Wallace Hall Academy

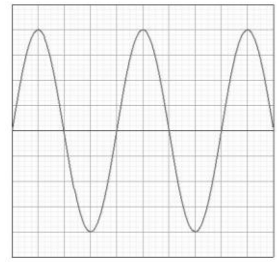
CfE Higher Physics

Unit 3 - Electricity
Notes

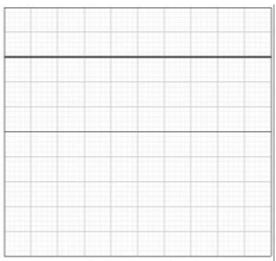
Name ___________________

Electrons and Energy

Alternating current and direct current



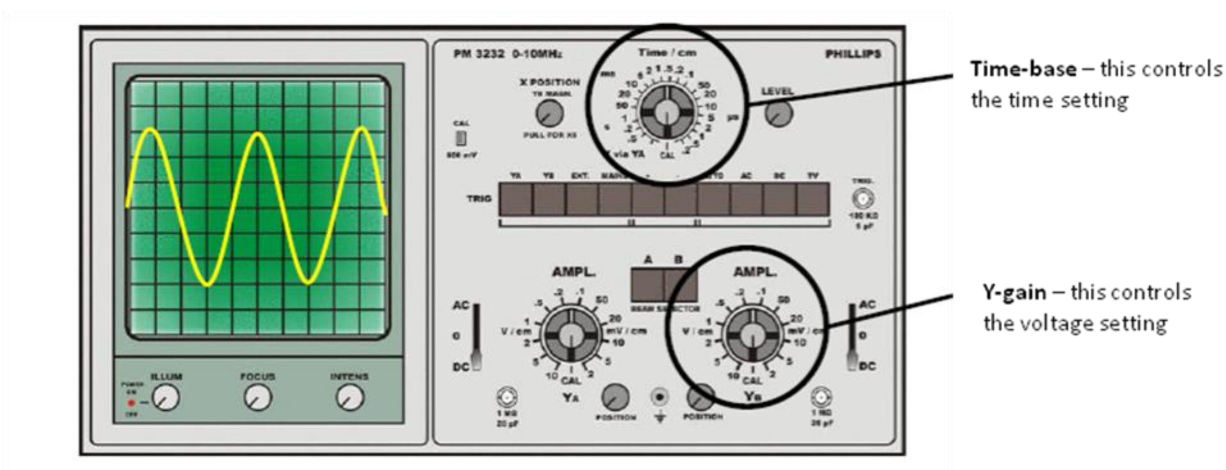
Alternating current – electrons flow back and forth several times per second. On an oscilloscope trace an a.c. signal varies above and below the 0 V line.



Direct current – electrons flow in one direction from a negative terminal to a positive terminal. On an oscilloscope trace a d.c. signal has a constant value.

Measuring frequency and peak voltage of an a.c. signal

The values for voltage and time on an oscilloscope can be read from the number of divisions on the screen multiplied by the scale shown on one of two dials on the control panel at the side of the screen. The voltage axis, called the y-gain, is usually given as volts/div (V div^{-1}) or volts/cm (V cm^{-1}) and the time axis scale, known as the time-base, is shown as multiples of seconds/div (s div^{-1}) or seconds/cm (s cm^{-1}).



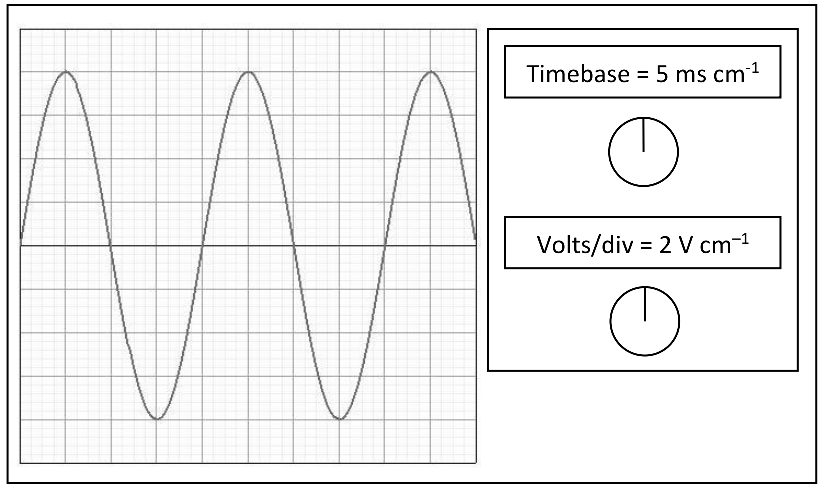
The **peak voltage** is defined as the distance from the maximum positive value to the centre line.

The **frequency** of an a.c. signal is calculated from its period. This is the time for one complete cycle of the current as it moves in one direction then the other, so we measure the horizontal distance on the screen for one complete wave.

Example:

An oscilloscope trace is shown.

a. Calculate the peak Voltage.
b. Calculate the period of the signal.
c. Calculate the frequency of the signal.



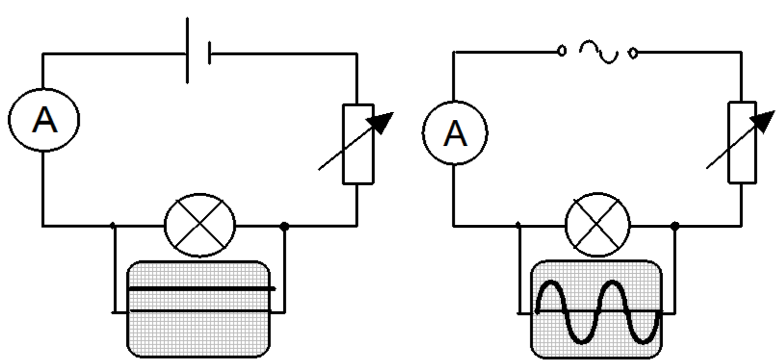
Solution:

Alternating current – peak and rms

As we have seen an a.c. signal varies above and below 0 V. The peak positive Voltage and peak negative Voltage both deliver the same amount of energy per Coulomb of charge, just in a different direction. If an average of an a.c. signal is taken it is equal to the peak Voltage divided by $\sqrt{2}$. This value is known as the root mean square rms Voltage or d.c. equivalent Voltage. It is called the d.c. equivalent Voltage as it allows a.c. and d.c. Voltages to be compared.

The rms value is what is quoted on a power supply so that a fair comparison between a.c. and d.c. can be made eg a 6 V battery (d.c.) will produce the same brightness of light bulb as a 6 V rms a.c. supply.

In the two circuits shown the variable resistors are adjusted until the lamps are of equal brightness. The value of the peak Voltage from the a.c. circuit will be greater than the Voltage from the d.c. circuit. However, when the peak Voltage from the a.c. circuit is converted to an rms value it will be the same value as the d.c. Voltage.



The equations used to calculate rms Voltages and currents are shown below.

$$V_{peak} = \sqrt{2}\ V_{rms}$$

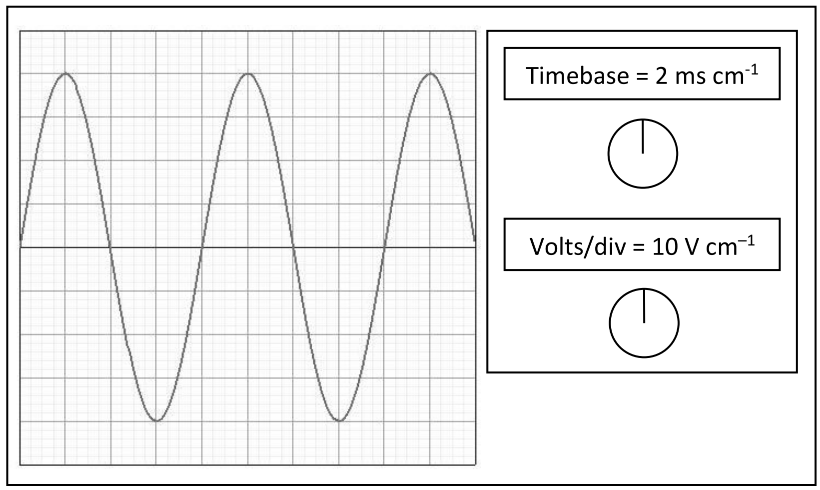
$$I_{peak} = \sqrt{2}\ I_{rms}$$

Where V_{peak} is the peak Voltage (V), V_{rms} is the rms Voltage (V), I_{peak} is the peak Current (A), I_{rms} is the rms Current (A)

Example:

An oscilloscope trace is shown.

a. Calculate the peak Voltage.
b. Calculate the rms Voltage.
c. Calculate the period of the signal.
d. Calculate the frequency of the signal.



Solution:

Important notes:

- Readings on meters that measure a.c. are rms values, not peak values. e.g. a multimeter switched to a.c. mode will display rms values.
- For power calculations involving a.c. always use rms values.
- The mains supply is usually quoted as 230 V a.c. This is of course 230 V rms. The peak voltage rises to approximately 325 V.

Power, voltage, current and resistance

PIVR in series and parallel circuits (Revision of National 5)

This section will cover basic electricity definitions and the use of PIVR in series and parallel circuits. The content will be revision of National 5 work but you will find some of the circuits more complex.

Electric current

An electric current is a flow of charged particles called electrons. The size of the electric current is the charge per second.

$$Q = It$$

Where Q is charge (C), I is current (A) and t is time (s)

Potential difference

Potential difference (Voltage) is the energy supplied per Coulomb of charge passing through the supply. For example a 12 V supply will provide **12 J of energy per Coulomb of charge passing through the supply.**

Electrical power

Power is the amount of energy transferred per second. It is described by the following equation.

$$P = \frac{E}{t}$$

Where p is power (W), E is energy (J) and t is time (s).

Equations

The following equations are known as the PIVR equations and can be used to determine power, current, Voltage or resistance in a circuit.

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

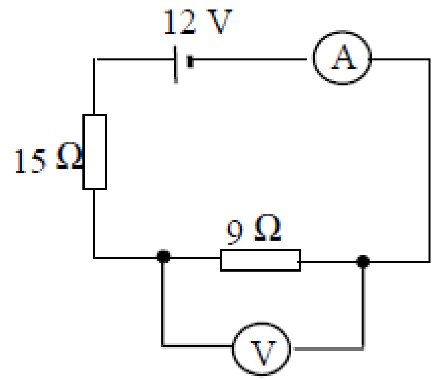
Where P is power (W), I is current (A), V is Voltage (V) and R is resistance (Ω).

As well as the 4 equations shown above there are also a number of equations linking current, Voltage and resistance which are specific to series or parallel circuits.

	Series	Parallel
Current	$I_S = I_1 = I_2 = I_3$	$I_S = I_1 + I_2 + I_3$
Voltage	$V_S = V_1 + V_2 + V_3$	$V_S = V_1 = V_2 = V_3$
Resistance	$R_T = R_1 = R_2 = R_3$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$

Example:
A simple series circuit is shown.

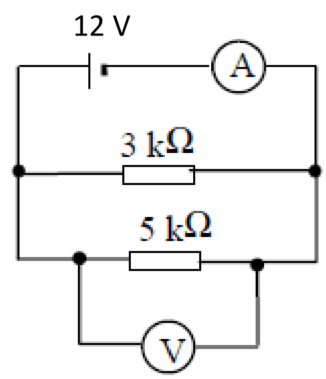
a. State what is meant by a potential difference of 12 V.
b. Calculate the reading on the Ammeter.
c. Calculate the reading on the Voltmeter.
d. Calculate the power rating of the 15 Ω resistor.



Solution:

Example:
A simple parallel circuit is shown.

a. Calculate the total circuit resistance.
b. Calculate the reading on the Ammeter.
c. Calculate the reading on the Voltmeter.
d. Calculate the energy transferred per second in the 3 kΩ resistor.

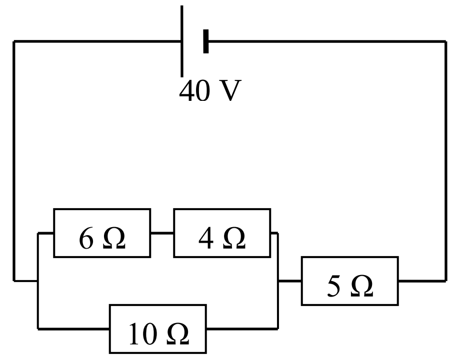


Solution:

There are a number of different ways of tacking circuit problems using ratio's etc. but sometimes consistent application of V = IR is the best solution. The key with this method is to apply the correct Voltages, currents and resistances. The example below will demonstrate this technique.

Example:

A parallel circuit is shown.



a. Calculate the total resistance of the circuit.
b. Calculate the current through the 5 Ω resistor.
c. Calculate the Voltage across the 5 Ω resistor.
d. Calculate the Voltage across the 10 Ω resistor.
e. Calculate the current through the 10 Ω resistor.
f. Calculate the current through the 6 Ω resistor.
g. Calculate the Voltage across the 4 Ω resistor.

Solution:

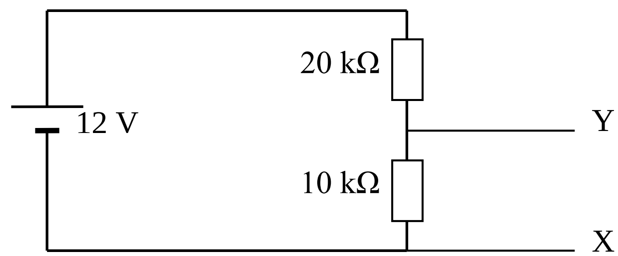
This example will show you that consistent application of V = IR also works for simple potential divider circuits.

Example:

A potential divider circuit is shown.

a. Calculate the current flowing through the 10 kΩ resistor.

b. Calculate the potential difference between X and Y.



Solution:

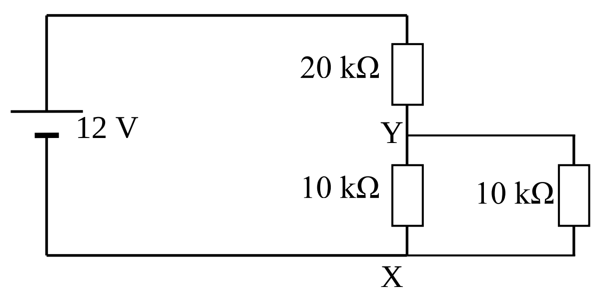
Example:

A second 10 kΩ resistor is added in parallel with the first.

a. Calculate the total resistance of the circuit.

b. Calculate the current flowing through the 20 kΩ resistor.

c. Calculate the potential difference between X and Y.



Solution:

Electrical sources and internal resistance

Internal resistance

Electrical sources such as cells, batteries and power supplies are not perfect and as such energy is lost inside them due to their internal resistance. While this is a new concept we have not considered before the calculations behind it are not and can be easily explained by the Physics of potential dividers.

The diagram below shows a cell alongside two resistors. Write down the potential difference alongside each component.

When considering internal resistance all we are doing is moving one of the resistors next to the cell. Redraw the circuit below and again write the potential difference alongside each component.

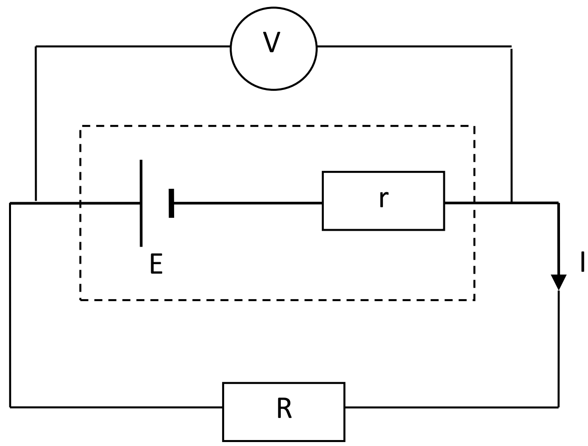
The Voltage 'lost' inside the power supply is called the 'lost volts'.

The resistance inside the power supply is called the 'internal resistance'.

The electromotive force (emf) is the maximum energy the power supply provides per Coulomb of charge. This is achieved when no current flows as there will be no lost volts.

The terminal potential difference (tpd) is the actual energy per Coulomb of charge the power supply provides.

The diagram below shows all of the important parts of a circuit when describing emf and internal resistance.



The tpd is equal to the emf minus the lost Volts so the following equation can be created.

$$\mathbf{E = V + Ir}$$

Which can also be written as.

$$\mathbf{E = IR + Ir}$$

Where E is the emf (V), V is the tpd (V), I is the current in the circuit (A), r is the internal resistance (Ω) and R is the external resistance (Ω).

<u>Example:</u>
A cell has an emf of 12 V and is attached to a resistor of 40 Ω with a current of 250 mA flowing. Calculate the internal resistance.

<u>Solution:</u>

There are 3 conditions to consider when performing internal resistance calculations.

Open circuit (I = 0 A)

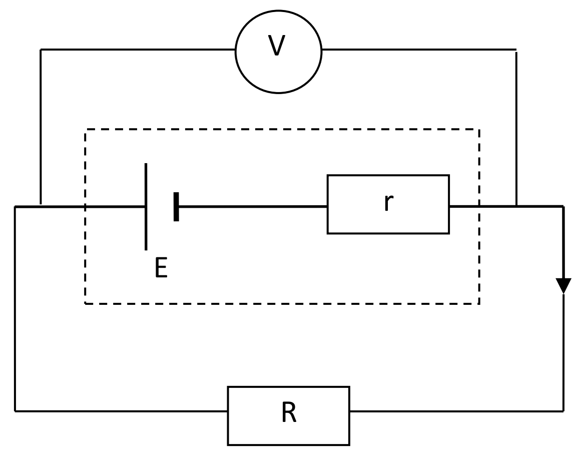
In this scenario there are no lost volts (Ir) as no current flows so emf = tpd.

Circuit under load (R = any given value not 0 Ω or infinite Ω)

This is the most common type of problem and will require use of the RIVEr analysis shown on the previous page.

Short circuit (R = 0 Ω)

When a wire is placed across the terminals of a power supply it short circuits the external circuit and means all of the current flows through the wire meaning the only resistance in the circuit is the internal resistance making the current very high.



Example:
The circuit shown to the right has an emf of 15 V. The reading on the ammeter is 280 mA. The external resistor has a value of 50 Ω.

a. State what is meant by an emf of 15 V.
b. Calculate the value of the internal resistance.
c. Calculate the value of the lost volts.
d. A second external resistor is placed in parallel with the original, describe and explain what happens to the reading on the Voltmeter.
e. A wire is now placed across the terminals of the cell, calculate the short circuit current.

Solution:

Measuring emf and internal resistance experiment

Aim: To measure the emf and internal resistance of a cell.

Diagram:

Method:

Results:

Resistance (Ω)	Current (A)	tpd (V)
20		
16		
12		
8		
4		

Calculations: The analysis shown below will demonstrate what needs to be plotted.

Conclusion:

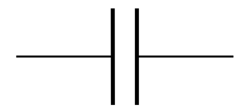
Evaluation:

Capacitors

Capacitors

Capacitance is the ability (or capacity) of a component to store charge. A device that stores charge is called a **capacitor**. Capacitance is measured in **Farads** (F)

Practical capacitors consist of two conducting layers separated by an insulator. The simplest type is two metal plates with an air gap between them. The circuit symbol for a capacitor is shown to the right.



Experiment to determine capacitance

Aim: To determine the relationship between charge and Voltage of a capacitor and to determine the capacitance of the capacitor.

Diagram:

Method:

Results:

Time (s)	Current (μA)	Q (C) (=I t)	V (V)
0	100		
10	100		
20	100		
30	100		
40	100		
50	100		
60	100		

Calculations: The analysis shown below will demonstrate what needs to be plotted.

Conclusion:

Evaluation:

Capacitance

From the previous experiment we have shown that the following equation is true for capacitance.

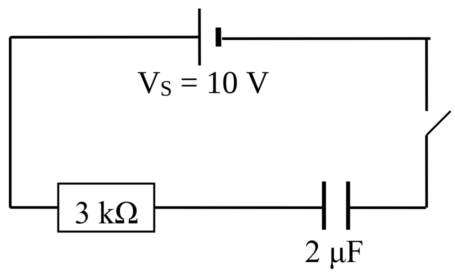
$$C = Q/V$$

Where C is capacitance (F), Q is charge stored (C) and V is potential difference across the capacitor (V).

The capacitance of a capacitor is the charge stored per unit Volt.

Example:
At a certain point, for the circuit shown the potential difference across the resistor is 6.5 V.

a. Calculate the current flowing in the circuit at this time.
b. Calculate the charge stored on the capacitor at this time.



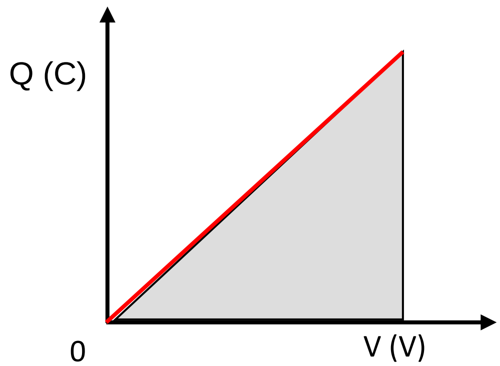
Solution:

Charging a capacitor

Charging a capacitor is a challenging thing to do. Initially the electrons accumulate on one plate and flow away from the other but this becomes increasingly more difficult as we try to force negatively charged electrons onto an already negatively charged plate.

Energy stored on a capacitor

Because work must be done charging a capacitor this work is stored as energy on the capacitor. We have previously defined work done as $E_w = QV$ but as both Q and V increase as the capacitor charges we must calculate E as the area under the QV graph.



Because the shape of the graph is a triangle the energy stored on a capacitor at a given time is ½ QV.

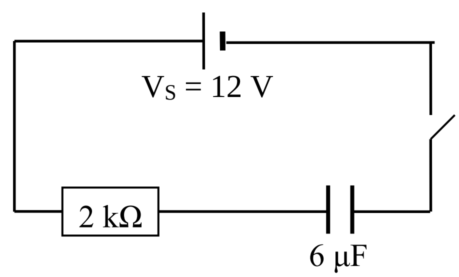
$$E = \tfrac{1}{2}QV = \tfrac{1}{2}CV^2 = \tfrac{1}{2}\frac{Q^2}{C}$$

Where E is the energy stored on a capacitor (J), Q is the charge stored on a capacitor (C), V is the potential difference across the capacitor (V) and C is the capacitance of the capacitor (F).

Example:

After 4.2 s, for the circuit shown the potential difference across the resistor is 8.2 V.

a. Calculate the initial charging current in the circuit.
b. Calculate the charge stored on the capacitor after 4.2 s.
c. Calculate the **maximum** energy that can be stored on the capacitor.



Solution:

Experiment to charge a capacitor

Aim: To determine how the potential difference across a capacitor varies as it charges.

Diagram:

Method:

Results:

Time (s)	V (V)
0	
10	
20	
30	
40	
50	
60	
70	
80	
90	
100	

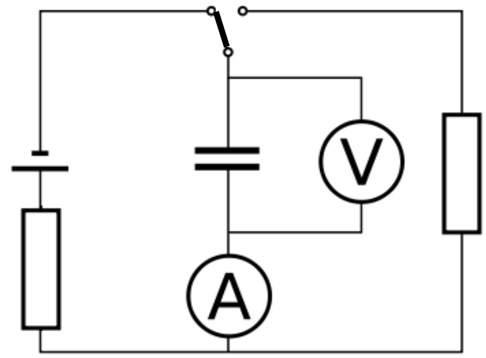
Plot Voltage versus time.

Conclusion:

Evaluation:

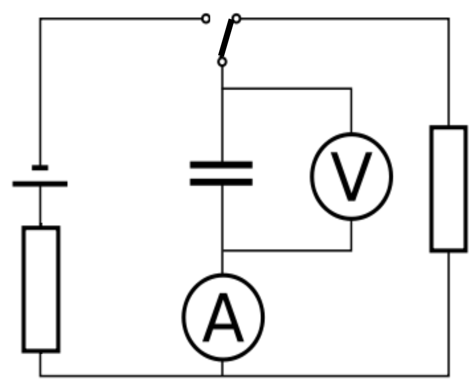
Current and Voltage variation during the charging process

During the charging process charge accumulates on the capacitor which increases the Voltage across it and reduces the current flowing in the circuit.



Current and Voltage variation during the discharging process

During the discharging process, charge which had accumulated on the capacitor dissipates around the circuit as the Voltage across the capacitor decreases, until the current eventually reaches 0 A.



Factors affecting charging and discharging times

Capacitance of capacitor

Increasing the capacitance of the capacitor creates a bigger bucket to fill so the charging time will increase. The converse is also true.

Resistance of resistor

Increasing the resistance of the resistor creates a smaller current so the charging time will increase. The converse is also true.

Potential difference of supply Voltage

Increasing the potential difference of the supply Voltage creates a larger current so the charging time will decrease. The converse is also true.

Resistors and capacitors in AC circuits

Resistors and capacitors behave very differently when AC signals with varying frequencies are applied.

Electrons at Work

Conductors, Semi-conductors and Insulators

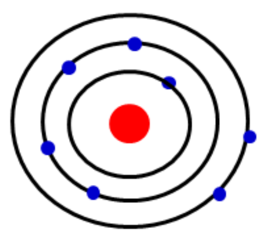
All materials can be classified as conductors, semi-conductors or insulators depending on their resistance.

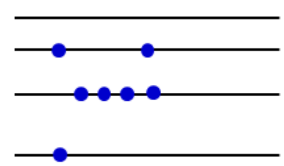
Material	Charge carriers	Resistance (per metre)	Examples
Conductor	Many free electrons	10 Ω	Copper, steel, aluminium.
Semiconductor	A few free electrons	10^6 Ω	Silicon, Germanium, Selenium.
Insulator	No free electrons	10^{12} Ω	Wood, air, plastic.

Electron arrangement in atoms

In an individual atom electrons can exist in discrete energy levels.

More than one electron can exist in any one energy level but they cannot exist between the levels.





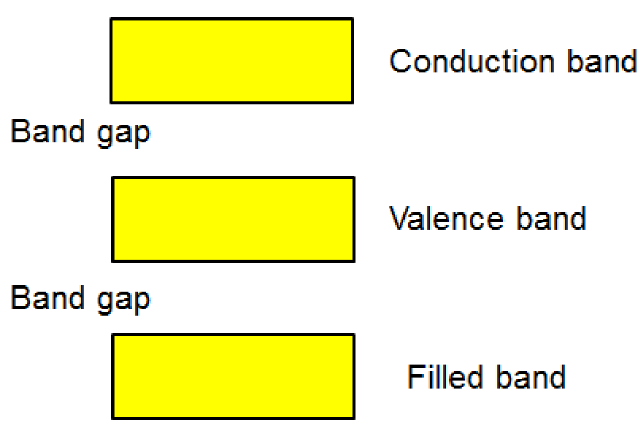
Band Theory

In a solid the neighbouring atoms are closely packed and their energy levels form a continuous band. The two highest bands are called the valence band and conduction band.

The spaces in between the bands are called band gaps. These are energy gaps that electrons need to jump across to go from one band to another.

Electrons in the conduction band are free to move. Electrons only exist in this band in conductors. In insulators and semi-conductors the conduction band is empty.

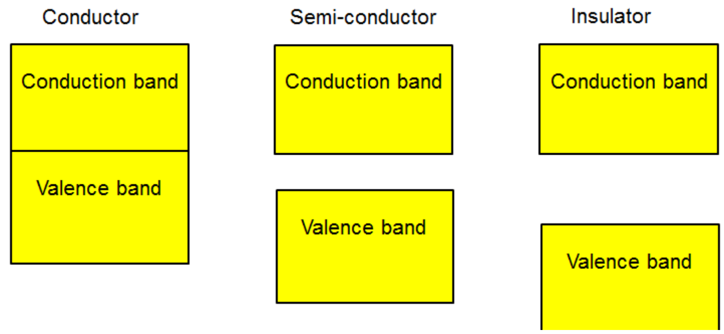
The valence band is completely full in insulators and semi-conductors.



There is no band gap in conductors, this means electrons can flow easily from one atom to another.

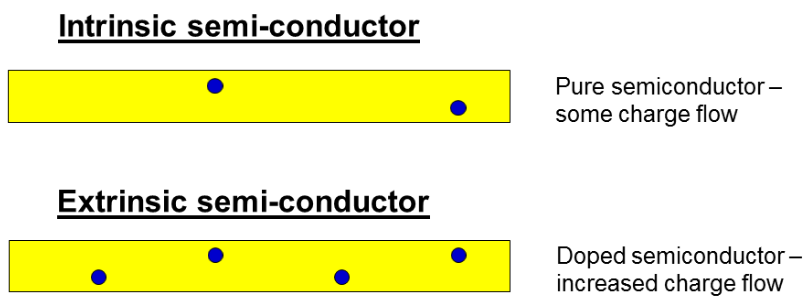
There is a small band gap in semi-conductors but **with an increase in temperature electrons can be given enough energy to jump** from the valence to conduction band. This means an **increase in temperature results in an increase in conduction because of a decrease in resistance**.

There is a large band gap in insulators and electrons almost never cross it.

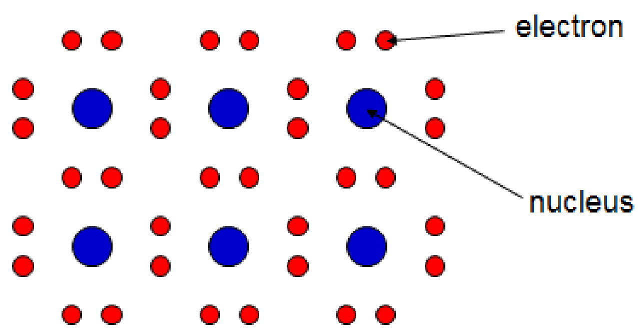


Doping

A pure semiconductor such as Silicon can have its resistance reduced by increasing the number of charge carriers in the Silicon. Charge carriers (such as electrons) in a material allow electric current to flow and reduce the resistance of a material if they are increased in number. **The process of decreasing the resistance of a semiconductor by adding impurities is called doping.**

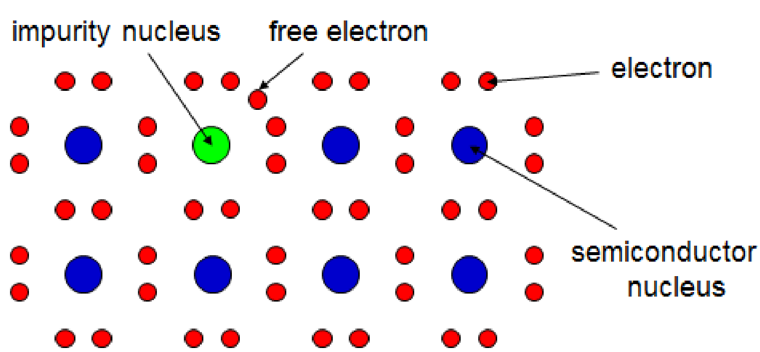


The two main semiconductors are Silicon and Germanium and each of these elements has 4 electrons in the outer energy level. As the outer energy level needs 8 electrons to be filled, adjoining atoms share electrons so they have an outer energy level with 8 electrons. This leaves only a few free electrons resulting from imperfections to provide current flow.



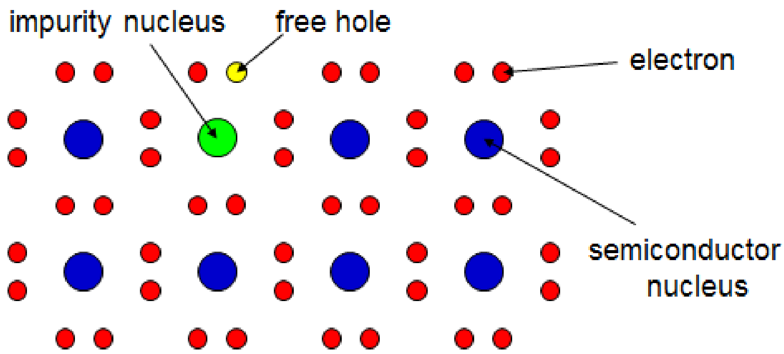
n-type doping

In order to increase current flow in semiconductors they can be doped with other atoms to increase the number of charge carriers. **In n-type semiconductors the majority charge carriers are electrons** as the semiconductor is doped with an atom with 5 electrons in the outer energy shell to leave 1 spare electron per impurity atom.



p-type semiconductors

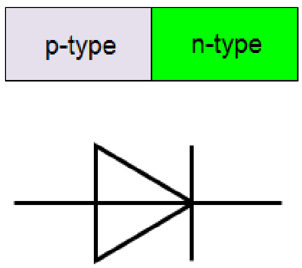
In p-type semiconductors the majority charge carriers are holes as the semiconductor is doped with an atom with 3 electrons in the outer energy shell to leave 1 spare hole per impurity atom.

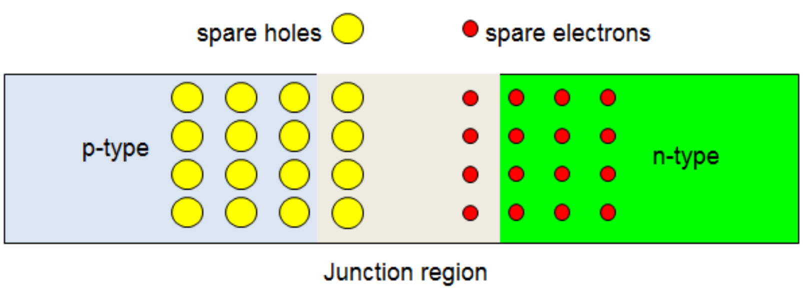


In doped semiconductors although the majority charge carriers can be positive (p-type) or negative (n-type) the semiconductor as a whole is still charge neutral. This is because the impurity atoms carry enough protons in their nucleus to counteract any change in the number of charge carriers.

p-n junctions

A p-n junction diode can be created by joining a p-type semiconductor to an n-type semiconductor. The point where they join is called the junction region and together they create a diode.

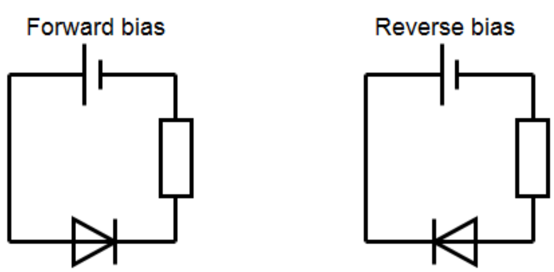




When n-type and p-type semiconductors are joined together spare electrons in the n-type recombine with spare holes in the p-type in the junction region to create a depletion layer where there are no free charge carriers and so no current can flow.

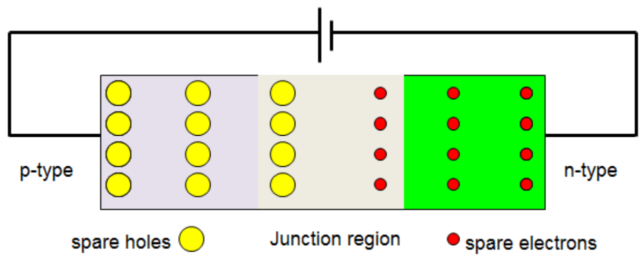
Biasing a p-n junction

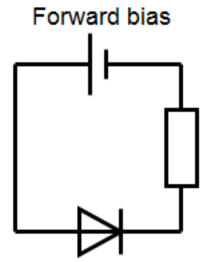
A p-n junction diode can be connected in two ways; forward bias and reverse bias.
Current will only flow when the diode is connected in forward bias.



Forward biased p-n junction

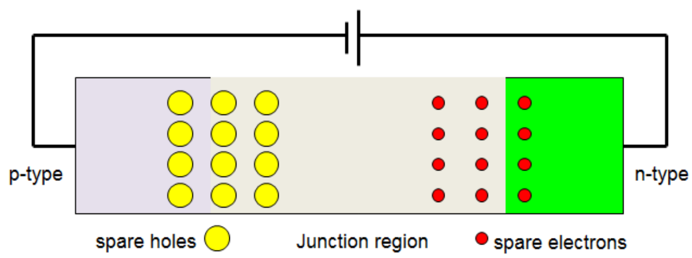
In order to overcome this depletion layer a diode can be connected in forward bias where the electrons are given enough energy to cross by the battery. The minimum voltage required to overcome the depletion layer is 0.7 V for Silicon.

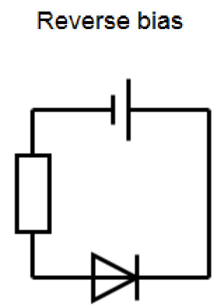




Reverse biased p-n junction

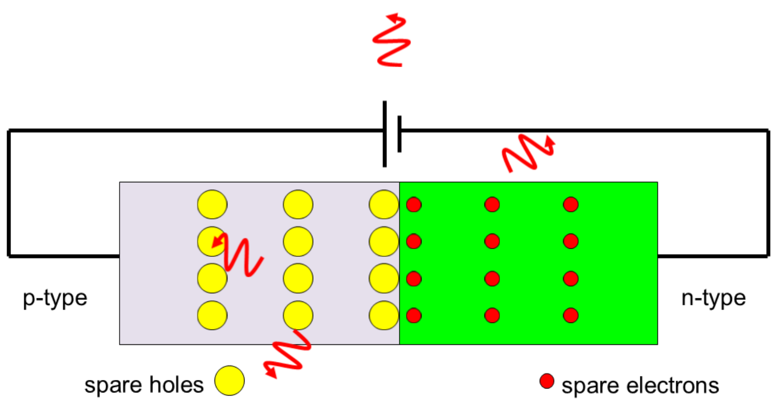
If the diode is connected in reverse bias the size of the depletion layer increases as negative electrons are attracted to the positive terminal of the battery and positive holes are attracted to the negative terminal of the battery.

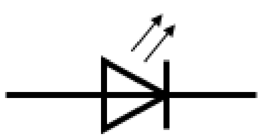




Light emitting diodes (LED's)

In an LED photons are produced when electrons and holes recombine in the junction region of a diode.





In an LED the applied Voltage lifts electrons into the conduction band from the valence band. The electrons then fall from the conduction band and combine with holes in the valence band and to conserve energy a photon is emitted from the junction region.

From previous topics we know that $E = hf$ and $E_w = QV$. The frequency of the photons produced by the recombination of electrons and holes in the junction region of a diode is given by,

$$hf = QV$$

where h is Planck's constant (6.63×10^{-34} Js), f is the frequency of the emitted photon (Hz), Q is the charge on an electron (1.6×10^{-19} C), and V is the potential difference across the LED (V). This means that different colours of LED have different switch on Voltages. The bigger the frequency or smaller the wavelength, the bigger the switch on Voltage will be.

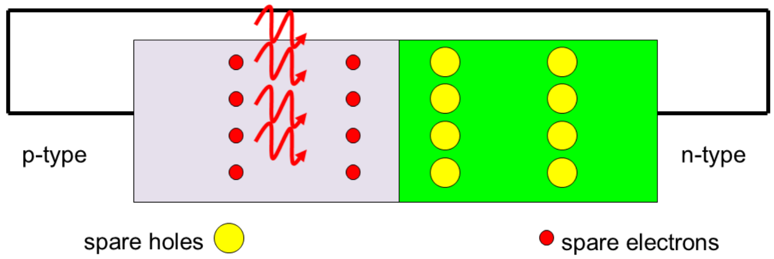
<u>Example:</u>
An LED has a potential difference of 2.2 V across it.

a. Calculate the energy of the emitted photons.
b. Calculate the frequency of the emitted photons.
c. Calculate the wavelength of the emitted photons.
d. This LED would be green. State a possible switch on Voltage for a blue LED.

<u>Solution:</u>

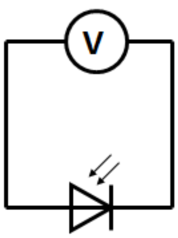
Photodiodes

Instead of light being created by the recombination of electrons and holes in the junction region of a diode we can create electron and hole pairs by shining light on a diode. By creating these electron-hole pairs we have created an electric current by shining light on a device. This type of device is called a photodiode.



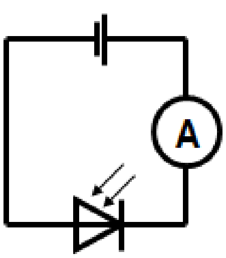
In a photodiode photons incident on the junction region cause electron-hole pairs to be created and a current to flow.

Photovoltaic mode

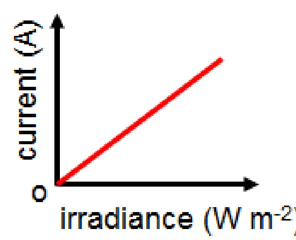


A photodiode can be connected in two ways. In **photovoltaic mode** the photodiode is used to supply power to a circuit. By putting light in we can get an electric current out, this is how a solar cell works. In photovoltaic mode a photon causes an electron and hole pair to be created in the junction region of the photodiode.

Photoconductive mode



In **photoconductive** mode the photodiode is connected in reverse bias with a cell. No current will flow in this mode but when light is shone on the photodiode electron hole pairs are created which causes a current to flow. Current and irradiance are proportional.



Electricity

Describe what is meant by e.m.f.

The energy given to every Coulomb of charge passing through the supply

Describe what is meant by an e.m.f. of 12 V.

12 J of energy are given to every Coulomb of charge passing through the supply

Describe what is meant by the term 'lost volts'.

Voltage lost across the internal resistance of a supply

Describe what is meant by the term 'terminal potential difference'.

Voltage across the terminals of a power supply

Describe what happens to the e.m.f. of a supply if the external resistance is increased.

No change, the e.m.f. is a fixed value

Describe what happens to the e.m.f. of a supply if the external resistance is decreased.

No change, the e.m.f. is a fixed value

Describe what happens to the t.p.d. of a supply if the external resistance is increased.

As the external resistance is increased, the current flowing decreases. This means the lost volts (Ir) decreases so the t.p.d. increases.

Describe what happens to the t.p.d. of a supply if the external resistance is decreased.

As the external resistance is decreased, the current flowing increases. This means the lost volts (Ir) increases so the t.p.d. decreases.

Describe what happens to the lost volts in a supply if the external resistance is increased.

As the external resistance is increased, the current flowing decreases. This means the lost volts (Ir) decreases.

Describe what happens to the lost volts in a supply if the external resistance is decreased.

As the external resistance is decreased, the current flowing increases. This means the lost volts (Ir) increases.

Describe how to short circuit a power supply.

Connect a wire across the terminals of the supply. All of the current will flow through the wire creating a very large current.

In a graph of potential difference versus current for a power supply explain how the e.m.f. of the power supply can be determined.

The y-intercept

In a graph of potential difference versus current for a power supply explain how the internal resistance of the power supply can be determined.

The negative gradient of the graph

Describe what happens to the current in a circuit containing a capacitor and a resistor when the frequency of the AC input is increased.

It increases proportionally

Describe what happens to the current in a circuit containing a lamp and a resistor when the frequency of the AC input is increased.

It stays constant

State the definition of capacitance.

Charge stored per Volt

Describe what happens to the charging time of a capacitor in series with a resistor when its capacitance is increased.

It increases as there is a bigger capacitor to fill

Describe what happens to the charging time of a capacitor in series with a resistor when its capacitance is decreased.

It decreases as there is a smaller capacitor to fill

Describe what happens to the charging time of a capacitor in series with a variable resistor whose resistance is increased.

It increases as the current decreases so it takes longer to fill the capacitor

Describe what happens to the charging time of a capacitor in series with a variable resistor whose resistance is decreased.

It decreases as the current increases so it takes less time to fill the capacitor

Describe what happens to the voltage across a capacitor as it charges in a circuit where it is in series with a resistor.

Starts at zero and increases to the Voltage across the supply

Describe what happens to the voltage across a capacitor as it discharges in a circuit where it is in series with a resistor.

Starts at the Voltage across the supply and decreases to zero

Describe what happens to the current through a capacitor as it charges in a circuit where it is in series with a resistor.

Starts at a maximum and decreases to zero

Describe what happens to the current through a capacitor as it discharges in a circuit where it is in series with a resistor.

Starts at a negative maximum and decreases to zero

Describe what happens to the voltage across a resistor as a capacitor in series with the resistor is charging.

Starts at the Voltage across the supply and decreases to zero

Describe what happens to the voltage across a resistor as a capacitor in series with the resistor is discharging.

Starts at zero and increases to the Voltage across the supply

Describe what happens to the current through a resistor as a capacitor in series with the resistor is charging.

Starts at a maximum and decreases to zero

Describe what happens to the current through a resistor as a capacitor in series with the resistor is discharging.

Starts at a negative maximum and decreases to zero

Describe the band gap structure in a conductor.

Conduction band and valence band overlap so electrons can flow between them easily

Describe the band gap structure in a semi-conductor.

Conduction band and valence band are separated by a small energy gap so some electrons can flow between them

Describe the band gap structure in an insulator.

Conduction band and valence band separated by a large energy gap so hardly any electrons flow between them

Describe what happens to the resistance of a semi-conductor if it is heated.

Resistance decreases as electrons can jump from valence band to conduction band more easily

Explain what doping a semi-conductor will do to its resistance.

It will reduce its resistance as the number of charge carriers will be increased

State the name of the majority charge carrier in an n-type semi-conductor.

Electrons

State the name of the majority charge carrier in a p-type semi-conductor.

Holes

Describe the overall charge of an n-type semi-conductor.

Neutral as there are less electrons but also less protons

Describe the overall charge of a p-type semi-conductor.

Neutral as there are more electrons but also more protons

Explain the purpose of a resistor when connected in series with an LED.

To protect the LED from too large a current flowing and breaking the LED

Describe what happens to the brightness of an LED if the current in a circuit is varied.

If the current increases the brightness increases and if the current decreases the brightness decreases or it goes off altogether.

Describe how an LED should be connected to ensure it is forward biased.

The p-type material should be connected to the positive terminal of the power supply and the n-type material should be connected to the negative terminal of the power supply.

Describe how light is emitted in an LED.

In an LED the applied Voltage lifts electrons into the conduction band from the valence band. The electrons then fall from the conduction band and combine with holes in the valence band and to conserve energy a photon is emitted from the junction region.

Describe how a current is created in a photodiode.

In a photodiode photons incident on the junction region cause electron-hole pairs to be created and a current to flow.