answer.

Lost volts was just calculated – looking at what it was based on:

load resistance → current drawn from battery → lost volts.

Load resistance, without the resistor, $R = 5\ \Omega$.
Current drawn from battery, $I = \frac{E}{(R+r)} = 0.86\ \text{A}$
Lost volts, $V_{lost} = Ir = 1.7\ V$

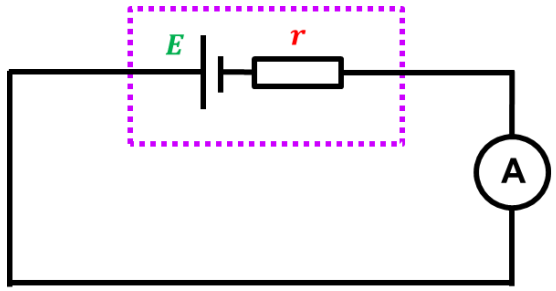
∴ lost volts increases

Short Circuits & Open Circuits

There are two special circuits we can use to determine the EMF and internal resistance of an electrical source.

Short circuit:

A short circuit has negligible load resistance ($R = 0\ \Omega$).



In a short circuit, the total resistance is equal to the internal resistance.

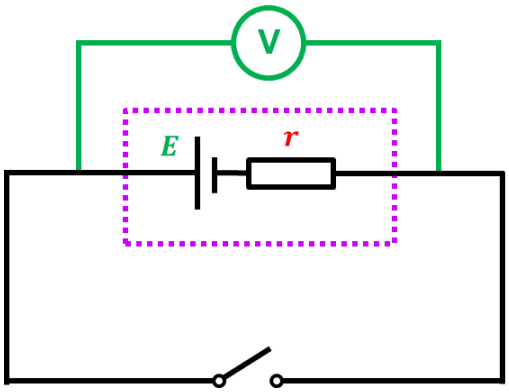
∴ the voltage across the internal resistor is equal to the EMF

∴ we can simplify $E = IR + Ir$ to become $\boldsymbol{E = Ir}$

∴ a short circuit is when the **maximum current** can be drawn from the battery (since resistance is minimised)

Open circuit:

An open circuit is a circuit which is broken, so no current can flow ($I = 0\ \Omega$).

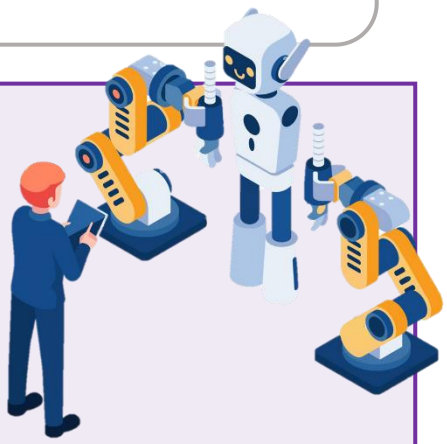


In an open circuit, there are no lost volts (since charge does not pass *through* the internal resistance).

∴ we can simplify $E = V + Ir$ to become $\boldsymbol{E = V}$

∴ measuring the voltage across the supply (V_{tpd}) provides the value of **EMF** of the supply.

Worked Example: The Robot



To take a quick measurement of the internal resistance of a cell, a robotics engineer measures:

i. the short circuit current ($0.12\ A$).
ii. the terminal potential difference across the cell when it is not part of a circuit ($1.55\ V$).

Determine the internal resistance of the cell.

Measuring V_{tpd} for an open circuit gives them the EMF, so E = 1.55 V.

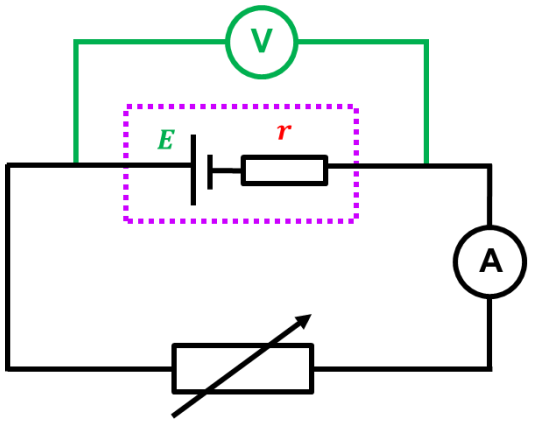
For a short circuit, E = Ir so:

$$E = Ir \qquad 1.55 = 0.12 \times r \qquad r = 13\ \Omega$$

Measuring Internal Resistance

A better way of determining the internal resistance of a cell is to use a graph (see page 20 of the *Skills & Uncertainties Notes* for an explanation why).

One way to achieve this is to set up the following circuit:

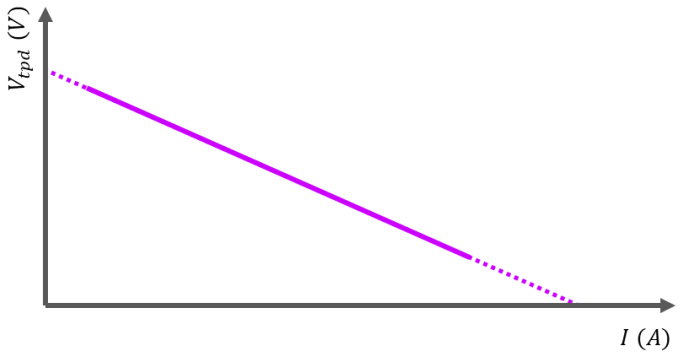


A variable resistor is used to vary the load resistance.

A voltmeter measures the voltage across the terminals of the battery (V_{tpd}).

An ammeter measures the current drawn from the cell.

Plotting the data, drawing a line of best fit, and extrapolating that line to meet the axes would produce a graph like this:



The y-intercept here is the point where no current is drawn from the cell (an open circuit).

$\therefore$ when $I = 0, V_{tpd} = E$

So the y-intercept tells us the EMF.

The x-intercept tells us the maximum possible current (the short circuit current).

The graph is a straight line: $y = mx + c$

Applying our labels and known values to the equation of a straight line:

$$V_{tpd} = mI + E$$

Rearranging that to a more familiar form: $E = V_{tpd} - Im$

And comparing this to the equation on the relationship sheet:

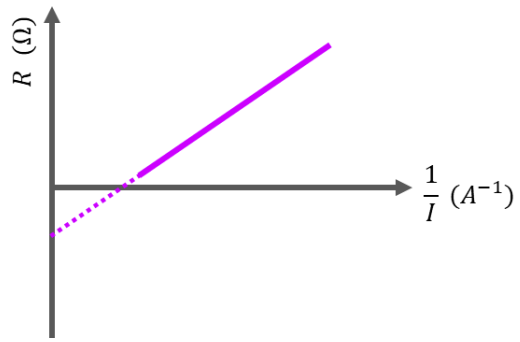
$E = V_{tpd} - Im$ and $E = V + Ir$ $\therefore$ $r = -m$

$\therefore$ from a graph of V_{tpd} vs I :

- **the short circuit current, I_{max}, is equivalent to the x-intercept**
- **the EMF, E, is equivalent to the y-intercept**
- **the internal resistance, r, is equivalent to ($-1 \times$ the gradient of the line)**

Another (less common) way to determine the internal resistance by graphing is to vary the load resistance (and measure with an ohmmeter) and measure the current drawn from the supply (using an ammeter in series).

This would produce the following graph:



Rearranging $E = I(R + r)$ to fit to the equation of a straight line for this graph ($R = m\frac{1}{I} + c$) shows m aligns with E, and r with $-c$.

∴ from a graph of R vs $\frac{1}{I}$:

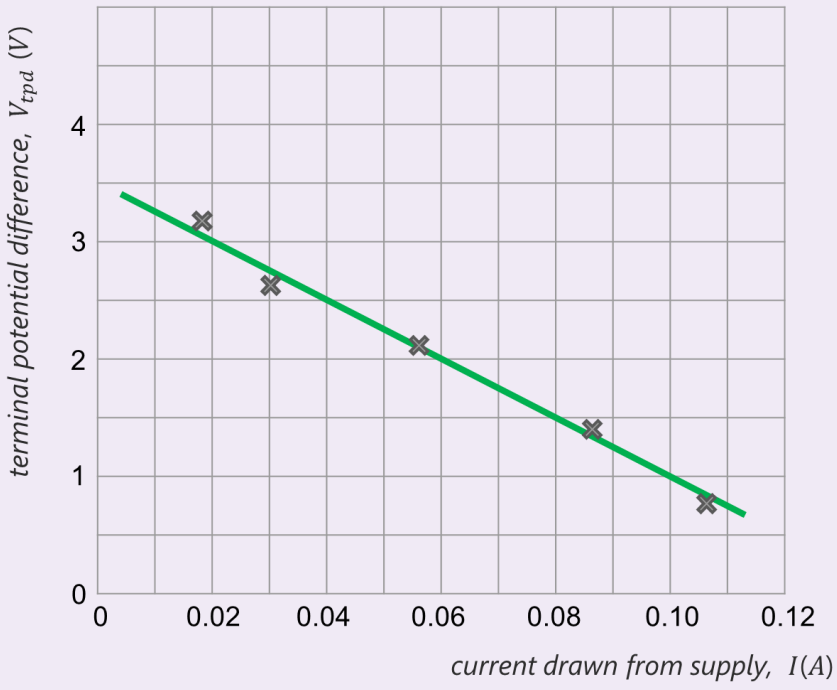
- **the internal resistance, r, is equivalent to the ($-1 \times$ the y-intercept)**
- **the EMF, E, is equivalent to the gradient of the line**

Worked Example: The Unknown Internal Resistance

A physicist varies the load resistance in a circuit and for each measures the:

- terminal potential difference using a voltmeter,
- current drawn from the supply with an ammeter.

From their data, they plot the graph shown:



Using their graph:

(a) **Determine** the EMF of the supply.

(b) **Determine** the internal resistance of the supply.

(a) The EMF is equivalent to the y-intercept.

∴ E = 3.5 V

(b) The internal resistance is equivalent to -1 × the gradient of the line.

First, pick two points <u>on the line</u>:

(x_1, y_1) *and* (x_2, y_2)

$(0.02, 3)$ *and* $(0.10, 1)$

Then use these to find the gradient:

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{1 - 3}{0.10 - 0.02} = -25$$

∴ r = 25 Ω

SQA Course Specification Higher

Capacitors

- Knowledge that a capacitor of 1 farad will store 1 coulomb of charge when the potential difference across it is 1 volt.

- Use of an appropriate relationship to solve problems involving capacitance, charge and potential difference.

- Use of an appropriate relationship to determine the charge stored on a capacitor for a constant charging current.

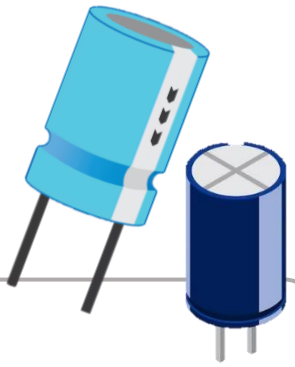
- Knowledge that the total energy stored in a charged capacitor is equal to the area under a charge-potential difference graph.

- Knowledge of the variation of current and potential difference with time for both charging and discharging cycles of a capacitor in an RC circuit (charging and discharging curves).

- Knowledge of the effect of resistance and capacitance on charging and discharging curves in an RC circuit.

- Description of experiments to investigate the variation of current in a capacitor and voltage across a capacitor with time, for the charging and discharging of capacitors.

Capacitors



A capacitor is an electrical component which temporarily stores and then releases energy. A capacitor consists of two electrically conductive plates, separated by a layer of insulating material.

The circuit symbol for a capacitor is:



Capacitance is a measure of the ability of an object to store electric charge.

Capacitance is the **charged stored** on a capacitor per **volt of p.d.** across it.

Mathematically we can write this as:

capacitance (F) → $C = \frac{Q}{V}$ ← charge stored (C)

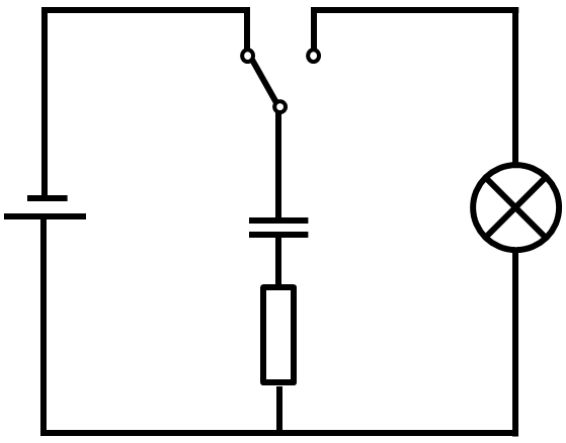
potential difference (V) ←

Capacitance is measured in units known as Farads.

A capacitor can be a useful component in a circuit where a rapid burst of energy is required – for example, camera flashes, defibrillators.

A circuit based around a capacitor often looks like this:

When the switch is connected to this side the capacitor charges. →



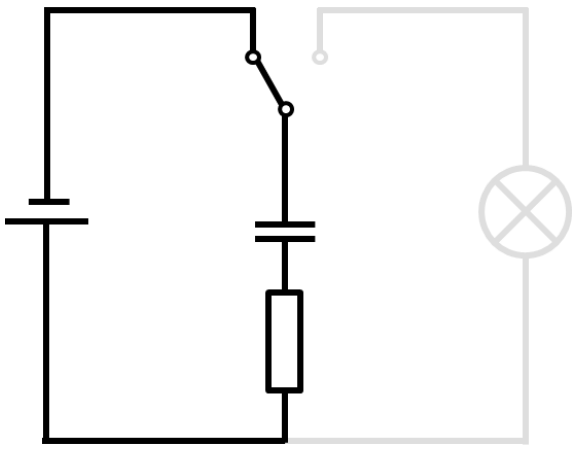
← When the switch is connected to this side the capacitor discharges and the bulb will flash.

The switch allows the capacitor to connect to either the cell (to charge) or the bulb (to discharge).

The resistor in series with the capacitor is used to control the *rate* of charge/discharge (as it controls the current in either circuit).

Charging Capacitors

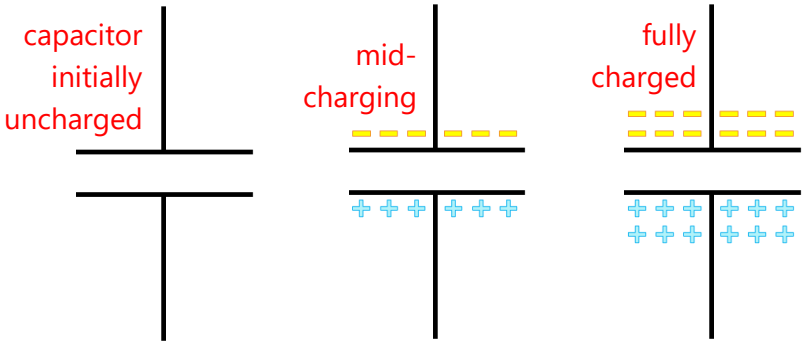
A capacitor charges when it is directly connected to an electrical supply, such as the cell below:



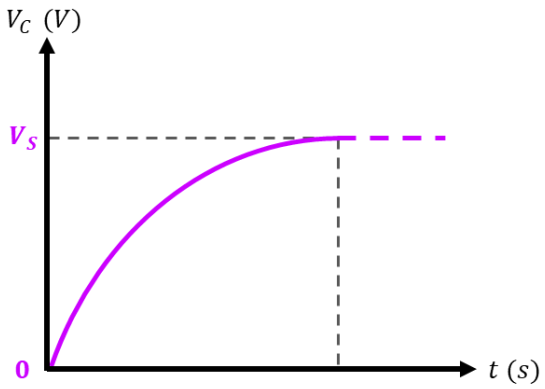
- Before the capacitor is connected to the cell, it is uncharged and electrically neutral on each side.
- As soon as the capacitor is connected to the cell, the p.d. provided by the cell will push electrons round the circuit.
- Electrons cannot move across the capacitors insulating layer, so they build up on one of the plates (and positive charge builds up on the other plate due to electrons being pulled towards the cell) – a p.d. develops across the **capacitor**.

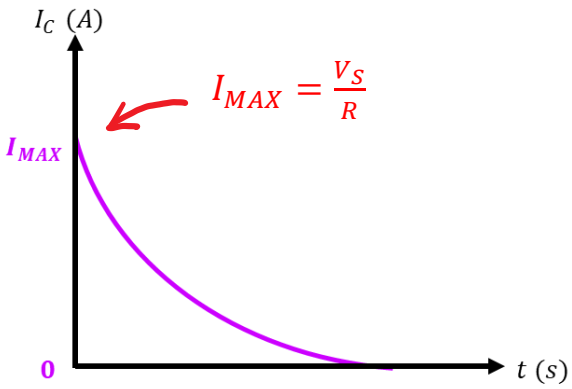
this is just a series circuit, so at any point:

$V_S = V_C + V_R$



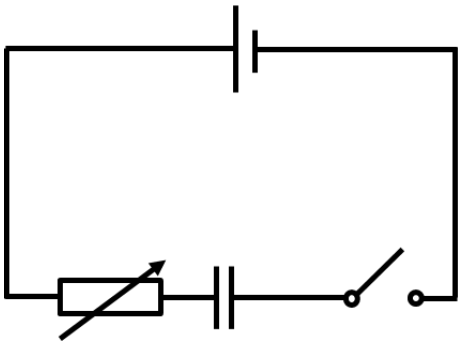
As the capacitor charges, the p.d. across it (V_C) and current through it (I_C) vary:





- The p.d. across the capacitor increases from $0\ V$ to a maximum value equivalent to the p.d. across the cell, V_S.
- The current in the circuit starts at its maximum value, then decreases to $0\ A$ as p.d. builds across the capacitor.
- Once $V_C = V_S$, there is an equal *electrical push* both ways round the charging circuit. This means there is no more current flow, and no more charge will build up on the plates.

Capacitors with a Constant Charging Current



During charging, the p.d. across a capacitor increases as charge builds up on the plates. As this happens, the current naturally decreases due to the electrical push from the capacitor working more and more against the electrical push from the supply.

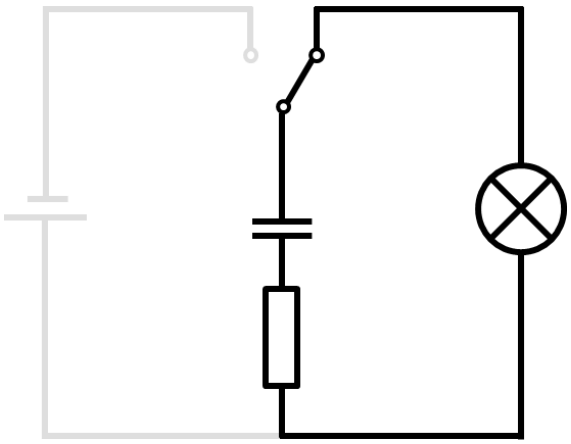
Some circuits place a variable resistor next to the capacitor, which can maintain a constant current during charging.

If the charging **current** is **constant** then the charge built up at any point is:

$$Q = It$$

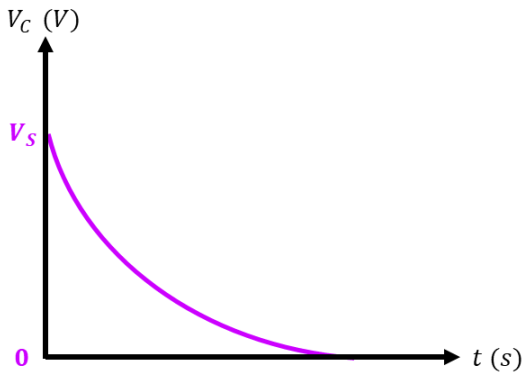
Discharging Capacitors

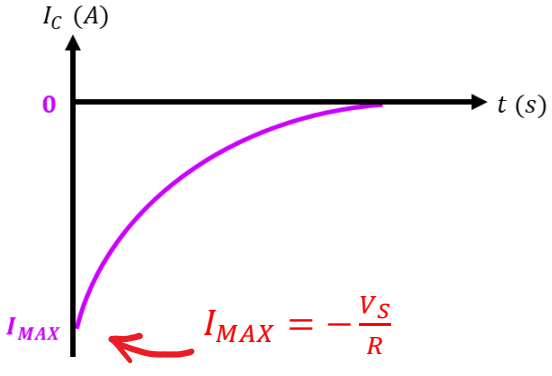
A capacitor *discharges* when it is *no longer directly connected to an electrical supply* – in the discharge circuit, the capacitor briefly acts as the electrical source as it discharges.



- Before the capacitor is disconnected from the cell, it is charged. There is a p.d. across the plates.
- As soon as the capacitor is connected to the bulb in the discharge circuit, the p.d. across the capacitor pushes electrons around the circuit (in the opposite direction to the charging circuit!).
- The p.d. across the capacitor decreases as it discharges (because electrons repel each other).

As the capacitor discharges, the p.d. across it (V_C) and current through it (I_C) vary:





- The p.d. across the capacitor decreases from a maximum value equivalent to the p.d. across the cell, V_S, to $0\ V$.
- The current in the circuit starts at its maximum value (negative to show that it is the opposite direction compares to the charging circuit), then decreases to $0\ A$ as p.d. across the capacitor decreases to $0\ V$.
- Once $V_C = 0\ V$, there is no longer any *electrical push* round the discharging circuit. This means there is no more current flow.

Controlling Capacitor Circuits

For various applications of a capacitor circuit, we may wish to control how long it takes to charge/discharge. There are two ways we can control the rate of charge/discharge:

- Varying the ***resistance*** of the resistor in the circuit (increasing the resistance decreases the maximum current and charging/discharging takes longer).
- Varying the value of ***capacitance*** of the capacitor (increasing the capacitance means *more charge* is stored per volt of p.d. and charging/discharging takes longer).



The Bucket Analogy

A useful way of visualising and understanding the above is to imagine bucket being filled up with water from a tap:

- The water flowing from the tap represents electrical current.
- The bucket represents the capacitor.

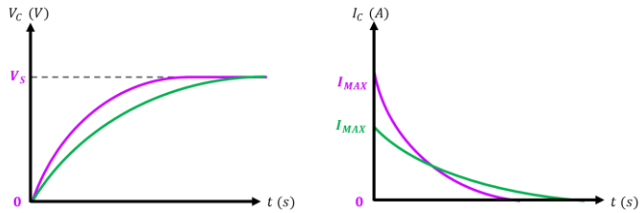
Varying resistance:

Increasing the resistance in a circuit decreases the value of current – in our bucket analogy this is like turning the tap down.

Resistance increases

∴ maximum current decreases (water flow rate decreases)

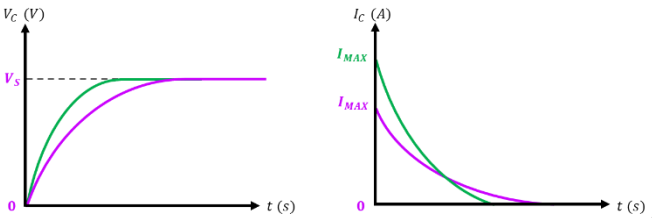
∴ capacitor takes longer to charge/discharge (bucket takes longer to fill up)



Resistance decreases

∴ maximum current increases (water flow rate increases)

∴ capacitor takes less time to charge/discharge (bucket fills up more quickly)



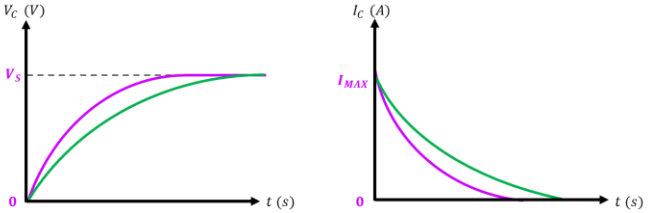
Varying capacitance:

Increasing the capacitance is like using a bigger bucket (and decreasing capacitance would be like using a smaller bucket).

Capacitance increases

∴ capacitor takes longer to charge/discharge (bucket takes longer to fill up)

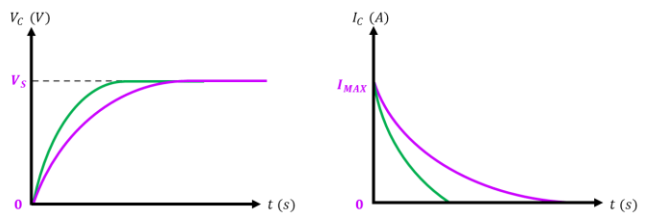
\+ no change to maximum current (water flow rate affected)



Capacitance decreases

∴ capacitor takes less time to charge/discharge (bucket fills up more quickly)

\+ no change to maximum current (water flow rate affected)



Energy Stored by a Capacitor

As charge and p.d. build up across the plates of a capacitor, energy is stored. The amount of energy stored by a capacitor can be calculated by:

$$E = \frac{1}{2}QV = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C}$$

where:

- E is the energy stored by the capacitor (J)
- Q is the charge build up on the capacitor (C)
- V is the voltage across the capacitor plates (V)
- C is the capacitance of the capacitor (F)

These equations are ***only for capacitors*** – do not use them to calculate energy in any other context.

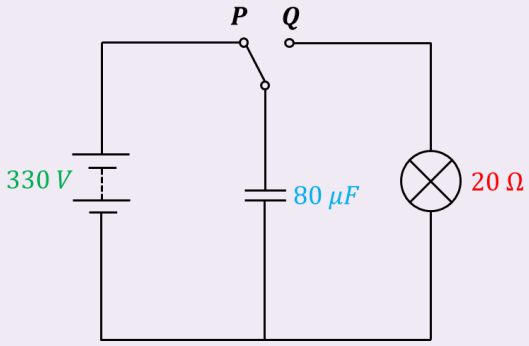
This means that we can easily control how much energy can be stored by capacitor by:

- Changing the maximum voltage across the capacitor (by changing the supply voltage).
- Using a different capacitor with a different value of capacitance.

Worked Example: The Camera Flash



A photographer builds the circuit shown for her camera flash:



The power supply has negligible internal resistance.

a) When the switch is moved to position P the capacitor charges.
State the potential difference across the capacitor when it is fully charged.

b) **Calculate** the maximum energy stored by the capacitor.

c) **Suggest** a change she could make to the circuit to allow the capacitor to store more energy.

(a) When fully charged, the voltage across the capacitor is equal to the supplied voltage.

$\therefore V_{C(MAX)} = 330\ V$

(b) The maximum amount energy is stored on the capacitor when it is fully charged ($V_C = 330\ V$).

$$E = \frac{1}{2}CV^2$$

$$E_{MAX} = \frac{1}{2} \times (80 \times 10^{-6}) \times (330)^2$$

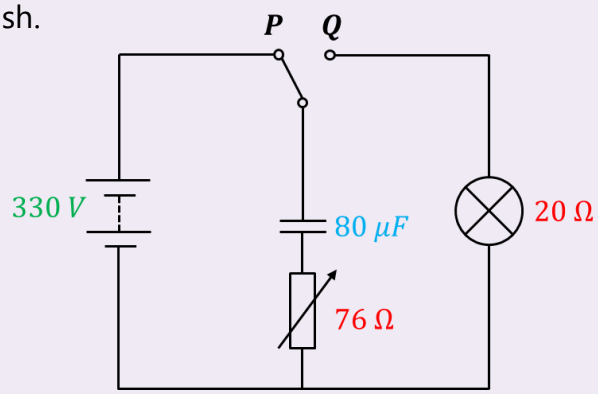
$$E_{MAX} = 4.4\ J$$

(c) We just calculated energy based on C and V.
$\therefore$ increase the capacitance
OR increase the supplied voltage

Worked Example: The Camera Flash (continued)

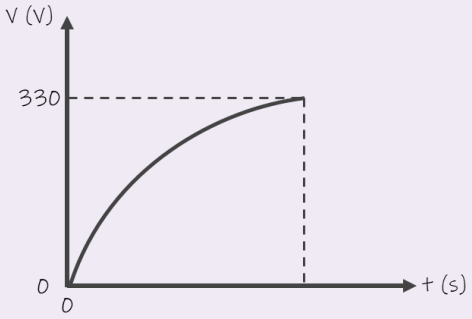


The photographer adapts her circuit so that she has more control over the duration of the flash.



d) When the switch is in position P the capacitor charges.

Sketch a graph of potential difference V against time t for the capacitor to fully charge.



e) At a point during the charging process the potential difference across the **resistor** is $120\ V$.

Calculate the charge stored by the capacitor at this point of the charging process.

The voltage across the **resistor** is 120 V. The **supplied** voltage is 330 V.
∴ V_C = 210 V at this point (since the resistor and capacitor are in series).

$$C = \frac{Q}{V} \qquad 80 \times 10^{-6} = \frac{Q}{210} \qquad Q = 0.17\ C$$

f) When the switch is moved to position Q, the capacitor discharges and the lamp flashes.

Show that the maximum magnitude of discharge current in the circuit is 3.4 A.

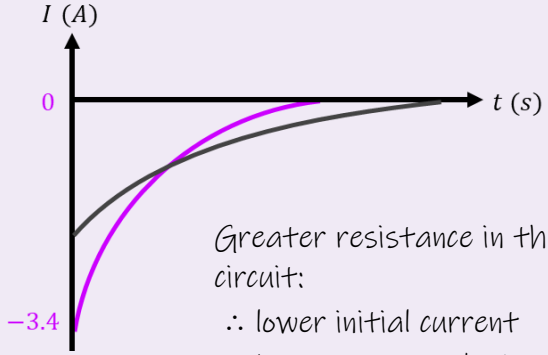
The maximum discharge current occurs right at the start of discharging, when the maximum voltage is across the capacitor. The total resistance in the circuit is 96 Ω (variable resistor and lamp in series).

$$V = IR \qquad 330 = I_{MAX} \times 96 \qquad I_{MAX} = 3.4\ A$$

g) The graph shows how the current I varies with time t as the capacitor discharges.

The photographer increases the resistance of the variable resistor.

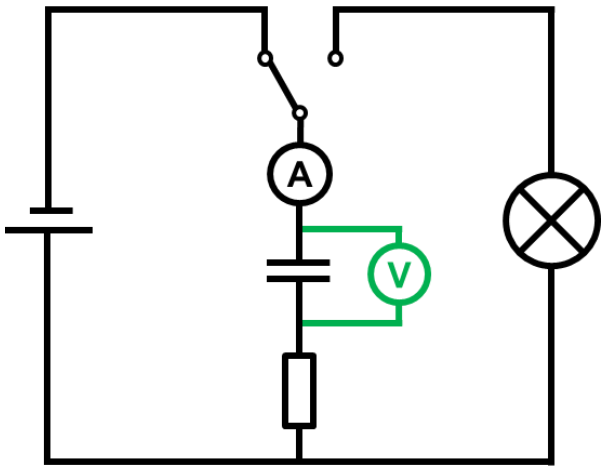
Add a line to the graph to show how the current now varies with time as the capacitor discharges.



Greater resistance in the circuit:
∴ lower initial current
∴ longer time to discharge

Measuring Voltage/Current During Charging/Discharging

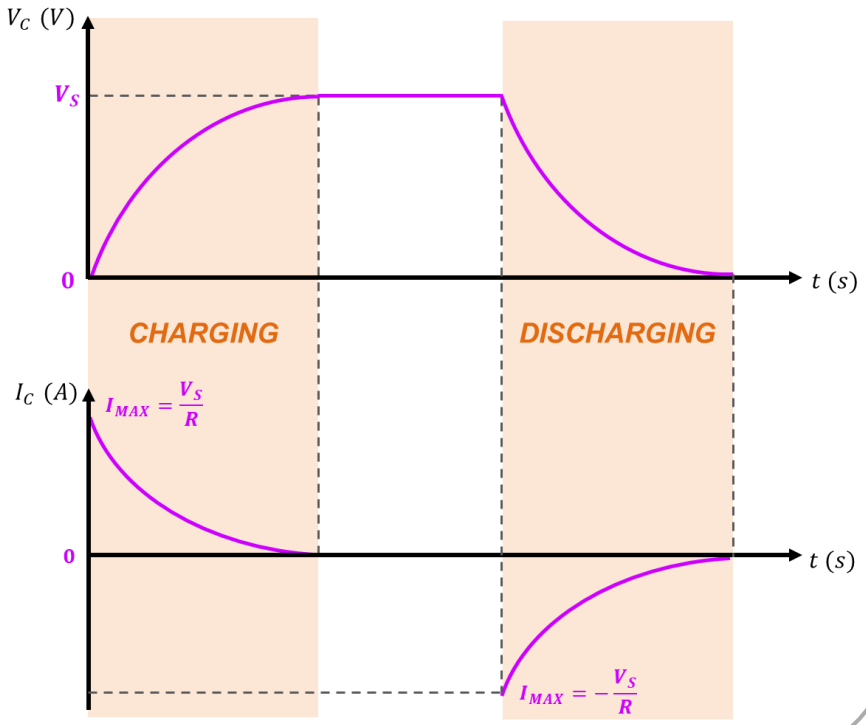
We can observe the variation of current in a capacitor and voltage across a capacitor with time (for both charging and discharging of capacitors) using the circuit below.



Where:

- The ammeter measures the current through the capacitor.
- The voltmeter measures the voltage across the capacitor.

Graphing voltage across the capacitor vs time:



Graphing current through the capacitor vs time:

Measuring Capacitance Experimentally

Consider the definition of capacitance – the charged stored per unit of p.d.. From this we have the relationship $C = \frac{Q}{V}$.

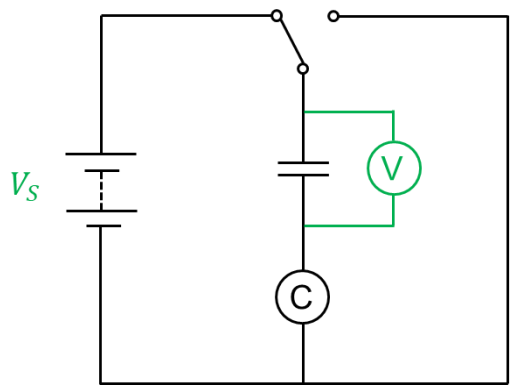
If we rearrange this relationship to fit the form $y = \boldsymbol{m}x$:

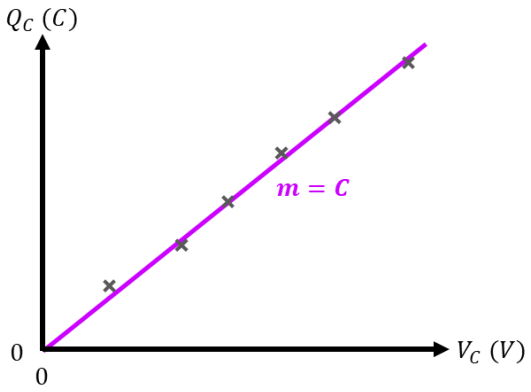
$$C = \frac{Q}{V} \qquad \Longrightarrow \qquad Q = \boldsymbol{C}V$$

Then we can determine the value of capacitance by:

- Measuring the voltage across a capacitor while it charges/discharges (using a voltmeter).
- Measuring the corresponding charge on the capacitor for each voltage measurement (using a coulombmeter).
- Plotting a graph of charged stored (y-axis) against p.d. (x-axis), with a line of best fit.
- Calculating the gradient of the line (which will be equivalent to the value of capacitance).

The circuit for the experiment and a sketch of the expected graph are shown below:





From this graph we could also determine the energy stored by the capacitor at any point. The energy stored by a charged capacitor is equal to the area under a charge-p.d. graph – giving us $E = \frac{1}{2}\,QV$ as we've already seen.

SQA Course Specification Higher

Semiconductors and p-n junctions

- Knowledge of the terms "conduction band" and "valence band".

- Knowledge that solids can be categorised into conductors, semiconductors or insulators by their band structure and their ability to conduct electricity. Every solid has its own characteristic energy band structure. For a solid to be conductive, both free electrons and accessible empty states must be available.

- Qualitative explanation of the electrical properties of conductors, insulators and semiconductors using the electron population of the conduction and valence bands and the energy difference between the conduction and valence bands.

- The electrons in atoms are contained in energy levels. When the atoms come together to form solids, the electrons then become contained in energy bands separated by gaps.

- For metals we have the situation where one or more bands are partially filled.

- Some metals have free electrons and partially filled valence bands, therefore they are highly conductive.

- Some metals have overlapping valence and conduction bands. Each band is partially filled and therefore they are conductive.

- In an insulator, the highest occupied band (called the valence band) is full. The first unfilled band above the valence band is the conduction band. For an insulator, the gap between the valence band and the conduction band is large and at room temperature there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction. There is no electrical conduction in an insulator.

- In a semiconductor, the gap between the valence band and conduction band is smaller and at room temperature there is sufficient energy available to move some electrons from the

valence band into the conduction band allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor.

- Knowledge that, during manufacture, semiconductors may be doped with specific impurities to increase their conductivity, resulting in two types of semiconductor: p-type and n-type.

- Knowledge that, when a semiconductor contains the two types of doping (p-type and n-type) in adjacent layers, a p-n junction is formed. There is an electric field in the p-n junction. The electrical properties of this p-n junction are used in a number of devices.

- Knowledge of the terms "forward bias" and "reverse bias". Forward bias reduces the electric field; reverse bias increases the electric field in the p-n junction.

- Knowledge that LEDs are forward biased p-n junction diodes that emit photons. The forward bias potential difference across the junction causes electrons to move from the conduction band of the n-type semiconductor towards the conduction band of the p-type semiconductor.

- Photons are emitted when electrons "fall" from the conduction band into the valence band either side of the junction.

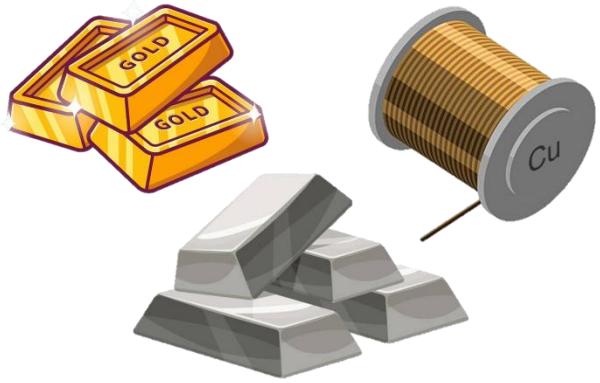
- Knowledge that solar cells are p-n junctions designed so that a potential difference is produced when photons are absorbed. (This is known as the photovoltaic effect.) The absorption of photons provides energy to "raise" electrons from the valence band of the semiconductor to the conduction band. The p-n junction causes the electrons in the conduction band to move towards the n-type semiconductor and a potential difference is produced across the solar cell.

Conduction

Previously, we defined *electr*ic current as "the flow of *electr*ic charge – usually *electr*ons – through an electrical conductor". We can put materials into categories based on their ability to conduct electricity:

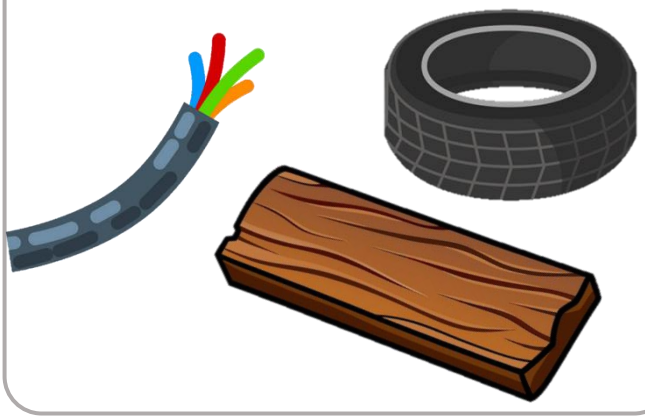
An electrical conductor:

A material that allows electric charges to pass through it.



An electrical insulator:

A material that does not allow electric charges to pass through it.

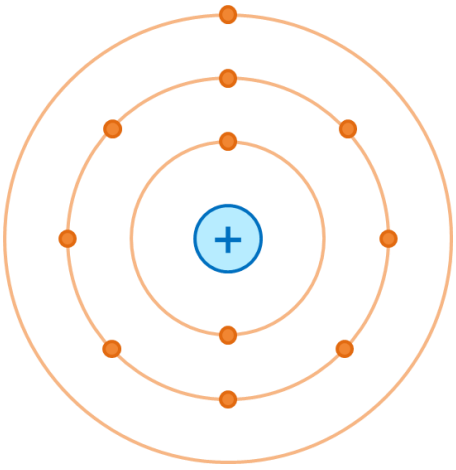


Whether a material will conduct electricity or not depends on whether the electrons in the material are free to move. We're going to look at a third category of materials known as *semiconductors* – these *sometimes* behave like insulators, but can be made to behave like conductors by adding impurities to the material or by adding energy (e.g. applying heat, light, voltage).

Band Theory

The Bohr Model of the Atom

There are several different models of the atom described by different physicists over time. The model that is useful for understanding semiconductors is the Bohr model, which describes the atom as a small positive nucleus surrounded by negative electrons orbiting at specific distances (known as electron "shells" or "energy levels").



Each energy level can only hold a certain number of electrons, and electrons *cannot* be in the space between levels.

Lots of Atoms Together

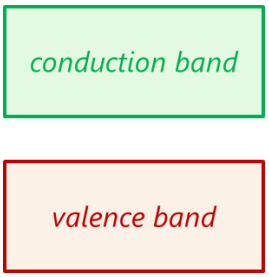
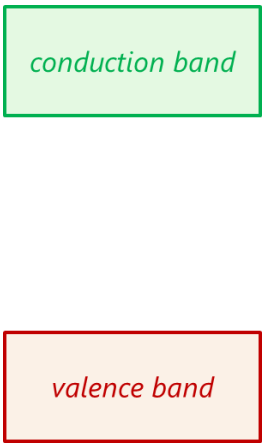
Even a tiny sample of a material consists of billions of trillions of atoms. When these atoms are packed close together (e.g. to form a solid chunk of copper) their energy levels can be bunched up into *bands*:

- The ***valence band*** – the highest occupied (by electrons) energy levels in a solid material (at absolute zero temperature).
- The ***conduction band*** – the energy levels in a solid material where electrons are free to move.

The ***band gap*** is the energy difference between the ***valence band*** and the ***conduction band*** – the amount of energy an electron in the ***valence band*** would need to gain to jump to the ***conduction band*** and move through the material.

Band Gaps for Different Types of Solid Materials

Band gaps for conductors, semiconductors, and insulators are often represented in diagrams like this:

Conductors	***Semiconductors***	***Insulators***
		
The valence band and the conduction band overlap.	There is a **small band gap** between the valence band and the conduction band.	There is a **large band gap** between the valence band and the conduction band.
The valence band is only partially full.	The valence band is full.	The valence band is full.
Electrons in the valence band can move.	Electrons in the valence band only need a small amount of energy to jump to the conduction band where they can move.	Electrons in the valence band need a *large* amount of energy to jump to the conduction band.
Conduction occurs.	Conduction occurs if energy is added (e.g. the material is heated).	Conduction cannot occur.

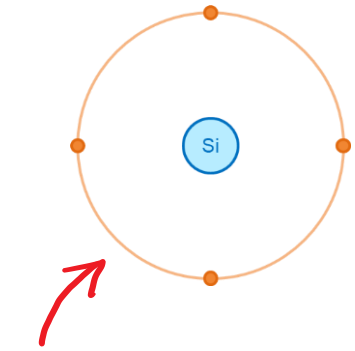
Doping Semiconductors

Another way of making a semiconductor more conductive is by doping the semiconductor – adding an impurity (an atom from a different element) which provides either:

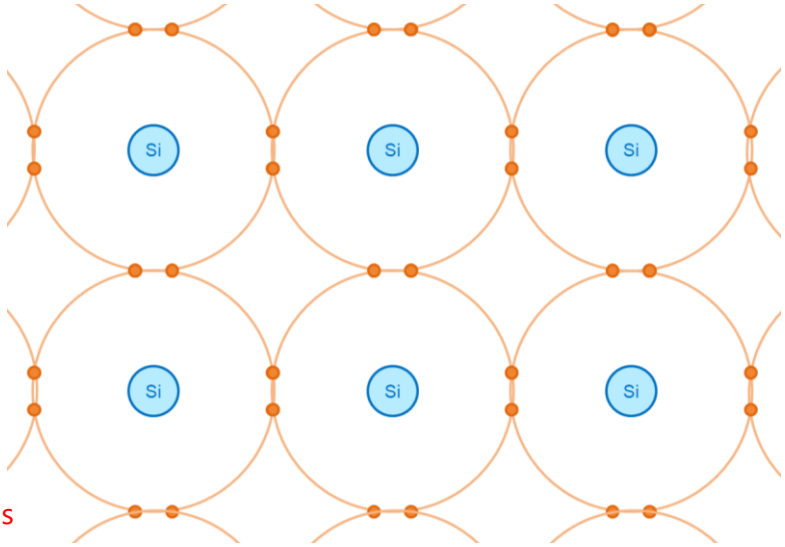
- Missing spaces (AKA "holes") which other electrons can move into.
- Extra electrons which can move freely.

Silicon is a commonly used semiconductor, which we will look at to understand doping.

A silicon atom has 4 electrons (out of 8 possible spaces) in it's highest occupied level. However, when lots of silicon atoms together, they share these electrons in a way that leaves the valence band full:



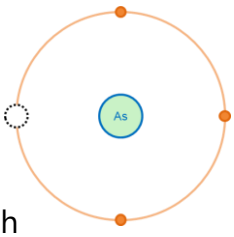
one silicon atom

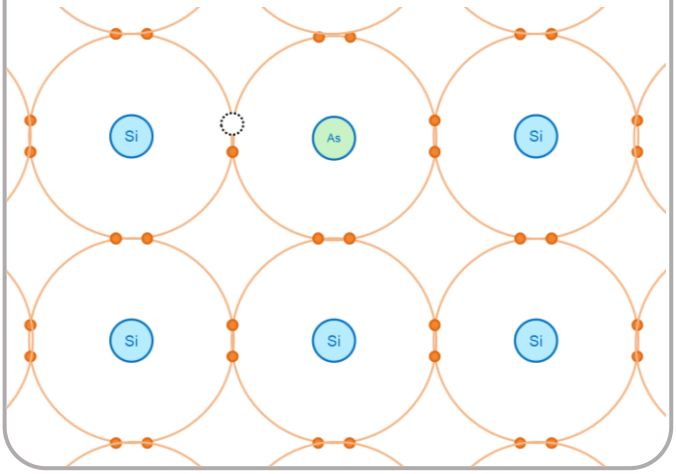


lots of silicon atoms

P-type semiconductors:

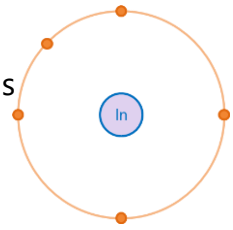
A p-type semiconductor is created when impurities atoms with only 3 outer electrons are added. This creates a ***positive hole*** which another electron can move into, which then leaves another hole behind. The positive hole *appears* to move through the material.

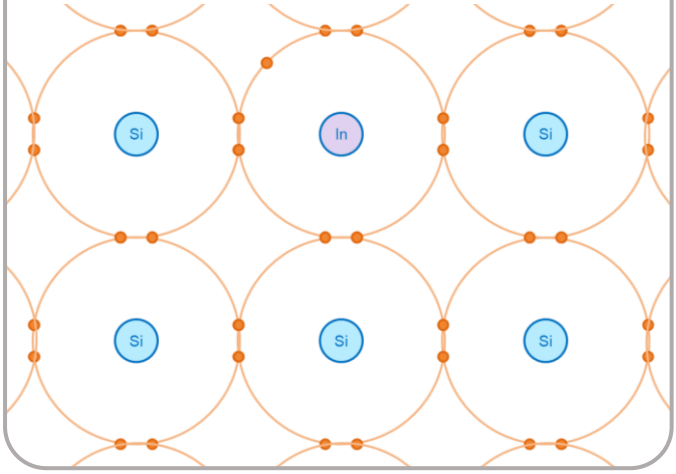




N-type semiconductors

An n-type semiconductor is created when impurity atoms with 5 outer electrons are added. This adds an ***extra negative charge*** which can move freely through the material.

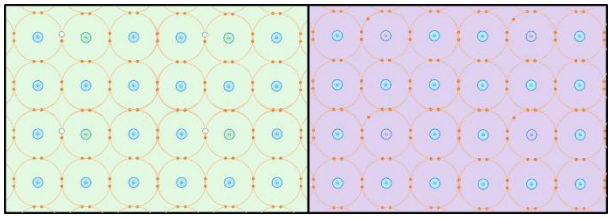




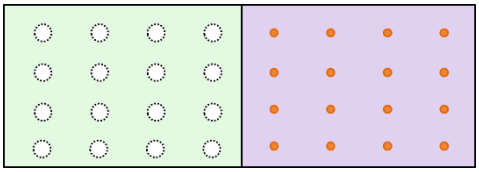
P-N Junctions

It is possible to create a semiconductor crystal that is p-type on one side and n-type on the other.

We could represent that like this:

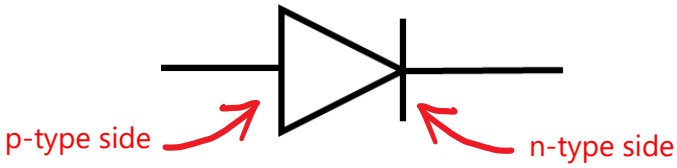


Or simplify and just represent the *charge carriers* – the **p**ositive holes and the **n**egatively charged electrons:



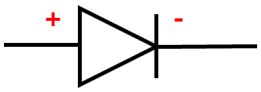
A p-n junction can be used to create a diode – an electrical device which acts like a one-way valve for electrical current (it allows current to flow one way and acts as an insulator if it flows the other way).

The circuit symbol for a diode is:



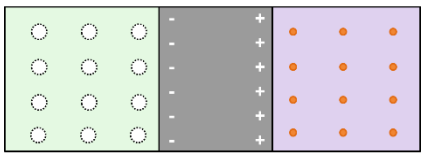
There are 3 ways we can describe a p-n junction diode, based on how it is positioned in a circuit:

Unbiased p-n junction

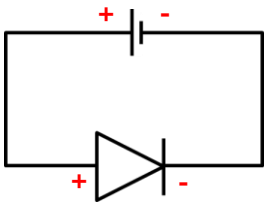


No external voltage applied – no battery/cell connected.

Free electrons cross the junction and combine with positive holes, leaving a ***internal electric field*** in the middle. This functions as an insulator, stopping further movement of charges.



Forward biased p-n junction

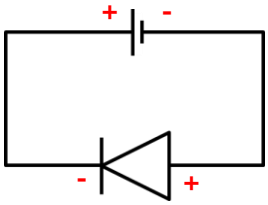


The ***n-type*** side of the p-n junction connected ***to the negative*** side of the battery (and p-type with positive).

The external voltage (from the cell) **reduces the internal electric field** and allows electrons to flow around the circuit.

Conduction occurs.

Reverse biased p-n junction



The ***n-type*** side of the p-n junction connected ***to the positive*** side of the battery (and p-type with negative).

The external voltage (from the cell) pulls the charge carriers further away from the junction, **increasing the internal electric field**.

Conduction <u>cannot</u> occur.

Applications of P-N Junctions

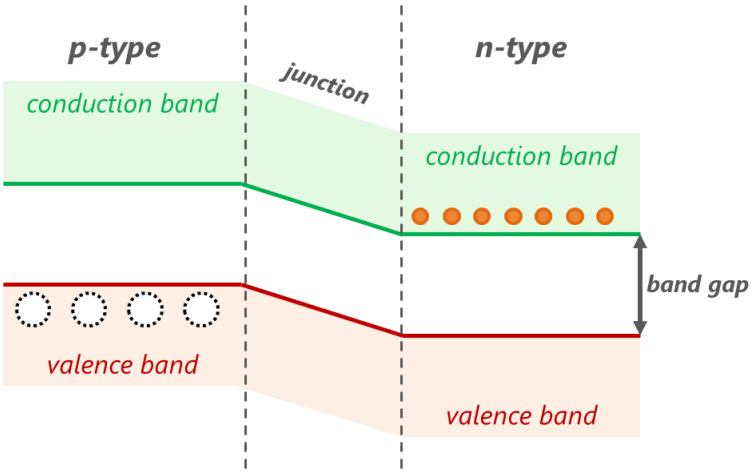
P-n junctions can be used to create useful electrical components such as LEDs and solar cells. To understand how these function we need to look again at **band theory**.

Applying Band Theory to a P-N Junction

The diagram below shows a p-n junction. On this diagram the higher up, the more energy an electron possesses:

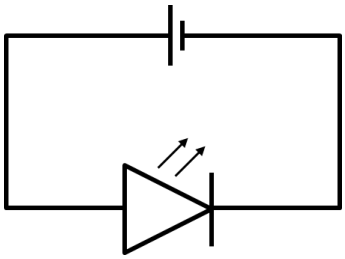
- An electron needs to ***gain energy*** to go ***from the valence band to the conduction band***.
- An electron ***loses energy*** if it falls ***from the conduction band to the valence band.***

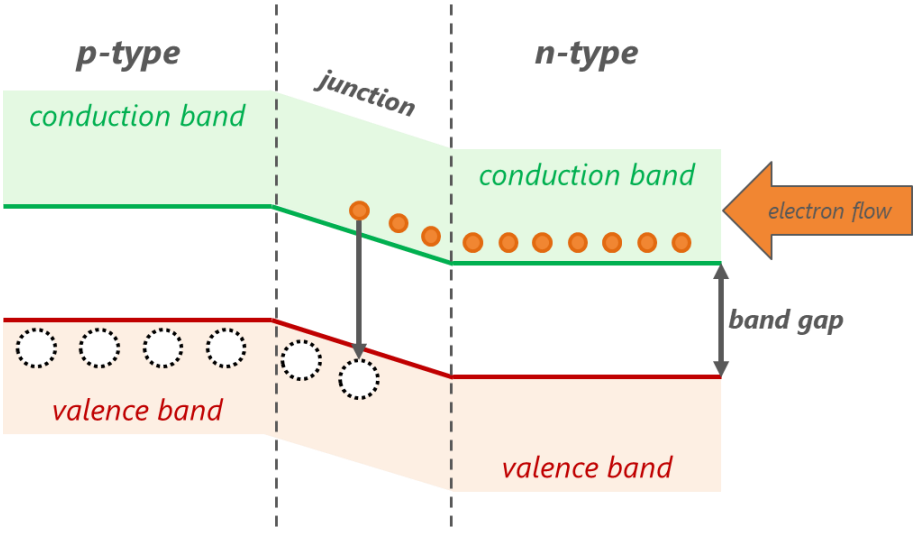
The difference in heights of the valance/conduction bands on the diagram (between p-type and n-type) represents the internal electric field that electrons need to overcome to allow for conduction.



How an LED Operates

An LED is a forward biased p-n junction diode that emits photons (particles of light):





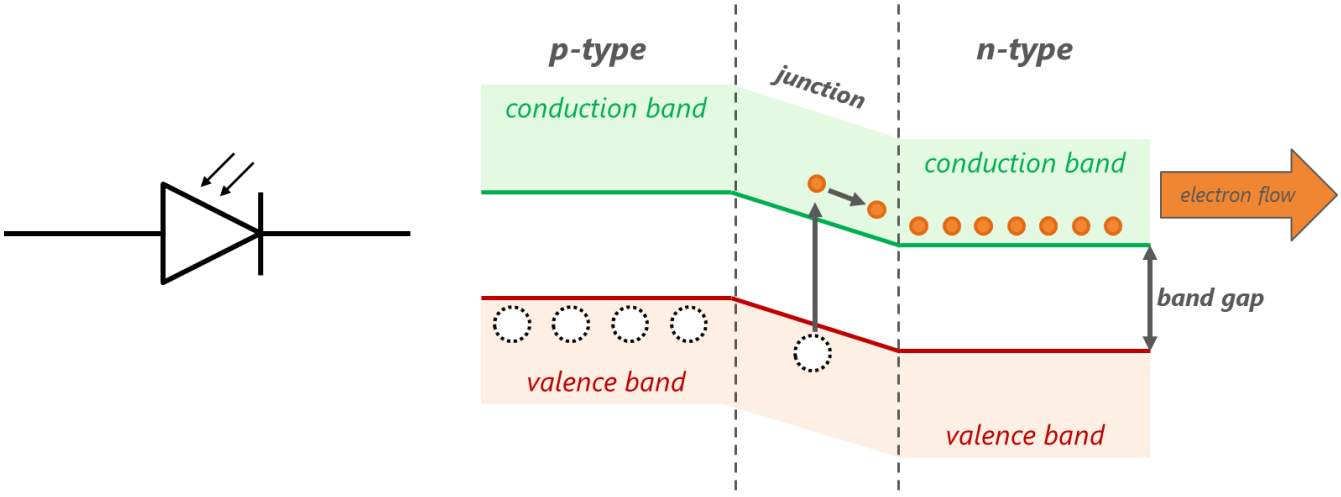
1. The external p.d. applied by the battery provides ***electrons*** with enough energy to move ***from the conduction band of the n-type towards the conduction band of p-type.***

2. At the junction, ***electrons*** fall ***from the conduction band to the valence band***, to recombine with a positive hole in the valence band.

3. As the electrons drops to this lower energy level, a ***photon is emitted.*** The bigger the drop, the higher energy the photon has (which accounts for different colours of light).

How a Solar Cell Operates

A solar cell (AKA a *photovoltaic cell* or *photodiode*) is a p-n junction designed to *supply* the voltage in a circuit:



1. A solar cell *produces* a p.d. when a *photon* is absorbed. This is known as the ***photovoltaic effect***.

2. An absorbed ***photon provides*** enough ***energy*** for an ***electron in the valence band*** to jump ***up to the conduction band*** (leaving behind a positive hole).

3. At the p-n junction, the ***internal electric field*** pulls these ***electrons*** (now in the conduction band) ***towards the n-type*** semiconductor (and the holes towards the p-type). This ***creates a potential different across the solar cell***, allowing it to be used as a voltage supply.

Worked Example: The P-N Junction



A process engineer from the semiconductor industry is delivering a lecture on how they manufacture their semiconductors.

a) The engineer explains that a p-n junction is made of two doped semiconductors next to each other.

(i) **State** what is meant by a *doped semiconductor*.

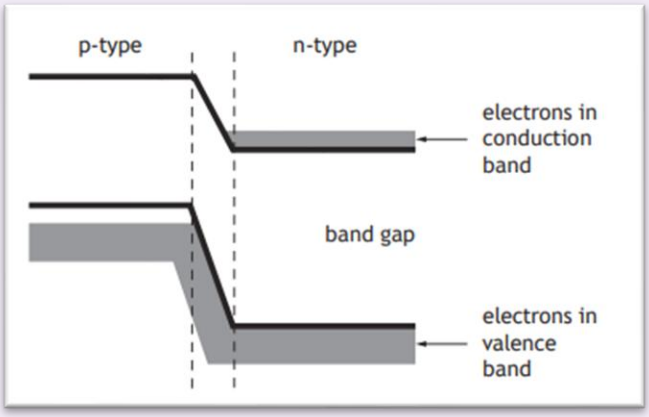
A semiconductor that has specific impurities added to it.

(ii) **State** whether doping increases, decreases, or has no effect on the conductivity of a semiconductor.

Increases.

b) The engineer shows the audience a variety of LEDs of different colours.

They display the following diagram and explain how an LED produces light.



Explain, using **band theory**, how the LED emits light.

When the LED is forward biased and an external voltage is applied:

- Electrons in the conduction band of the n-type move towards the conduction band of the p-type.
- Electrons fall from the conduction band to the valence band.
- The energy lost by the electrons is emitted as photons.

c) The engineer connects a red LED and a blue LED, in turn, to the battery. Both are forward biased. However, the red LED lights and the blue LED does not. .

Explain, using **band theory**, why the blue LED will not operate with this battery.

The electrons in the conduction band of the n-type do not gain enough energy to move towards the conduction band of the p-type.

d) The engineer explains that p-n junctions can also be used to make solar cells, which produce a potential difference when light is incident on the p-n junction.

State the name of this effect.

A semiconductor that has specific impurities added to it.