A-Level Physics
Revision notes 2015

Contents

Units, Quantities and Measurements

Base units

All units in science are derived from seven base units:

Mass	kilogram	kg
Distance	metre	m
Time	second	s
Current	ampere	A
Amount	mole	mol
Temperature	Kelvin	K
Light Intensity	candela	cd

Derived units

There are many other units that we use, but all of these are derived by multiplication or division of some combinations of the base units.

You can think of it like letters and words. We have 26 letters in the alphabet but we have thousands of words in our language. **Here are some of the derived units**:

Quantity	**Unit**	**Symbol**	**Base unit equivalent**
Velocity	metre per second	ms^{-1}	ms^{-1}
Acceleration	metre per second squared	ms^{-2}	ms^{-2}
Force	Newton	N	$kg\ ms^{-2}$
Work or Energy	joule	J	$kg\ m^2s^{-2}$
Power	watt	W	$kg\ m^2s^{-3}$
Pressure	Pascal	Pa	$kg\ m^{-1}s^{-2}$
Frequency	hertz	Hz	s^{-1}
Charge	coulomb	C	A s

Prefixes

Now you have units, you often need to group these into larger or smaller numbers to make them more manageable. For example, you don't say that you are going to see someone who lives 100,000 m away from you; you say they live 100 km away from you.

Here a quick list of the common quantities used:

Name	Symbol	Scaling factor	Common example
tera	T	10^{12} 1,000,000,000,000	Large computer hardrives can be terabytes in size.
giga	G	10^{9} 1,000,000,000	Computer memories are measured in gigabytes.
mega	M	10^{6} 1,000,000	A power station may have an output of 600 MW (megawatts).
kilo	k	10^{3} 1,000	Mass is often measured in kilogrammes (i.e. 1000 grammes).
deci	d	10^{-1} 0.1	Fluids are sometimes measured in decilitres (i.e. 0.1 litre).
centi	c	10^{-2} 0.01	Distances are measured in centimetres (i.e. 100th of a metre).
milli	m	10^{-3} 0.001	Time is sometimes measured in milliseconds.
micro	µ	10^{-6} 1,000,000th	micrometres are often used to measure wavelengths of electromagnetic waves.
nano	n	10^{-9}	nanometres are used to measure atomic spacing.
pico	p	10^{-12}	picometres used to measure atomic radii.

Vectors and Scalars and Linear Motion

Vectors versus Scalars

Vectors and scalars are two types of measurements you can make.

- A **scalar** measurement only records the **magnitude** (or amount) of whatever you are measuring.
- A **vector** measurement records the **magnitude** of the thing you are measuring and the **direction**.

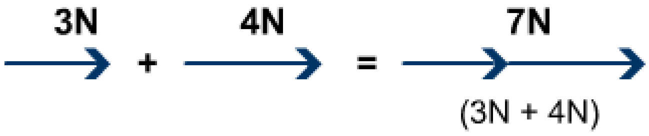
Vector Addition

Adding scalars is easy because you can just add the numbers.

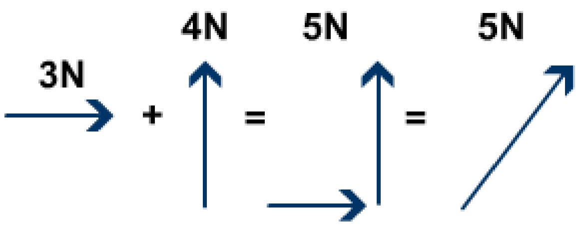
For Example: 3kg + 4 kg = 7 kg

Adding vectors needs much more care. You have to take into account their magnitude and direction.

For Example: What are 3N + 4N? Well, it depends on the directions! Look at the possibilities...



Note: 1N is not balanced

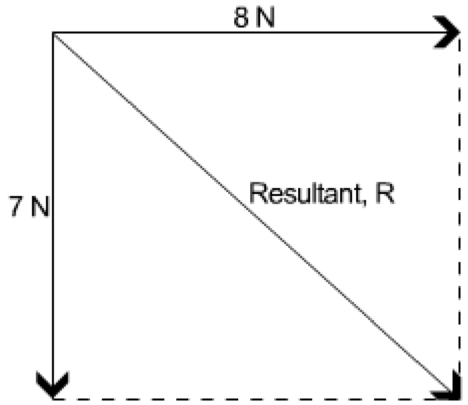


So in other words, you add vectors geometrically (using geometry). You should be able to do this using accurate diagrams (don't forget your protractor) or by using Pythagoras.

Resultant Vectors

The **resultant vector** is the one that you get when you add two or more vectors together. It is a single vector that has the same effect as all the others put together. Finding the resultant vector when the forces are in different directions can be tricky if you don't like Pythagoras, so here's a couple to get you going!

Worked Example:

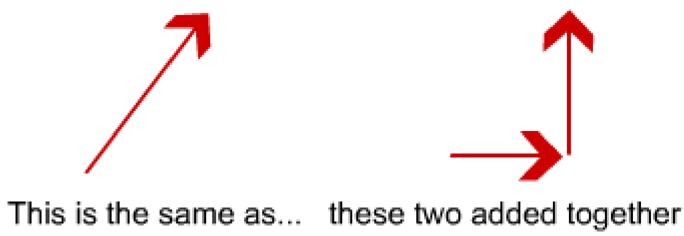


Using Pythagoras: $R^2 = 8^2 + 7^2$

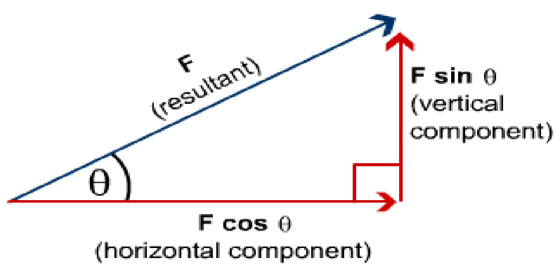
So, $R = \sqrt{113} = 10.6$ N

Resolving Vectors into Components

We have just shown that any two vectors can be represented by a single resultant vector that has the same effect. Guess what?! You can do the same thing in reverse! Any single vector can be represented by two other vectors (components), which would have the same effect as the original one:



You need to use trigonometry to find the two components of a vector. Remember the two components will always be at right angles.



Check that you understand how to calculate the values of the components.

Speed and Velocity

Both speed and velocity tell us how far something is travelling in unit time. As velocity is a vector it must also tell us what direction the object is travelling in.

$$\text{Speed (m/s)} = \frac{\text{distance moved (m)}}{\text{time taken (s)}}$$

$$\text{Velocity (m/s)} = \frac{\text{displacement change (m)}}{\text{time taken (s)}}$$

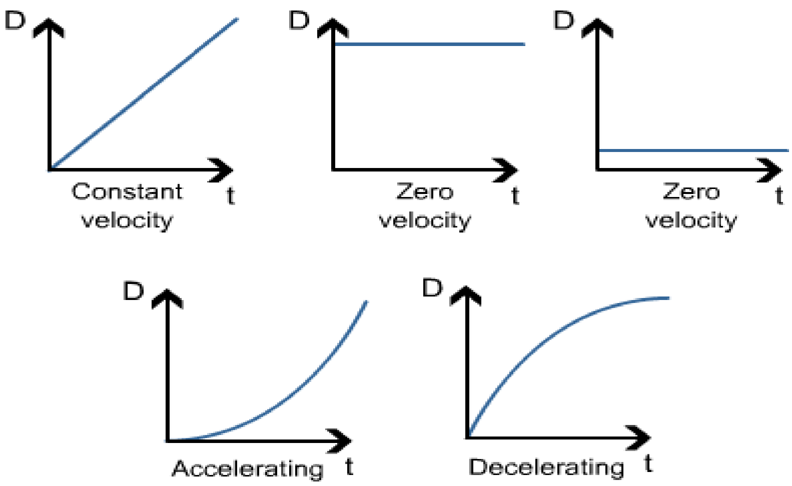
Acceleration

Acceleration tells us how rapidly something is changing speed - for instance, the change in speed in unit time. **Deceleration** is the same thing, but we give it a negative sign as the speed will be decreasing.

$$\text{Acceleration (m/s}^2\text{)} = \frac{\text{Change in velocity (m/s)}}{\text{time taken (s)}}$$

Displacement-time graphs

These show the motion of an object very clearly and allow you to find position and velocity at any time. Any graph that you see will be a combination of these sections.

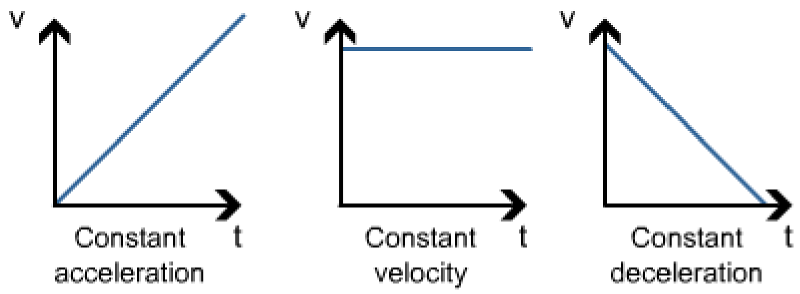


Notice that the gradient = $\dfrac{\text{Change in D}}{\text{Change in t}}$ = the velocity at any time.

When the velocity is changing, as on the lower two graphs, you can find the velocity at any point by drawing a tangent touching the graph at that point by drawing a tangent touching the graph at that point and working out its gradient using the same equation.

Velocity-time graphs

These fare similar to displacement-time graphs, but this time velocity is on the y-axis. Here are the only possibilities that you'll come across at A-level.



Notice that the gradient = $\dfrac{\text{Change in velocity}}{\text{Change in time}}$ = acceleration or deceleration.

You also need to know that the area under the line gives you the displacement of the object up to that point.

Acceleration-time graphs

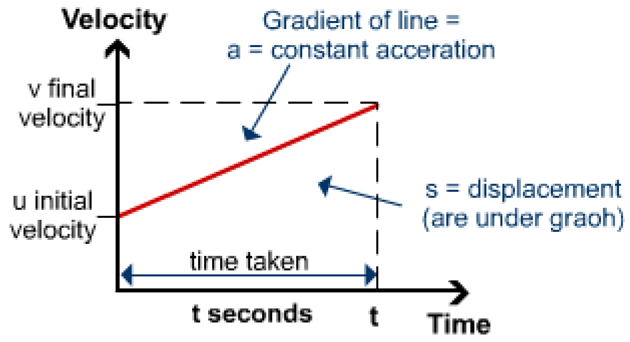
Note: **All three of the movement graphs are related to each other as the:**

- Gradient of D/t graph gives you the points on the v/t graph.
- Gradient of v/t graph gives you the points on the a/t graph.

Equations of Motion

If acceleration is constant, a quicker way than drawing graphs to find acceleration, velocity or displacement is to use some equations.

The symbols for displacement, initial velocity, etc. are shown on the diagram.



Projectiles

Vectors at right angles to one another are independent.

If you are considering the effect of two (or more) vectors on an object, it is important to remember that:

Vectors at right angles to each other do not have any effect on each other.

An easy example: no matter how hard you push down on an object, you will never make it accelerate sideways.

Projectile Motion - ignoring friction

If a stone is thrown horizontally from a cliff top it follows what is called **projectile motion.**

Vertically it has constant acceleration downwards (due to gravity).

Horizontally it has constant velocity (for instance, no acceleration or deceleration if there is no friction).

Some useful tricks:

To find out about the ball at the highest point in its flight, remember that at that point vertically: v = 0 m/s.

(For that instant it is travelling horizontally so it has no vertical velocity at all).

To find the time for the whole flight you usually have to find the time for half the flight by considering the time for the vertical velocity to reduce to zero from its initial value (for instance, the time it takes the ball to stop moving any higher) and then double it.

What if velocity and acceleration are in opposite directions?

Direction is important

To show different directions we use a positive or negative sign. It doesn't matter whether you choose up or down, left or right as positive, as long as you stick to it for the rest of the question.

For example:

If you are going to the right at $10ms^{-1}$ but accelerating to the left (for instance, decelerating) at $2ms^{-2}$, then $u = +10ms^{-1}$ and $a = -2ms^{-2}$

Acceleration due to gravity

Objects in a gravitational field experience a downward force, their weight. If unbalanced, this will produce a downward acceleration. This crops up frequently in A-level questions. However, it's easy to deal with. Simply always use acceleration as:

$a = g = 9.81\ ms^{-2}$ downwards.

For example:

Drop a stone from a cliff.

Initially, $t = 0$, $u = 0$, and $a = +\ 9.81\ ms^{-2}$ (*Note:* I've chosen down to be positive here)

Or

Throw a stone upwards at $10\ ms^{-1}$

Initially, $t = 0$, $u = 10ms^{-1}$ and $a = g = -9.81ms^{-2}$. (*Note:* I've chosen up to be positive here to show that it doesn't matter which one you choose as long as you're consistent.)

Equations

Equations of Motion

Learn to derive and use

$v^2 = u^2 + 2\ as$

$v = u + at$

$s = ut + ½\ at^2$

$$s = \frac{(v+u)}{2}.t$$

Symbols

s = displacement

u = initial velocity

v = final velocity

a = acceleration

t = time

g = acceleration due to gravity, 9.81 ms^{-2}

Circular Motion

Forces in circular motion

Note: Put your calculator into radians mode before using circular motion equations!

Remember Newton's First law?

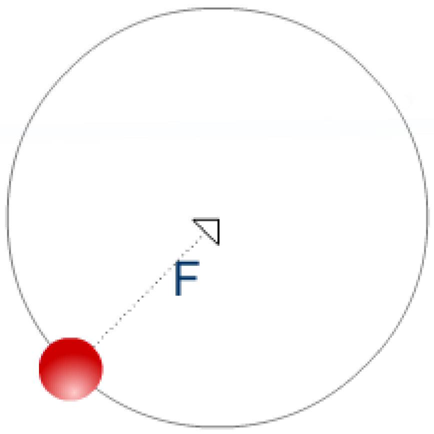
"If an object continues in a straight line at constant velocity, all forces acting on the object are balanced."

Or another way of putting it...

"An object at rest tends to stay at rest and an object in motion tends to stay in motion with the same speed and in the same direction unless acted upon by an unbalanced force."

Objects moving in circular motion clearly aren't going in a straight line so the forces can't be balanced.

There is a resultant force. This is called the **centripetal force.**



The centripetal force is always directed towards the centre of the circle (along the radius of the circle).

Angular acceleration and centripetal force

If an object is moving with constant speed in circular motion, it is not going at constant velocity. That's because velocity is a **vector**. Although its **magnitude** remains the same, its **direction** varies continuously.

This resultant force, the **centripetal force**, causes the **centripetal acceleration**. It is always at 90^{o} to the direction of movement of the object - and that's why the object doesn't speed up!

Centripetal acceleration can be calculated using:

$$a = \frac{v^2}{r}$$

Where:

v = velocity (m/s)

a = centripetal acceleration (m/s^2)

r = radius of the circle (m)

And from Newton's Second Law:

F = ma, so

$$F = \frac{mv^2}{r}$$

This is an equation for **centripetal force.**

Vertical circles

When an object is moving in circles that are vertical, its weight has to be taken into consideration.

Note: If you are using v = ω r in your syllabus, you can substitute this into the equations for centripetal force and acceleration to find values using angular velocity.

Angles in radians

The radius of a circle and its circumference are related by the equation...

Circumference = 2πr

As long as you use angles in radians you can write this general equation:

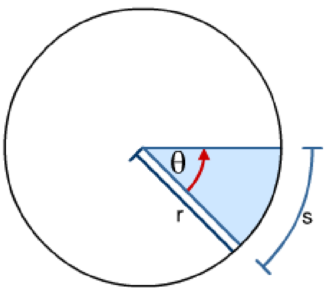
s = rθ

Where:

s = arc length covered

r = radius of circle

θ = angle in radians



θ is measured in radians

Angular speed

In linear or straight-line motion, we measure speed by looking at how much **distance** is covered each second. You can do that in circular motion too, but it's often better to use **angular speed, ω.**

Angular speed measures the angle of a complete circle (measured in radians) you cover per second.

For instance,

$$\omega = \frac{\theta}{t}$$

Where:

θ = angle in radians

t = time taken in seconds.

If you consider that the time taken for a complete rotation is the period, T, then

$$\omega = \frac{2\pi}{T}$$

because 2 is the angle covered (in radians) when you do a complete circle.

Remembering that $T = \frac{1}{f}$ you can also write this as

ω = 2пf

The relationship between angular speed and linear speed

If you are going round in a circle of radius, r, and you are travelling at a linear speed, v ms^{-1}:

The distance covered in 1 rotation = 2пr

The time for one rotation = T, the period.

Linear speed $v = \frac{2\pi r}{t} = 2\pi rf$ So, v = 2&rf and w = 2pf or $2\pi f = \frac{v}{r}$ = w and v = wr

So we can relate angular and linear speed.

Equations

ω = 2пf

$v = r\omega$

Symbols

ω = angular speed, rad s^{-1}

f = frequency, Hz (No. of rotations per second)

T = the period of rotation, s

v = linear speed, ms^{-1}

r = radius of rotation, m

a = centripetal acceleration, ms^{-2}

F = centripetal force, N

Forces

The Basics

Forces are vectors, so we can find a resultant force on an object, no matter how many forces are acting on it. If the resultant force is zero, the forces must be **balanced**.

Balanced forces cause **no acceleration** (This means that the object will remain stationary or carry on moving at a constant velocity.)

If the resultant force is not zero the forces are unbalanced. Unbalanced forces cause **acceleration** in the direction of the resultant force.

Every force has a partner force that is the same size but acts in the opposite direction on another object.

Calculating force

F = ma

Where:

F = force (N)

m = mass (kg)

a = acceleration (m/s^2)

Newton's first law of motion

"Bodies will continue to move with a uniform velocity (which includes being stationary) unless acted on by a resultant force."

Newton's second law of motion

"Resultant force is equal to the rate of change of momentum."

This forms the basis of Newton's equation, F = ma.

Newton's third law of motion

"Every force acting on an object has an equal and opposite force which acts on another object."

Friction

Friction is caused by rubbing. It can be the surfaces between two solids rubbing, a solid surface and a liquid or a gas, etc. Anything! When friction is caused by fluids (liquids or gases) we tend to call it drag or air resistance.

"Friction dissipates energy." That means that energy moves from kinetic energy to heat energy, where it is lost to the surroundings.

Terminal velocity

For a falling object, when the air resistance force up has grown so big that it matches the weight down there is no resultant force and therefore no acceleration. The object will travel at a constant speed. This is called the **terminal velocity**.

It's not just falling objects that have a terminal velocity. You have one when you run! Think about it.

Pressure

Pressure is caused by forces acting on a surface. The greater the force or the smaller the surface area, the greater the pressure produced.

We can calculate pressure using:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

Where:

P = pressure (N/m^2 or Pa, Pascals) - Note: 1 Pa = 1 N/m^2

F = force (N)

A = surface area (m^2)

Transmitting forces

Solids can transmit forces easily. If you push one end of a metal bar the other end will push whatever is near to it in the same direction. Liquids and gases can't do this.

Pressure is useful because it can be used to transmit forces from one place to another using liquids and gases.

Note: Energy can't be created from nowhere, so the small area will have to move down much further than the larger area moves up!

This idea is used in **hydraulic systems** - for example, car brakes. A person puts a small force onto the foot pedal, which creates a large force on the car brakes pads.

Momentum and Impulse

Definition of momentum

Linear momentum, P, is defined as the mass, m, of an object multiplied by its **velocity, v,** so:

P = mv

Units: $kgms^{-1}$ or Ns

(Sometimes momentum is given the symbol M). Momentum is a **vector.**

Principle of the conservation of momentum

The Principle of the Conservation of Momentum states that: if objects collide, the total momentum before the collision is the same as the total momentum after the collision (provided that no external forces - for example, friction - act on the system).

That's amazingly useful because it means that you can tell what is going to happen after a collision before it has taken place.

Principle of Conservation of Energy: Of course, energy is also conserved in any collision, but it isn't always conserved in the form of kinetic energy, so be careful.

So what is its momentum afterwards?

Defining force

Force can be defined as the rate of change of momentum as:

$$F = ma$$

$$\text{But, } a = \frac{v - u}{t}$$

$$\text{So, } F = m\left(\frac{v - u}{t}\right) = \frac{mv - mu}{t} = \frac{\text{change in momentum}}{\text{time}}$$

Perfectly Elastic collisions

(A special case)

- All momentum is conserved (not surprisingly - it always is!)
- Kinetic energy is conserved (that's what makes this special).
- Relative speed of approach = relative speed of separation.

Perfectly Inelastic collisions

(Another special one)

- All momentum is conserved (as always).
- Kinetic energy is not conserved.
- The relative speed of separation is zero.

Inelastic collisions

(The usual old case)

- All momentum is conserved (again).
- Kinetic energy is not conserved (again).
- You can't say anything about the speed at which they leave each other without doing a calculation.

Changing momentum

From Newton's Second Law and the definition of force:

$$F = \frac{mv - mu}{t}$$

(**mv** = final momentum, **mu** = initial momentum)

To achieve any particular **change in momentum,** you can either have a **large force** multiplied by a small time or a **small force** multiplied by a large time.

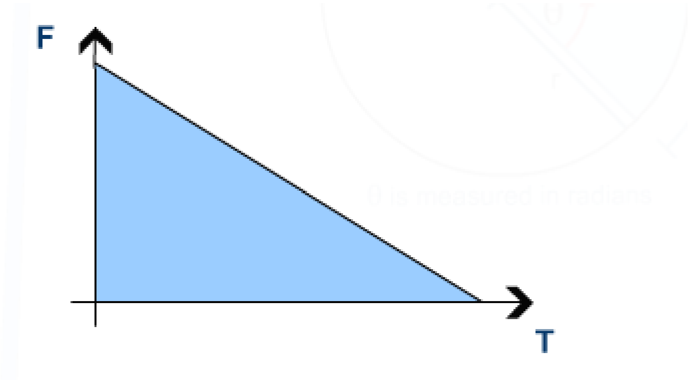
Change in momentum is called impulse,

So, impulse = mv - mu and $F = \dfrac{\text{impulse}}{t}$

hence impulse = Ft

Force-time graphs

We can plot graphs of the force during a collision against time.



We can find the impulse, or change in the momentum, by calculating the area under the force-time graph

Moments, Couples and Equilibrium

Calculating moments

Factors affecting moments

When you push a door closed, it doesn't travel in a straight line - it **turns** around the hinges. This is an example of a **moment (or torque).**

So there are three things that are important:

- The size of the force.
- The direction of the force.
- The distance from the force to the hinge.

Definition of Moments (or Torque)

"A moment is defined as a force multiplied by the perpendicular distance from the line of action of the force to the pivot."

Units: Nm. Symbol, M (or sometimes T)

Principle of Moments

For equilibrium:

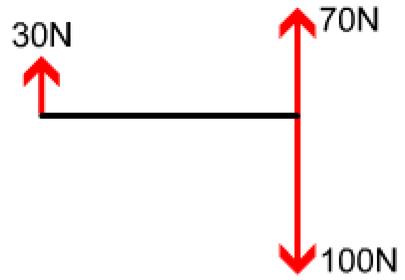
The sum of the clockwise moments about a point = sum of the anticlockwise moments about that point.

Couples

If you have two forces (for instance, a couple of forces) acting on an object and the forces are:

- parallel
- in opposite directions
- of equal size
- not along the same line of action

...you have got a couple.


30N
70N
100N

Equilibrium Conditions

You need to check that two conditions are satisfied before you can say that something is in **equilibrium.**

- The sum of the forces in any direction = 0. If this is satisfied, the object will have no linear acceleration (for instance, it won't accelerate in any direction).
- The sum of the moments about any point (not just the pivot point) = 0. If this is satisfied, there is no angular (or circular) acceleration (for instance, the object won't rotate faster or slower.)

We write these two in short hand as:

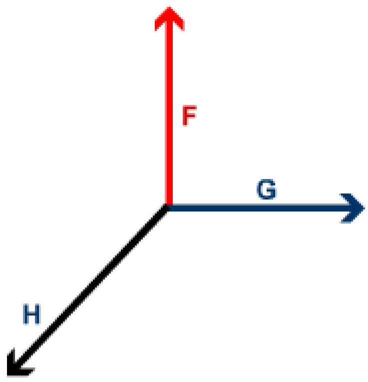
$\Sigma F = 0$

$\Sigma M = 0$

Triangle of Forces

This is a quick way of finding out if the forces acting on an object are in **equilibrium.**

This object experiences three forces.



If it is in equilibrium then drawing accurate vector diagrams of each force one after the other will produce a **closed triangle.**

Centre of Gravity (and Centre of Mass)

Why is it useful?

When doing moment calculations you can say that all the weight of an object acts through the Centre of Gravity.

What's the difference between Centres of Gravity and Mass?

Centre of Gravity = the point where all the weight seems to be concentrated.

Centre of Mass = the point where all the mass seems to be concentrated.

Where can you find the Centre of Gravity?

For **regular shapes** it is the geometrical centre of the object - for example, the centre of a cube or a sphere.

For **irregular shapes**, hang the object from a point on its edge and the Centre of Gravity will end up vertically below the point you are hanging it from.

Work, Energy and Efficiency

Define work

Energy can be quite difficult to understand, but can be thought of as **'the capacity of a body to do work'.**

The Principle of Conservation of Energy

Nothing to do with turning off your stereo when you leave a room. This fundamental piece of science says that you cannot destroy or create energy. (If you find a way - keep it quiet until you have taken out a patent - and you'll be a rich person!)

People often say that you use up energy. That is misleading because it suggests that once it is used you can't get it back. In fact, when you use energy, you are simply converting it into other forms of energy - so it is still out there it is just no longer in the nice, useful form that you had it in a moment before.

Quite often if you can't quite put your finger on where the energy has gone (i.e. what form you have turned it into) you have turned it into heat, which is lost to the surroundings.

Efficiency

A light bulb is designed to turn electrical energy into light energy. But most bulbs produce a lot of heat energy too. That energy has not been lost but it has been wasted -you don't say "It's cold in here. Turn on the light!" do you.

To measure the efficiency of a device, calculate what percentage of the total energy put in, became useful output energy.

The Work Equation

At the heart of energy is the equation:

Work = force x distance moved in the direction of the force

Or

W = F s

The point that causes the most confusion here is that the distance moved is actually a vector because its direction is important.

Kinetic Energy

K.E. = ½ mv^2

Units: J, joules

Kinetic energy stored in an object that is moving equals the amount of work done accelerating it to that speed.

Gravitational Potential Energy

E_p = P.E. = mgh

Units: J, joules

Potential Energy is the energy stored in objects which have been lifted against a gravitational field (or in fact a magnetic or electric field - see later).

Equations and Definitions

W = F s

Work = force x distance moved in the direction of the force

$$E_k = \frac{1}{2} mv^2$$

E_p = mgh

$$\text{Efficiency (\%)} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100$$

U = E_k + E_p

Symbols

W = work done, J

F = force, N

s = displacement, m

t = time, s

v = velocity, ms^{-1}

K.E. or E_k = kinetic energy, J

E_p = potential energy, J

Power and Internal Energy

Power

Work done = mgh

Power is defined as the rate at which you do work.

Units: W, watts. 1 watt = 1 joule per second (= 1 Js^{-1})

The equation is:

Power = Work Done / Time Taken

Another useful equation can be derived from this. **Notice that:**

Work done, W = force x displacement =Fs

So power = $\frac{Fs}{t}$ or $F\ \frac{s}{t}$

And $\frac{s}{t}\ v$

So **P =Fv**

So **Power = Force x velocity**; remembering that the force and velocity must be in the same direction.

Internal energy

If you look at the atoms that make up everything or anything, they are moving around (more at higher temperatures) and feeling forces acting on them due to their neighbours (attraction and repulsion).

This means that the atoms themselves have got kinetic energy (K.E.) and potential energy (P.E.). This is known as the atoms **internal energy.**

You need to know that the **internal energy, U**, of a substance is made up of two components.

U = K.E. + P.E. = $E_k + E_p$

Equations and Definitions

W = F s

Work = force x distance moved in the direction of the force

$$\text{Power} = \frac{\text{work}}{\text{time}} = \text{force x velocity}$$

Power is the rate at which you do work.

$$E_k = \frac{1}{2} mv^2$$

E_p = mgh

$$\text{Efficiency (\%)} = \frac{\text{useful energy output}}{\text{total energy input}} \text{ x } 100$$

U = E_k + E_p

Symbols

W = work done, J

F = force, N

s = displacement, m

t = time, s

v = velocity, ms^{-1}

K.E. or E_k = kinetic energy, J

E_p = potential energy, J

u = internal energy, J

Current, Charge and Voltage

Charge

Charge is a property of certain particles. A particle with charge will experience a force in an electric field (or in a magnetic field if the charge is moving).

Charge is either positive or negative. Objects with a similar charge will repel. Objects with opposite charges will attract.

Charge is measured in coulombs, C. The amount of charge on an object can be found using a coulomb meter.

An electron always has a negative charge of -1.6×10^{-19} coulombs. Protons have an equal amount of positive charge. One coulomb is equal to the charge on 6.25×10^{18} electrons, which is a serious number of electrons.

The Conservation of Charge

It is not possible to destroy or create charge.

You can cancel out the effect of a charge on a body by adding an equal and opposite charge to it, but you can't destroy the charge itself. That's the **Principle of the Conservation of Charge.**

Static Electricity

Static electricity is caused by the transfer of electrons from one object to another. Normally neutral atoms can lose or gain electrons to become either positively or negatively charged. These charged atoms are called **ions.**

Static electricity is **never** caused by the movement of protons.

The easiest way to charge an object with static electricity is by using friction. The Van de Graaff generator uses friction to charge up a metal dome.

Current Electricity

Current electricity is about moving charged particles. If you allow the charge that builds up in static electricity to flow, you get a current.

Current is the rate of flow of charge; it is the amount of charge flowing per second through a conductor.

The equation for calculating current is:

$$I = \frac{Q}{t}$$

Where:

I = current (amperes, A)

Q = charge flowing past a point in the circuit (coulombs, C)

t = time taken for the charge to flow (seconds, s)

How can you get the Charge to Flow?

Well, first you need to have a conductor for it to flow through and then you need to attract or repel the charged particles to make them move. The amount of attracting or repelling you do is measured in volts and is called the voltage or the potential difference (p.d. for short).

Work is being done on these charged particles to make them move, so the voltage is a measure of the amount of energy that is provided per coulomb of charge.

1 volt = 1 joule per coulomb.

The equation for calculating voltage is:

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

Where:

V = voltage (volt, V)

W = amount of energy (joule, J)

Q = charge (coulomb, C)

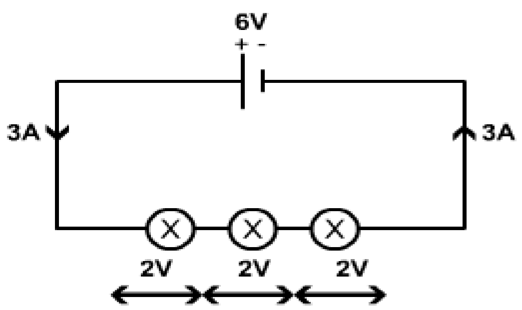
Circuit Rules

As the charged particles flow around a circuit they **don't get used up**; it is the energy that the charged particles carry that decreases as they move around the circuit.

Voltage changes as the charge moves around the circuit.

There are two main types of circuits you need to know about and each has two rules that make calculations simpler:

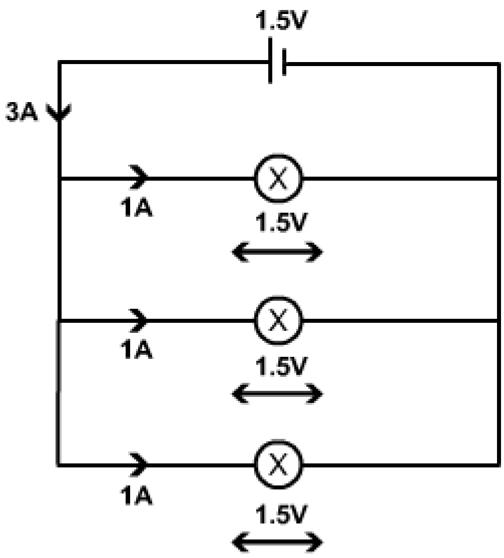
Series circuits:



In a series circuit...

- the current is the same all the way around the circuit.
- the voltage is divided between the components in the circuit.

Parallel circuits:



In a parallel circuit...

- the current divides to travel along each loop.
- the voltage is the same across each loop.

Conventional Current

Originally scientists believed that it was positively charged particles that flowed in circuits and so circuits are always labelled with the current flowing from the positive to the negative terminal of a cell in a circuit. We call this current the **conventional current.** The electrons are actually flowing in the opposite direction!

Conventional current is the flow of positive particles. All references to current in diagrams and questions at A-level refer to conventional current, unless it's specifically stated otherwise in the question.

Measuring Current and Voltage:

To measure current we use an **ammeter.** It is placed in series in a circuit to measure the amount of charge flowing through it per second. (You can compare it to a turnstile counting people into a stadium.)

To measure voltage we use a **voltmeter.** It is placed in parallel to compare the potential at two different points, either side of a component. It can then measure the potential difference or voltage across the component.

Drift Velocity

You will now already know that current is a measure of the amount of charge moving per second. **This means that current is dependent on:**

- the speed at which charged particles are moving.
- the charge they are carrying.
- the number of charged particles that are moving.

Charged particles do not travel in a straight line through a conductor, because they collide with other particles in the material. We therefore use the average speed the particle travels at **along** the conductor. This is called the **drift velocity.**

Current can be calculated using the equation:

$I = vAnq$

Where:

I = current (amperes, A)

v = drift velocity (m/s)

A = cross-sectional area of the conductor (m^2)

n = charge density (m^{-3}) This is the number of charge carriers that can move per m^3

q = charge on each charge carrier (coulombs, C)

Comparing Materials

Different materials will have different values of n, the number of charge carriers per m^3.

Good conductors such as metals have the most charge carriers. Semiconductors have about 1×10^{10} times fewer charge carriers than metals. At low voltages insulators have no free electrons so that a current is unable to flow.

Conductors and Insulators

Metals are good **conductors** (poor insulators). Electrons in the outer layers of metal atoms are **free to move** from atom to atom. So if one end of a piece of metal is made positive, the electrons will be attracted towards it and because they are free, they can move towards it.

Static charge only builds up on **insulators.** These are materials that will not allow the flow of charged particles (nearly always electrons) through them. Insulators are materials made from atoms that **hold onto their electrons** very strongly. The voltage across an insulator has to be extremely high before an electron is given enough energy to free itself and move through the material.

Semi-Conductors

Semi-conductors have far fewer free electrons than metals so do not conduct as well. However, if they are given energy electrons are able to free themselves from their atom and flow, which greatly reduces the resistance of the material. Some semi-conductors are light sensitive, as the light energy is able to free the electrons. There are about 5 naturally occurring semi-conductors.

Solids, Liquids and Gases

Although in circuits we deal with electrons carrying charge, in liquids and gases other particles are also able to carry charge, such as ions in the process of electrolysis.

Equations

Current, charge and voltage

$Q = It$

$W = QV$

Symbols

Current, charge and voltage

Q = charge, C

I = current, A

t = time, s

W = work, J

V = potential difference, V

Resistance

Resistance, Ohm's Law and Conductance

The more resistance there is the more energy that is needed to push the same number of electrons through part of the circuit.

Resistance is measured in **ohms, Ω,** and the resistance of a component can be found using an **ohmmeter.**

Resistance can be calculated using the equation:

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

Where:

R = resistance (ohms, Ω)

V = potential difference (volts, V)

I = current (amps, A)

For certain components, such as metal resistors at a constant temperature, the resistance, R, doesn't change. These components obey **Ohm's Law.**

Ohm's Law states that the current through a metallic conductor is proportional to the potential difference across it if the temperature remains constant.

Any resistor that obeys Ohm's Law is called an **ohmic resistor**. Any resistor that doesn't do this is cleverly called a**non-ohmic resistor**.

Conductance

Conductance, G, is the opposite of resistance, and tells us how easy it is for a current to flow through something. Conductance is measured in siemens, S.

1 S = 1 ohm^{-1}

Conductance can be calculated using the equation:

or

Where:

G = conductance (siemens, S)

I = current (amps, A)

V = potential difference (volts, V)

R = resistance (ohms, Ω)

Voltage-Current Graph for a Metal Conductor

When metals are heated it causes the atoms in the metal to vibrate more.

Imagine an electron in a current travelling through heated copper. It's trying to flow through the metal but the atoms are vibrating more, so they are going to get in the way more, causing more collisions. More collisions gives more resistance. We say the atoms have a larger **collision cross section.**

So increasing temperature of a wire leads to increasing resistance (and of course a decrease in conductance).

That means that the higher the current passing through a wire the greater its resistance will become. So most resistors don't obey Ohm's Law unless the temperature is kept constant.

Current-Voltage Graph for a Diode

Diodes behave like ohmic resistors when the current is travelling through them in the correct direction. However, if the current is reversed the resistance of the diode is extremely high.

Thermistors and Light-dependent Resistors

Some devices, made from semiconductors, break the rule we've just explained (typical) and reduce their resistance as temperature increases. This is because the extra energy makes the atoms release electrons, allowing them to move more easily, this in turn reduces the resistance.

These devices are called **thermistors.** These are often used in temperature controls.

Light-dependent resistors conduct better when light falls on them and releases more electrons.

Combinations of Resistors

If you have more than one resistor in a circuit it is often useful to be able to calculate the total resistance of the combination.

In series: $R_T = R_1 + R_2 + R_3$

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

Resistivity

What factors affect the resistance of a material?

1. **Length** - the further electrons have to travel through material, the more collisions they will have so the higher the value of resistance.
2. **Area** - a bigger area means that in any 1 second more electrons will be able to travel through a piece of wire. More electrons means more current which means less resistance.
3. **Material** - if you swapped all the copper wire in a circuit for wood you'd notice a lot less current and a lot more resistance in the circuit. The ability of a material to conduct is called its resistivity, p. Resistivity is measured in ohm-metres (Ωm).
4. **Temperature** - but we've covered that in '**current-voltage graphs**'.

Therefore $R = \frac{\rho . l}{A}$ and so resistivity, $\rho = \frac{R . A}{l}$ ohm.metre (Ωm)

Conductivity

As conductance is the reverse of resistance, so conductivity is the reverse of resistivity.

So conductivity, $S = \frac{1}{p} = \frac{l}{RA}$

Conductivity is measured in Sm^{-1}

EMF and Potential Difference

In any circuit there are components that put energy in to the circuit and components that take energy **out**. From now on, we will say that any device putting energy into a circuit is providing an **electo-motive force (emf)** and any device taking it out has a **potential difference (pd)** across it.

Both emf and pd are measured in **volts, V,** as they describe how much energy is put in or taken out **per coulomb** of charge passing through that section of the circuit.

The best way to think of them is:

Emf - is the amount of energy of any form that is changed into electrical energy per coulomb of charge.

pd - is the amount of electrical energy that is changed into other forms of energy per coulomb of charge.

Internal Resistance

Where is the heat energy coming from?

It's from the current moving through the inside of the cell. The resistance inside the cell turns some of the electrical energy it produced to heat energy as the electrons move through it.

Therefore, inside the cell, energy is put into the circuit by the cell **(the emf)** but some of this energy is changed into heat by the internal resistor **(a pd).**

So the pd available to the rest of the circuit (the external circuit, as some questions may refer to it) is the emf voltage minus the pd lost inside the cell:

V = E - Ir

Where:

V = pd across the external circuit (V)

E = emf of the cell (V)

I = current through the cell (A)

r = value of the internal resistance

(Ir = the p.d. across the internal resistor)

Note: V is sometimes called the terminal pd as it is the pd across the terminals of the cell

High and Low Voltage Power Supplies

Power supplies delivering low voltages and higher currents, like a car battery, need to have a low internal resistance, as shown above. High-voltage power supplies that produce thousands of volts must have an extremely high internal resistance to limit the current that would flow if there was an accidental short-circuit.

Finding Internal Resistance Experimentally

As V = E - Ir, if you plot a graph of terminal pd, V, against current, I, the gradient of the graph will be equal to the internal resistance of the cell.

If there is more than one cell in series the internal resistances of the cells must be added.

Equations

Resistance

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

$$R = \frac{\rho l}{A}$$

Emf, E = I (R + r) - for the internal resistance, r, of a cell.

Symbols

Resistance

R = resistance, Ω

V = potential difference, V

I = current, A

ρ = resistivity, Ωm

l = length, m

A = area, m^2

r = internal resistance of a power source, Ω

Kirchoff's Laws and Potential Dividers

Kirchoff's First Law

At any junction in a circuit, the sum of the currents arriving at the junction = the sum of the currents leaving the junction.

In other words - charge is conserved. If this doesn't happen you'd either get a massive build-up of electrons at a junction in a circuit or you would be creating charge from nowhere! That's not going to happen.

Kirchoff's Second Law

Here is the second principle:

In any loop (path) around a circuit, the sum of the emfs = the sum of the pds.

In other words - energy is conserved. The total amount of energy put in (sum of the emfs) is the same as the total amount of energy taken out (sum of the pds).

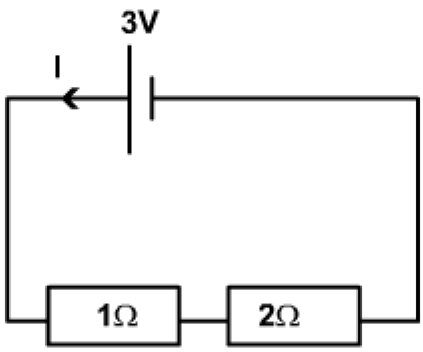
Note: pd = V = IR so Σpd = ΣIR

Potential

As charge flows around a circuit it uses up its energy (its **electrical potential energy**) and turns it into other forms, such as heat and light.

Fortunately for us, electrons use **more** energy going through **larger** resistances and **less** energy going through **smaller** resistances. This means the larger the resistor, the greater the voltage needed across it for the same current to flow through it. In maths language, **the ratio of resistances gives you the ratio of voltages.**

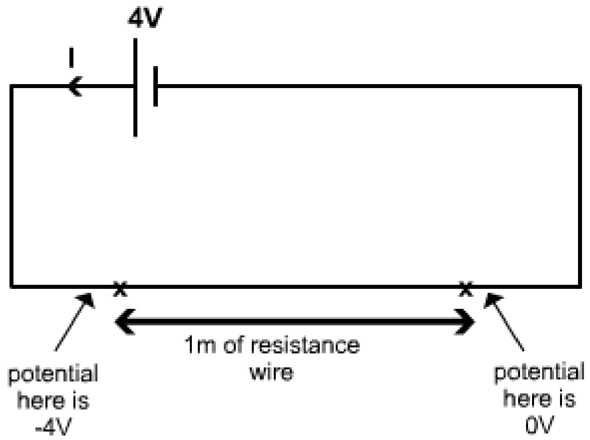
Let me show you with a simple example:



Imagine the current leaves the cell with 3V. The current will use 1V ($1JC^{-1}$) in going through the 1Ω resistor and $2JC^{-1}$ in getting through the 2Ω resistor.

Potential Dividers

In this circuit you have a long piece of resistance wire.



As the charge passes through the wire it uses up its potential. Note this simple connection:-

Halfway through the wire it has used **half** the potential

1/4 of the way through the wire it's used a **1/4** of the potential.

1/8 of the way through the wire it's used an **1/8** of the potential.

You can write this as a ratio:

$$\frac{\text{length current has passed through}}{\text{total length}} = \frac{\text{amount of potential used}}{\text{total potential}}$$

Using Potential Dividers to find EMFs

Potential dividers can be used to find the emf of a cell.

Remember:

$$\frac{\text{length current has passed through}}{\text{total length}} = \frac{\text{pd}}{\text{total pd}} = \frac{\text{resistance passed}}{\text{total resistance}}$$

This ratio can be used to measure all sorts of resistances, potential differences and emfs.

Power and Energy

As electricity is all about energy, there are a few energy and power equations that you need to be able to derive and use...

Work Done (or Energy) and Power Equations

The definition of voltage tells us that $V = \frac{W}{Q}$

So, W = VQ

The definition of current tells us that, Q = It

So, W = V I t (Learn this!)

Of course, we already know that:

$$\text{Power} = \frac{\text{work}}{\text{time}} = \frac{VIt}{t}$$

So, Power = V I (Learn this!)

Power and Resistance Equations

From Ohm's law we know that V = IR. If this equation is substituted into the equation P = IV we can get two new equations:

Power = I^2R

or

$$\text{Power} = \frac{V^2}{R}$$

Learn these!

The kWhr

Electrical energy is measured in units of the kWhr so that people can be charged for the amount that they use. At the moment, 1 kWhr of energy costs about 7p.

energy = power x time

kWhr = kW x hr

Alternating Currents

Alternating Currents

Cells produce currents that travel in the same direction all of the time, **direct currents.** However, this is not always useful - for instance, transformers will only work if the current is constantly changing.

An alternating current is constantly changing direction. It is normally sinusoidal.

The **frequency** of an alternating current supply, f, is the number of cycles completed per second. Measured in Hertz (Hz).

The period, T, of an alternating supply is the time taken to complete one cycle.

The peak values of current, I_o, and voltage, V_o, are the maximum values at the crest or trough. They are equivalent to the amplitude of a wave. Sometimes we quote the peak-to-peak value, which is of course, double the peak value.

RMS Values

RMS values are the d.c. equivalent of an a.c. value. In other words, if you had two circuits, one d.c. and one a.c., and you wanted them to use exactly the same amount of power (energy each second) then you would choose the d.c. values of current and voltage to be the same as the rms values of current and voltage in the a.c. circuit.

Equations

Alternating currents

$$V_{rms} = \frac{V_0}{\sqrt{2}}$$

$$I_{rms} = \frac{I_0}{\sqrt{2}}$$

$$\text{Peak Power} = V_o I_o$$
$$\text{Average Power} = 1/2\ V_o I_o = V_{rms} I_{rms}$$

$$I = I_0 \sin \omega t$$
$$V = V_0 \sin \omega t$$

where

$$\omega = 2\pi f \quad \text{or} \quad \frac{2\pi}{T}$$

(CALS. IN RAD MODE)

Symbols

Alternating currents

V_o = peak voltage, V

I_o = peak current, A

V_{rms} = rms voltage, V

I_{rms} = rms current, A

ω = angular frequency, Hz

t = time, s

T = period, s (time for one cycle of the pd or current.)

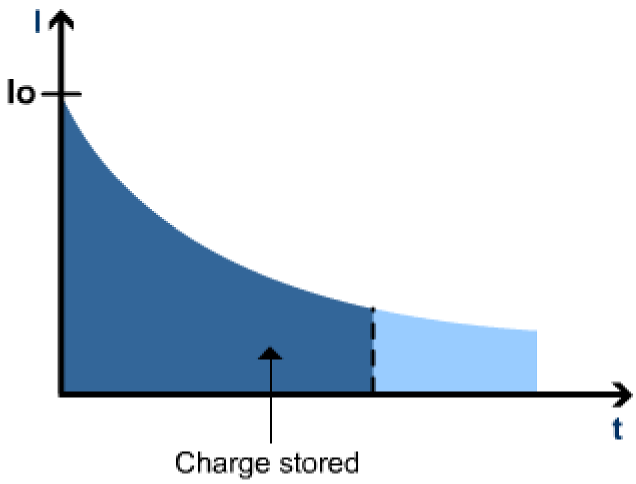
Capacitors

How Capacitors Work

The simplest capacitors **are big plates of metal close to each other but not touching.** When connected to a potential difference (e.g. a battery), the battery tries to push electrons through the wire away from its negative terminal. Although there isn't a **complete circuit**, you can imagine that you can shove a few extra electrons onto a big sheet of metal. Let's face it, given the choice between being stuck at a negative terminal or going to a neutral metal plate, electrons will get up and move! So you get a flow of electrons to the plate i.e. you get a current without a complete circuit, but only for a short period of time.

Charging Capacitors

What happens to current as time passes?



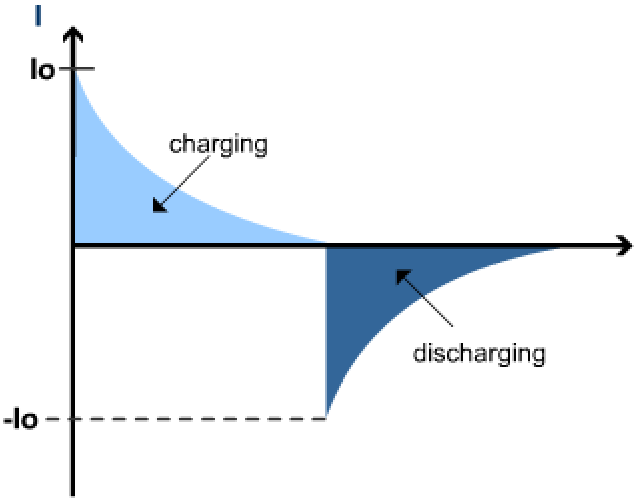
As explained above, current falls away as it becomes less attractive for electrons to move to the plate from the cell.

Note: The area under the current-time graph is equal to the amount of charge stored on the plates.

Charge builds up - quickly at first (a lot of electrons arriving each second) and then more slowly. We have already said that **potential difference is proportional to charge**, so the p.d.-time graph is exactly the same shape as the charge-time graph.

When the capacitor is fully charged, the pd across the plates will equal the emf of the cell charging it.

Discharging Capacitors



Initially there is a large current due to the large potential difference across the plates. The current drops as pd drops.

Time Constant

Capacitors discharge exponentially. That means that their charge falls away in a similar way to radioactive material decay. In radioactivity you have a half-life, in capacitance you have a **"time constant".**

The rate of removal of charge is proportional to the amount of charge remaining.

Time constant T = RC

(R = Resistance mΩ, C = Capacitance mF)

The charge left on a capacitor and its discharge current both drop to half their initial values in 0.69 x RC seconds.

Energy Stored in a Capacitor

The potential difference across the plates of a capacitor is directly proportional to the charge stored on the plates. This gives a straight line through the origin on a voltage-charge graph. The area under this graph gives the energy stored in a capacitor.

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

Capacitors in Series

In series, capacitors will **each have the same amount of charge stored on them** because the charge from the first one travels to the second one, and so on.

The total charge stored is the charge that was moved from the cell, which equals the charge that arrived at the first capacitor, which equals the charge that arrived at the second, etc...

The voltage of the circuit is spread out amongst the capacitors (so that each one only gets a portion of the total).

Total capacitance C_T is calculated using...

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Capacitors in Parallel

Two small capacitors in parallel can be thought of as being the same as one big capacitor.

There is just as much '**plate**' on the left hand side for the charge to flow into in both of these diagrams.

So adding capacitors in parallel will increase the space available to store charge and will therefore increase the capacitance of the combination.

Total capacitance C_T is calculated using

$C_T = C_1 + C_2 + C_3$

Equations

$$Q = CV$$

$$Q = Q_o e^{-\left(\frac{t}{RC}\right)}$$

$$w = 1/2\ QV$$

$$w = 1/2\ CV^2$$

$$W = \frac{Q^2}{2C}$$

Symbols

C = capacitance, F

V = voltage, V

Q = charge, C

Q_o = initial charge (at time t = 0), C

t = time, s

R = resistance in circuit connected to the capacitor

W = energy stored in a capacitor, J

τ or RC = the time constant

C_T = capacitance of the combination, F

C_1= capacitance of capacitor 1, F

C_2 = capacitance of capacitor 2, F

Magnetic Fields

Magnetic Fields

A **magnetic field** is a region in which a particle with magnetic properties experiences a force, and in which a moving charge experiences a force.

There are two main classes of magnet:

1. Permanent magnets
2. Electromagnets

Field Shapes

Permanent Magnets:

Permanent magnets are common and are made of iron, cobalt or nickel alloys.

Magnetic fields can be represented by field lines; these lines are called **lines of flux.** These travel from North to South, i.e. in the direction an imaginary North pole would travel.

The region in between the poles shows equally spaced, parallel lines. This is called a **uniform field.** Field strength remains constant as you move around this area. Move out from the space between the poles and the field strength reduces. The lines of flux become further apart.

You should be able to draw the shape of the magnetic field due to:

a bar magnet

a single wire

two wires near to each other

a single loop of wire

a solenoid.

Temporary Magnets:

Around **any conductor that has a current flowing through it** there is a magnetic field. Switch off the current and the magnetic field disappears.

Remember: Conventional current is the flow of positive charges. So conventional current goes in the opposite direction to the electron flow.

Right Hand Grip Rule

A quick way to work out the direction of the magnetic field in a solenoid is the **right hand grip rule...**

Make a fist and stick your thumb out (as if hitchhiking). Your fingers are wrapped in a circle, same as the coils in the solenoid. If you make your fingers point in the same direction as the **conventional** current around the coil - your thumb points towards the end of the solenoid that is the North pole.

Neutral Points:

When two fields coincide they may cancel each other out and produce points where the magnetic field strength is zero. These points are called **neutral points.**

Magnetic field strength, B

Magnetic field strength is often called **magnetic flux density** and is given the symbol **'B'** (obviously!?!).

Magnetic field strength is defined as the force acting per unit current in a wire of unit length, which is perpendicular to the field.

Magnetic field strength is measured in **tesla, T.**

A magnetic field has a strength of 1T if a wire of length 1 metre experiences a force of 1N when a current of 1A flows in the wire.

Ferrous Cores

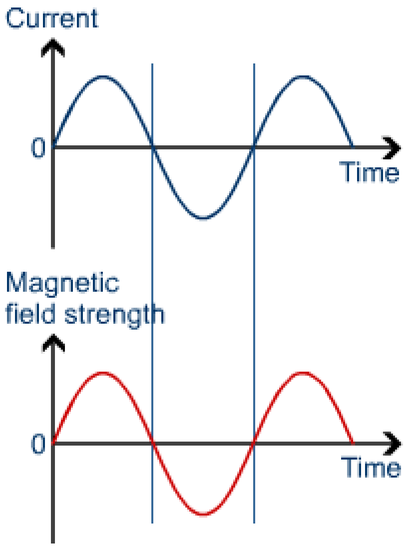
Placing a ferrous core (i.e. iron or steel) in the solenoid will increase the magnetic field strength. (Iron more so than steel, although steel will stay magnetic when the coil is removed.) A magnet created by a current is an electromagnet and has the advantage of having a controllable field strength which will not reduce with time.

Relationship between Current and Magnetic Field

The strength of a magnetic field is directly proportional to the current flowing.

$B \propto I$

Therefore, if an alternating current is flowing, a magnetic field around the conductor will be produced, that is in phase with the alternating current.



Calculating Fields near Wires and Solenoids

You will already know that the magnetic field near a current gets weaker as you move further away from the current.

The magnetic field strength is inversely proportional to distance:

$B \propto \frac{1}{r}$

The magnetic field strength is proportional to current:

$B \propto I$

Combining these relationships gives:

$B \propto \frac{1}{r}$ so B = 'a constant' x $\frac{I}{r}$

where the constant depends on the shape of the conductor.

Measuring Magnetic Field Strength

The strength of a magnetic field can be found using a device called the **Hall probe.** It works on a principle based on the Hall effect.

Forces in Magnetic Fields

Force on Parallel Wires

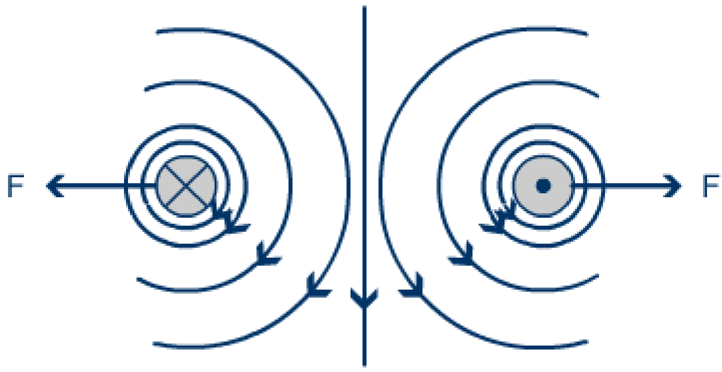
In two parallel wires carrying current:

-like currents attract

-unlike currents repel.

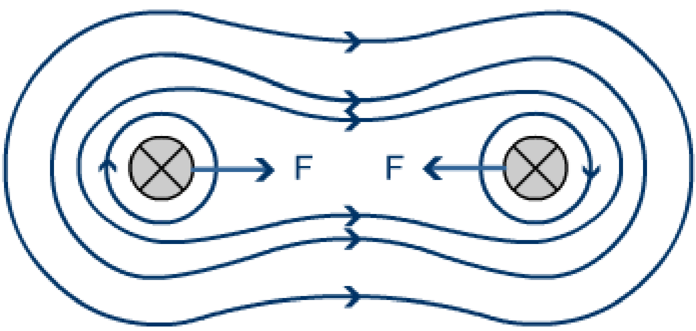
Learn the shapes of the fields.

Current flowing in opposite directions:



Strong field between wires forces them outwards

Currents flowing in the same direction:



Weak field between wires forces them inwards

The Motor Effect

When two magnets are close together, they affect each other and produce a force. The same happens when any two magnetic fields are close together.

If a wire carrying a current is placed in a magnetic field a force is produced. This is called the **motor effect.**

The direction of the force will depend on the direction of the magnetic field and the direction of the current in the field.

To make the force bigger:

1. Increase the size of the current.
2. Increase the strength of the permanent magnet.

Fleming's Left Hand Rule

Use Fleming's Left Hand Rule to get the direction of the force.

Se*c*ond finger - *c*onventional current

*F*irst finger - *f*ield direction

*T*humb - *t*hrust or force direction.

This can also be used to find the direction of force on a single charge travelling in a field.

Forces on Charged Particles

When a wire carrying a current through a field feels a force it is because the magnetic field pushes the electrons inside the wire to one edge of the wire. These electrons actually then apply force to the wire.

The same effect occurs if the electrons are not inside a piece of wire - for example, if they are in a beam crossing a vacuum.

We can calculate the force on a charged particle in a magnetic field using the equation:

$$\mathbf{F = Bq\ v\ \sin\theta}$$

Where:

F = force (N)

B = magnetic field strength (T)

θ = charge on the particle (C)

v = velocity of the particle (m/s)

Note: θ is the angle between the direction of the beam and the magnetic field direction.

Use Fleming's left hand rule to work out the direction of the force. Align your second finger with the beam of particles remembering that it points the way positive particles flow, the opposite way to electron flow.

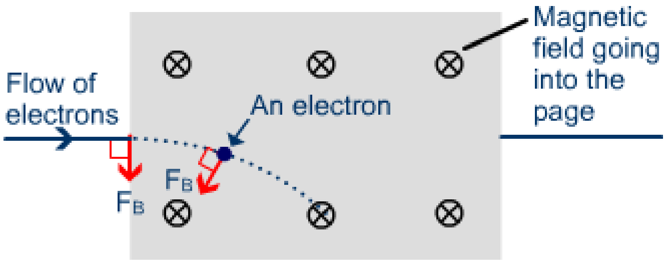
Finding the Charge-to-Mass Ratio of a Particle

When a charged particle enters a magnetic field we now know it will be forced to change direction. If it stays in the field it will continue to change direction and will move in a circle. The force produced will provide the centripetal force on the moving particle.

This idea is used in velocity-selectors, where particles of different mass-to-charge ratio will rotate in circles with a different radius.

The Hall Effect

The force acting on charged particles moving through a conductor in a magnetic field can become balanced by an equal but opposite force due to the build-up of charge on the edges of the conductor.



This results in a p.d. across the width of the conductor which is proportional to the strength of the magnetic field around the conductor. This is the **Hall Effect**. It can be used to measure the strength of a magnetic field because the size of the pd set up is directly proportional to the magnetic field strength.

Symbols

Magnetic Field Strength		Force on a Beam of Charged Particles	
F=	force, N	F=	force, N
B=	magnetic field strength or magnetic flux density, T	B=	magnetic field strength or magnetic flux density, T
I=	current, A	θ=	the angle between the magnetic field and the current.
l=	length, m	Q=	the charge on the particle, C
θ=	the angle between the magnetic field and the current.	v=	the speed of the charged particle, ms^{-1}

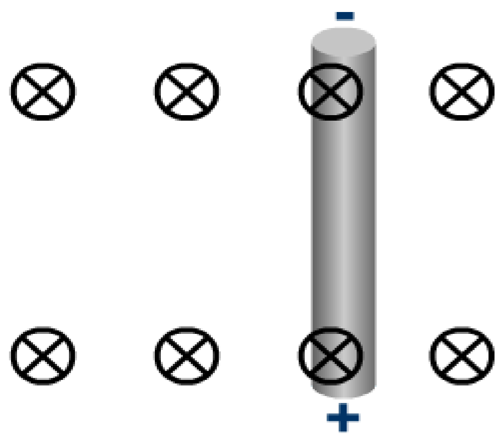
Electromagnetic Induction

Inducing EMFs

Method 1:

Pick up a metal rod and swing it about in a magnetic field - for example, the Earth's magnetic field. Although you won't realise it, you have just induced an emf across the ends of the rod.

A simple version would be this:



Note: The rod is not part of any circuit

As you swipe the metal bar to the left (as shown above) you sweep through the area of field shown by the crosses.

It's this movement through a field that induces (produces) an emf across the bar ends.

Factors Affecting the Amount of Induced EMF

Any of the following would mean that you induced more emf:

- A **longer** bar would **'sweep'** out more area of field.

- A **stronger** field would mean you swept through more field lines when moving the same distance.

- A **faster** swipe would mean you swept out more area of the field per second.

So the induced emf depends on the length of the conductor, the strength of the magnetic field and the speed at which the conductor cuts the field.

Magnetic Flux

The magnetic field strength, B, multiplied by the area swept out by a conductor, A, is called the magnetic flux, Φ.

$\Phi = BA$

Units of flux: weber, Wb.

Magnetic Flux Linkage, F

This is the magnetic flux for a coil. It is also measured in weber and has the symbol Φ. The difference is that a coil has more wire in the field, so for a coil, the equation becomes

'n' x the Magnetic Flux

where 'n' is the number of turns in the coil.

Faraday's Law

For a conductor in a changing magnetic field, the factors affecting the size of the induced emf are:

- How quickly the magnetic field is changing;

- The number of turns or loops of the conductor in the field.

This leads to **Faraday's Law,** which is that:

The emf induced is equal to the rate of change of magnetic flux linkage or the rate of flux cutting.

$$E = N\frac{\Delta BA}{t} = N\frac{\Delta \varphi}{\Delta t} = \frac{\Delta \Phi}{\Delta t}$$

Do you induce a Current or do you induce an EMF?

If you move a conductor through a magnetic field, you always induce an emf!

If there is a **circuit** available, the emf will push a current through it.

If there is **no circuit** you will still get an emf, but you won't get a current.

Symbols

Φ = magnetic flux, Wb

B = magnetic field strength, T

A = area of the field swept out or area of the coil, m^2

n = number of turns in a coil

E = induced e.m.f.

t = time, s

Δ = change in...

Lenz's Law

Lenz's Law

This is a 'stroppy' law. Basically, it rebels against everything!

Lenz's Law can be described as:

The emf is induced in a direction which opposes whatever causes the induction.

Energy Considerations - Where does all the E_k go?

If you roll a metal bar into a magnetic field it will slow and stop due to the force opposing its motion (the force that Lenz says will be set up).

Where does all the kinetic energy of the bar go?

Well in fact, the E_k is transformed into electrical energy.

So this is the source of the emf, transferred from other energy into electrical energy.

Transformers and Rectification

Transformers

The great thing about a.c. electricity is that you can transform it! For instance, you can step its voltage up or down.

Transformers work on the principles of **electromagnetism and electromagnetic induction.**

The iron core increases the flux density (or field strength) in the secondary coils. The larger the number of coils, the greater the flux linkage and therefore the greater the induced e.m.f. in the secondary coil.

You must have an alternating current in the primary coil or the field will not be changing and no emf will be induced in the secondary.

The Turns Rule

If you change the number of turns in the coils you change the induced emf. This allows you to change (transform) the voltage from the primary to the secondary coil.

The Turns Rule is:

$$\frac{N_s}{N_p} = \frac{V_s}{V_p}$$

Where:

N_s = number of turns on the secondary coil

N_p = number of turns on the primary coil

V_s = voltage across the secondary coil

V_p = voltage across the primary coil

Rectifying A.C.

You should be able to draw circuits and outputs for half wave and full wave rectification circuits.

Placing a capacitor in parallel with the resistor smoothes the current through the resistor by providing extra charge when the supply voltage drops.

Equations

Transformers

The turns rule:

$$\frac{N_s}{N_p} = \frac{V_s}{V_p} = \frac{I_p}{I_s}$$

Symbols

Transformers

N_s = the number of turns in the secondary coil

N_p = the number of turns in the primary coil

V_s = the voltage in the secondary coil

V_p = the voltage in the primary coil

I_s = the current in the secondary coil

I_p = the current in the primary coil

Simple Harmonic Motion and Damping

Basic Oscillations

The time taken for an oscillating object to complete one full oscillation is called the **time period, T.** It is measured in seconds.

If a number of oscillations are involved we can work out the time period by dividing the total time taken by the number of oscillations completed:

$$T = \frac{\text{Time in seconds}}{\text{No. of oscillations}}$$

The **frequency, f,** of oscillations is the number of oscillations undergone in one second, and is measured in **hertz (Hz).**

The frequency and the period can therefore be related as:

$$f = \frac{1}{t}$$

The **displacement** of an oscillating particle is the distance the particle has been moved from its equilibrium position.

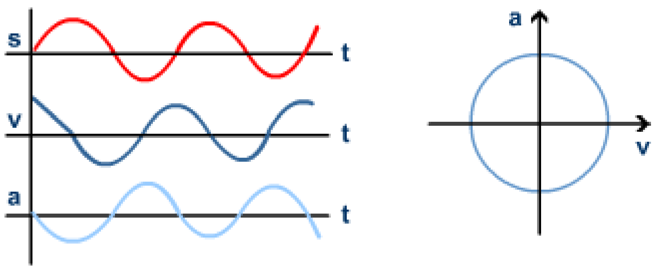
The **amplitude** of an oscillation is the maximum displacement of the vibrating object from the equilibrium position (its usual position).

Simple Harmonic Motion

Simple Harmonic Motion is a vibration whose time period stays the same even when its amplitude changes.

Simple harmonic motion occurs when the **displacement of the oscillator is proportional to the acceleration but in the opposite direction** or

$s \propto -a$



Finding Acceleration

The definition for simple harmonic motion tells us that:

$a \propto -s$

We can get rid of the proportionality sign by putting in a constant. **In this case, the constant is $(2\pi f)^2$, so:**

$a = -(2\pi f)^2 s$

Finding Displacement and Velocity

As shm oscillations follow a sine or cosine wave, we can find the displacement at any point using:

$$s = A\cos(2\pi f t) \text{ or } s = A\sin(2\pi f t)$$

Note: use cosine if your time starts when you are max displacement and sine if it starts when you are at the centre of the oscillation.

Where:

A = amplitude - not acceleration!

Velocity can be found using:

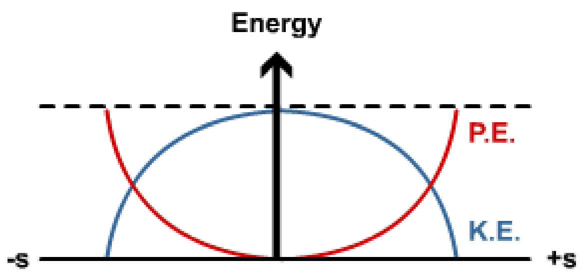
$$v = \pm\, 2\pi f\sqrt{A^2 - s^2}$$

So,

$$v_{max} = \pm\, 2\pi f A$$

Kinetic and Potential Energy

The total energy in S.H.M. is constant when no energy is lost to the environment. Energy changes from kinetic to potential.



Energy and Amplitude

The amplitude of a wave gives an indication of the amount of energy the oscillator has. This makes sense if you think of the spring and mass. The greater the amplitude the larger the amount of energy stored in the spring when it is extended. However,

PE = 1/2 ks^2 so energy must be proportional to the amplitude^2.

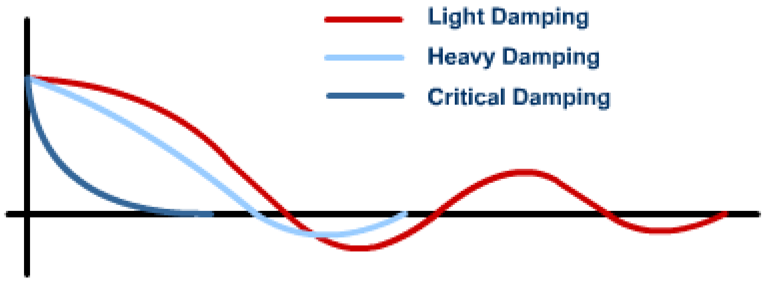
Damping

If energy is being removed from the system the oscillations are damped and the amplitude will decrease with time.

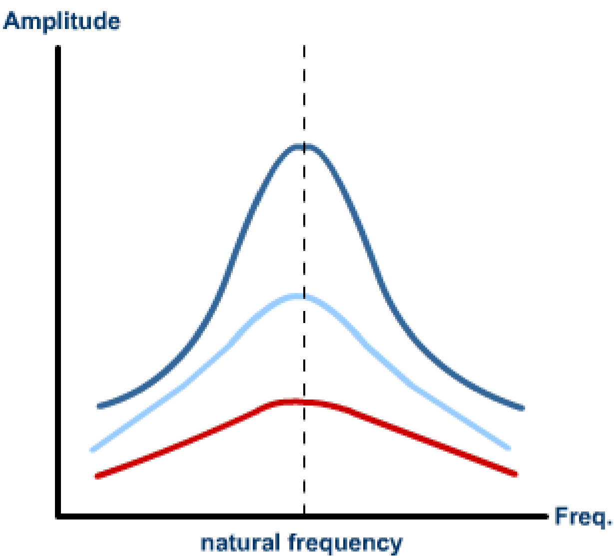
The greater the damping the quicker the vibrations will diminish.

Critical damping occurs when the displacement returns to zero in the quickest time, without going past the equilibrium position.

Free vibrations:



Forced vibrations:



Natural Frequency

Hit anything and it will vibrate. The amazing thing is that every time you hit it, **it will vibrate with exactly the same frequency**, no matter how hard you hit it.

The frequency of un-damped oscillations in a system, which has been allowed to oscillate on its own, is **called the natural frequency, f_0.**

In order to keep it vibrating after you've hit it, you need to keep re-hitting it periodically to make up for the energy being lost. We say that you need to apply a **periodic force** to it. (Although some people would just say that you are being unnecessarily violent.)

The frequency with which the periodic force is applied is called the **forced frequency.** If the forced frequency equals the natural frequency of a system (or a whole number multiple of it) then the amplitude of the oscillations will grow and grow. This effect is known as resonance.

Symbols

Simple Harmonic Motion

a = acceleration of the vibrating object, ms^{-2}

s = displacement of the vibrating object from its equilibrium condition. (Note - it's a vector)

ω = the angular frequency of the oscillation, Hz.

f = frequency of the oscillations, Hz

T = the period of oscillation, s

t = the time since the start of the oscillations, s

Reflection, Refraction and Polarisation

Reflection and Refraction

The intensity of a wave is proportional to its amplitude squared.

Intensity $\propto$ (Amplitude)^2

Laws of Reflection:

1. Angle of incidence = Angle of reflection
2. The image formed by a plane (flat) mirror is the same distance behind the mirror as the object is in front.
3. The image is laterally inverted and virtual

Rules of Refraction:

A wave speeds up or slows down when it enters a different medium.

If the wave slows down it bends towards the normal.

If the wave speeds up it bends away from the normal.

$$n = \frac{\sin i}{\sin r} = \frac{c_1}{c_2} = \frac{\lambda_1}{\lambda_2}$$

Frequency, Wavelength and Speed

Any part of the electromagnetic spectrum has a frequency that decides what type of wave it is. **This frequency does not change when the wave is refracted.** If the speed of the wave is reduced the wavelength of the wave must therefore also be reduced as:

Speed = frequency x wavelength

So the wavelength of blue light in air will be slightly longer than the wavelength of blue light in glass!

Snell's Law and the Refractive Index

So we know that waves slow down when they enter optically denser materials, and bend towards the normal line.

But can we predict how far waves will change direction?

If we label the angle of incidence as i and the angle of refraction as r, then it can be shown that when travelling from a vacuum into a material, the ratio $\frac{\sin i}{\sin r}$ remains constant for all values of i and r. This is **Snell's Law.**

We call the constant from Snell's law the **refractive index, n.**

Relative Refractive Index

So, what happens if you are travelling from a material that isn't a vacuum into another material?

Well it's simple:

If the wave is travelling from material 1 into material 2, the ratio of the sine of the angles is still constant, but now we use the **relative refractive index, $_1n_2$.**

$$_1n_2 = \frac{\sin \theta_1}{\sin \theta_2} = \frac{c_1}{c_2}$$

Also,

$$_1n_2 = \frac{n_2}{n_1}$$

Total Internal Reflection

If the angle of incidence is greater then the critical angle, C for that boundary the wave will totally internally reflect.

The refractive index of a material is given by:

$$n = \frac{1}{\sin C}$$

You should know how total internal reflection is used in optical fibres and reflecting prisms.

Uses of TIR:

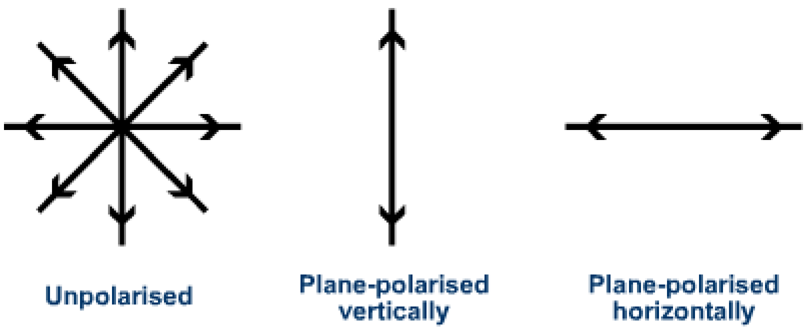
There are many uses for TIR starting from the simple replacement of mirrors with prisms in periscopes to the complicated world of fibre optics.

Optical Fibres

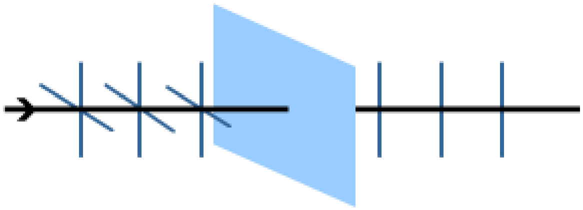
Optical fibres use TIR to send light pulses down glass fibres.

Polarisation

Transverse waves can oscillate in any plane. **Polarisation** is the process by which the oscillations are made to occur in one plane only.



This is done by passing the waves through a 'grid' so that only the waves that can fit through the slits can continue through:



Longitudinal waves cannot be polarised.

Symbols

Reflection and Refraction

n = refractive index

i = angle of reflection or refraction (depends on the equation)

r = angle of reflection or refraction (depends on the equation)

C = the critical angle

c = speed of light, ms^{-1}

λ = wavelength, m

Diffraction

Diffraction

A wave will diffract (spread out) as it goes through a gap or past an obstacle.

Note: The wavelength remains the same before and after the gap.

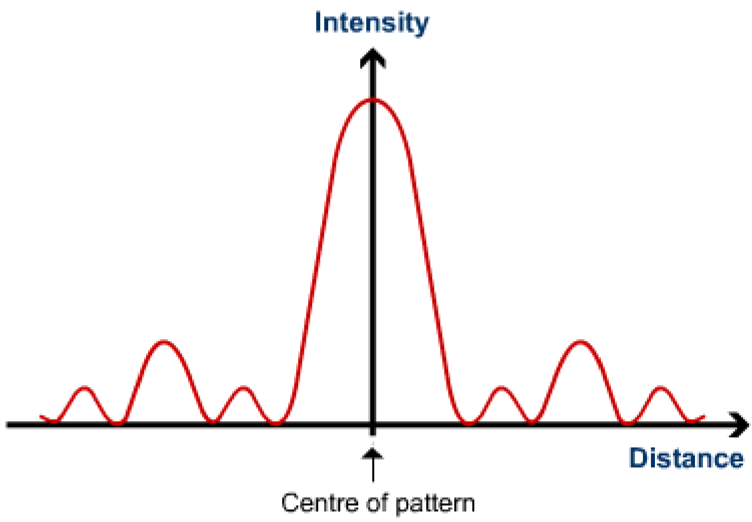
Remember this: The nearer the slit size is to the wavelength, the more the wave will diffract.

1. The smaller the gap the greater the diffraction.
2. The longer the wavelength the greater the diffraction.

You should be able to describe experiments such as the ripple tank or microwave kit that will show diffraction.

Single Slit Diffraction Pattern

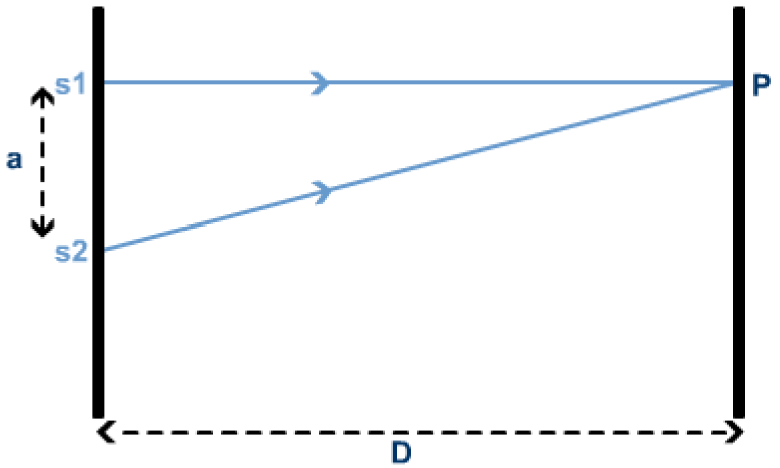
If a wave goes through a slit a diffraction pattern can be detected on the other side, with regions where the wave is intense and regions where the intensity falls to zero. A graph of intensity against distance from the centre of the pattern can be drawn:



Coherence:

Coherent waves are waves with a constant phase difference. (*Note:* They don't have to be in phase for this to be true.) They will have the same frequency and wavelength (they are normally produced from one source).

Young's Double Slits:



The pattern formed is of close, bright **"fringes"** of light.

A bright fringe occurs at P if $S_2P - S_1P = n\lambda$

A dark fringe occurs at P if $S_2P - S_1P = n\lambda + \frac{1}{2}\lambda$

Interference and Superposition

When two waves meet they will **interfere** and **superpose**. After they have passed they return to their original forms. This is true if they are coherent or not.

Path Difference

You will need to be able to work out whether there will be constructive or destructive interference at a point. We do this by comparing how far the two waves have travelled to reach the point. The difference in the distances will tell us if the waves are in phase or not.

Finding the Wavelength of Light

Using Young's double slits to find the wavelength of light:

$$\lambda = \frac{ax}{D}$$

λ = wavelength

a = distance between slits

x = fringe spacing

D = distance from slits to screen

Diffraction from a Diffraction Grating

Using a diffraction grating to find the wavelength of light:

$n\lambda = d\sin\theta$

d = slit spacing

θ = angle from centre

n = order of maximum

The pattern that you get with a large number of slits (a **diffraction grating**) is similar to the double slit pattern in that there are bright fringes on a dark background, but there are far fewer fringes and the gaps between them are much larger.

Double slit pattern:

(closely spaced bright fringes on a dark background)

Grating pattern:

(widely spaced bright fringes on a dark background)

Progressive Waves

Types of Waves

Mechanical waves are any waves that move through a medium. For example, water waves.

Progressive waves distribute energy from a point source to a surrounding area. They move energy in the form of vibrating particles or fields.

There are two different types of progressive waves:

- **Transverse waves** - vibrations are perpendicular to the wave motion - so if the wave is travelling horizontally, the vibrations will be up and down. For example, light and water.

- **Longitudinal waves** - vibrations are parallel to the wave motion - so if the wave is travelling horizontally, the particles will be compressed closer together horizontally, or expanded horizontally as they go along (we call the expanded bit a rarefaction). The particle movement is a series of compressions and rarefactions. For example, sound and some earthquake waves.

Displacement is the distance a particle moves from its central equilibrium position.

Amplitude is the maximum displacement from the central equilibrium position.

Phase angle is the position along the wave, which is normally measured in degrees or radians. One complete wave is 360 degrees, so from a peak to a trough will be a change in phase of 180 degrees.

Calculating the Speed of a Wave

We can calculate the speed of a wave using:

$$v = f \lambda$$

Where:

v = speed (m/s)

f = frequency (Hz)

λ = wavelength (m)

Standing Waves

Standing waves (also known as **stationary waves**) are set up as a result of the superposition of two waves with the same amplitude and frequency travelling at the same speed in opposite directions.

The waves are moving, but the position of the crests and troughs are stationary.

Speed of a Wave on a String

We can calculate the speed of a wave using:

$$v = \sqrt{\frac{F}{M}}$$

Where:

v = speed (m/s)

F = tension (N)

M = mass per metre of the string (kg/m)

Symbols

Progressive waves

λ = wavelength, m

a = slit spacing in Young's experiment, m

x = fringe separation in Young's experiment, m

D = the distance from the double slit to the screen in Young's experiment, m

d = the slit separation in a diffraction grating, m

n = order number of the fringe (always an integer)

θ = angle from the centre of the diffraction grating to the fringe you are considering (in degrees)

Electromagnetic Waves

Electro-magnetic Waves

All the waves in the electromagnetic spectrum...

- travel the same speed in a vacuum;

- can be reflected, refracted, diffracted and polarised;

- are transverse waves.

It is important that you are able to remember the different parts of the electromagnetic spectrum and their properties.

A list of the spectrum is shown below:

Type of ray:	**Gamma rays:**	**X-rays:**	**Ultraviolet:**	**Visible light:**
Production:	Emitted during radioactive decay	Produced by firing electrons at a metal target	Emitted by the Sun	Emitted by the Sun
Uses:	Medicine in chemotherapy	Medicine for looking at bones	Tanning	Seeing
Hazards:	Causes cancer by damaging cells	Causes cancer by damaging cells	Can cause skin cancer	Intense light can damage your sight
Wavelength (m):	$x10^{-12}$	$x10^{-10}$	$x10^{-8}$	$7x10^{-7}$ to $4x10^{-7}$
Frequency (Hz):	$x10^{20}$	$x10^{18}$	$x10^{15}$	$x10^{14}$
Photon Energies (eV):	400 k	4 k	4	0.4

Type of ray:	**Infra-red:**	**Micro-waves:**	**Radio-waves:**
Production:	Emitted by hot objects	Produced by changing currents in a conductor	Produced by changing currents in a conductor
Uses:	Conventional cooking	Microwave cooking and communications	Communication and media

Hazards:	Can burn	Can burn	Currently not considered to be hazardous
Wavelength (m):	$x10^{-5}$	$x10^{-3}$ to $x10^{-2}$	x 1
Frequency (Hz):	$x10^{12}$	$x10^{10}$	$x10^{8}$ to $x10^{10}$
Photon Energies (eV):	4 µ	40 µ	4

All of the waves in the electromagnetic spectrum are oscillating electric and magnetic fields. These fields are perpendicular to each other.

Matter and Antimatter

Matter and antimatter

Each matter particle has an antimatter counterpart that has **opposite charge and spin.**

Antimatter can be produced in particle collisions in accelerators.

The energy in a **linear accelerator** (LINAC) is limited by its **length.**

The energy in a **cyclotron** is limited by **relativistic mass increase.**

The energy in a **synchrotron** is limited by the emission of **synchrotron radiation.**

Particle annihilation - When a particle meets its antiparticle they annihilate. Their mass is converted into energy in the form of gamma-ray photons.

Pair-production - A single gamma-ray photon passing close to a nucleus (its recoil conserves momentum) can spontaneously produce a particle-antiparticle pair.

Mass spectrometers

The mass spectrometer was developed in the early part of the last century to determine the comparative masses of ionised atoms and, later, the relative abundances of isotopes.

Why the obsession with higher and higher energies?

In the late 1970s, the physicists at CERN (European Nuclear Research Centre) came up with a brilliant idea. If you could fire two particles in opposite directions and make them collide, you would effectively double the available energy at a stroke without increasing the maximum kinetic energy of the particles. This is the principle behind the large electron-positron collider (LEP) and in the proton-antiproton super proton synchrotron at CERN. The forces used to accelerate and bend the particles and antiparticles have the same effect on both but they act in opposite directions.

Use of $E = MC^2$

The existence of antimatter came as a surprise to physicists. This strange idea, however, reveals a much more fundamental idea about our universe: if particles of matter and antimatter can meet and annihilate producing **energy**, then **matter** itself can be **changed** into energy and vice versa!

Some scientists like to think of matter as being a 'frozen' form of energy. Under the correct conditions this energy can be recovered by 'unfreezing' the energy.

Einstein's famous equation $\mathbf{E} = \mathbf{mc}^2$ summarises this idea. To find out how much energy is produced when a certain mass is changed to energy ('unfrozen!') simply multiply the mass by the speed of light squared (c^2). As the speed of light is very large a tremendous amount of energy is released when a very small amount of mass is released.

Particle Classification and Interactions

Particle families

There are two main families of particle, the **leptons** and the **hadrons**.

Leptons

These are the lightest particles. Their name is derived from Greek: **Lepton is small.**

There are 3 types of lepton: the **electron**, **muon** and **tau**. In addition, each of these particles has an associated neutrino, and corresponding antiparticle, making a total of 12 family members. Leptons are truly fundamental.

Leptons are assigned a Lepton number (L). L = 1 for leptons and L = -1 for antileptons.

Hadrons

Hadrons are generally more massive than leptons. They are sub-divided into **baryons** (the most massive) such as protons and neutrons, and **mesons** (somewhat less massive) such as the pion and kaon.

Particle Numbers

In order to understand the interactions of these particles better they are assigned numbers as described below:

Charge (Q) is conserved in all interactions.

Baryons are assigned a **Baryon number (B)**. B = 1 for baryons and B = -1 for antibaryons. Baryon number is conserved in all interactions.

Strange quarks possess a property called **Strangeness (S)**. S = -1 for strange quarks and S = 1 for ant strange quarks.

Particle interactions

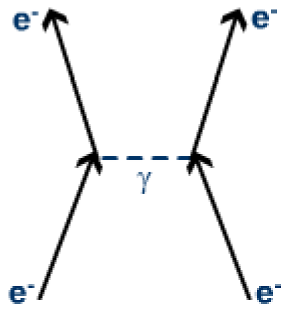
The 4 fundamental forces can be thought of as **interactions** between particles arising as a result of the exchange of **virtual particles.**

The four fundamental interactions are:

Interaction	Exchange particles	Range (m)
strong	**gluon** (between quarks) **mesons** (between hadrons)	10^{-15}

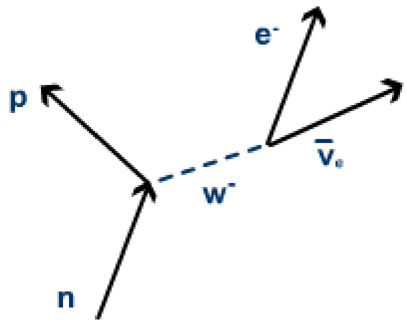
electromagnetic	virtual photon	∞
weak	W^+, W^-, Z^0	10^{-18}
gravitational	(graviton?)	∞

Such exchanges can be represented on a **Feynman diagram:**



Beta decay

Beta decay is a result of the weak interaction. A down quark in the neutron emits a W^- and changes into an up quark. The W^- decays into an electron and an antineutrino.



Conservation Laws

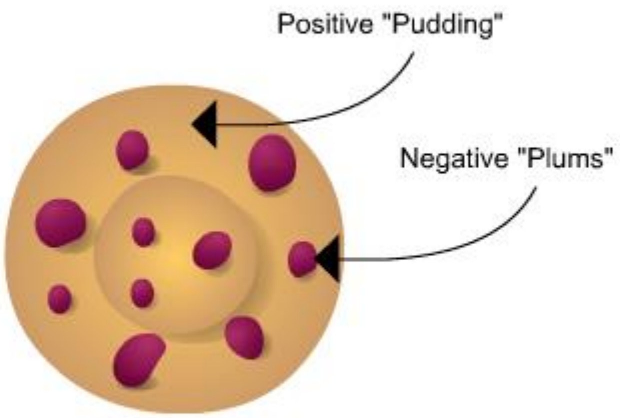
In any interaction charge (Q), lepton number (L) and baryon number (B) are conserved. (L = 1 for leptons, L = -1 for antileptons. B = 1 for baryons, B = -1 for antibaryons)

Atomic Structure

Rutherford alpha particle scattering experiment

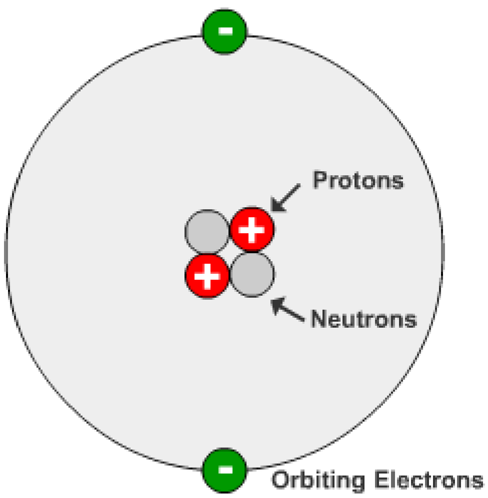
Rutherford's alpha particle scattering experiment changed the way we think of atoms.

Before the experiment the best model of the atom was known as the Thomson or **"plum pudding"** model. The atom was believed to consist of a positive material "pudding" with negative "plums" distributed throughout.



Particles in the atom

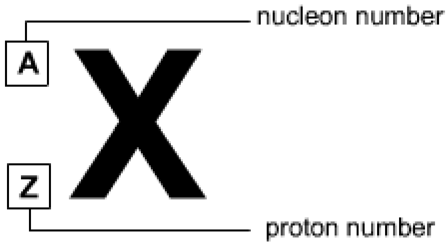
Atoms contain 3 types of particles: protons, neutrons and electrons.



It is important to understand that the picture above is a model of the atom. It conveys an impression of what the atom is like, but is not a completely true representation.

To describe the number of particles in a given atom, we use this notation:

Atomic notation



nucleon number: no. of protons + neutrons (Also called the mass number as electrons are relatively light so all the mass is in the nucleus.)

proton number is also called the atomic number as no two elements have the same number of protons.

Isotopes

The **number of protons in an atom is crucial.** It gives you the charge of the nucleus and therefore it gives you the number of electrons needed for a neutral atom. And the number of electrons governs how an atom behaves and reacts chemically with other atoms. In other words, it gives you its properties. So the number of protons makes the atom belong to a particular element. **Change the number of protons and you change the element.**

Radioactivity

Radioactivity

Some nuclei are unstable - they have too many or too few neutrons. This can result in the nuclei **spontaneously** and **randomly** splitting up and giving out energy to stabilise themselves. This is **radioactive decay** and isotopes of atoms that do this are called **radioisotopes**. It can't be affected by any process.

Background Radiation

We constantly receive radiation from a number of sources in our environment. Learn them! At this low level, the radiation is not damaging to us.

What is ionising radiation?

Alpha, beta and gamma

Ionising radiation comes in three varieties:

α (alpha) particles

β (beta) particles

γ (gamma) rays.

Properties of alpha, beta and gamma radiation

Type of radiation:	Symbol:	Formula:	Penetrating power:	Mass:	Charge:	Speed:
Alpha particle:	α	${}^{2}_{4}He^{+}$	Stopped by paper or skin	4	+ 2	Slow
Beta particle:	β	${}^{0}_{-1}e^{-}$	topped by thin metal	Negligible	- 1	Fast
Gamma rays:	γ	${}^{0}_{0}\delta$	Reduced by many cms of lead or a few metres of concrete	No mass	No charge	Speed of light

Separating alpha, beta and gamma

Electric Fields

The effect of the field depends on the charge of the radiation.

Alpha particles are positively charged and are therefore attracted to the negative plate in an electric field.

Beta particles are negatively charged and are therefore attracted to the positive plate in an electric field.

Gamma rays are unaffected.

Magnetic Fields

Use **Fleming's Left Hand Rule** to predict behaviour in magnetic fields. The "current" (second finger flow of charged particles) is the beam of radiation. Remember, the second finger shows conventional current so for beta particles point it in the reverse direction to the beam. For alpha particles it points in same direction as beam. Gamma rays have no charge so experience no force.

Note: alpha and beta particles follow circular paths in magnetic fields. The force due to the magnetic field is a centripetal force (see circular motion).

Cloud and bubble chambers

In order to study subatomic particles you need a method of detecting them. Over the years physicists have developed devices that can show the presence of particles and reveal their properties by the tracks that they leave. Two of the most important early detecting devices were **cloud** and **bubble chambers.** In modern high-energy research these devices are now obsolete. Spark and drift chambers are used as faster alternatives.

All of these devices work on a common principle: **charged particles** that pass through leave a path of detectable **ionised particles.** The technical details of each detector are slightly different but this principle is true nonetheless.

Uses of radioactive particles

Radioactive nuclides are made use of in many completely different ways. In whatever way they are used, it is always necessary to take precautions so the user is well protected from any radiation.

Four main uses of radioactive particles are: tracers, medical treatment, archaeological dating and scattering experiments.

Radioactive Decay Equations

Activity

Activity is defined as the rate of decay (or number of disintegrations per second) of a substance.

Half-life

Half-life is the time taken for half of the radioactive nuclei present to decay or the time taken for the activity of a sample to halve.

Carbon-14 Dating

Carbon-14 Dating is a useful example of the concept of half-life in practice. Carbon-14 is a radioactive isotope of carbon with a half-life of 5730 years.

Decay

Decay constant is the fraction of the total number of nuclei present that will decay in a unit time.

Equations and Definitions

Radioactivity

$A = \lambda N$

$\lambda = 0.693/ t_{½}$

$N = N_o \exp(-\lambda t)$

$A = A_o \exp(-\lambda t)$

Symbols

Radioactivity

A = activity of a sample. (**Units: Becquerel, Bq.**) Activity depends on number of particles present initially.

A_o = activity at the start

N = number of atoms

N_o = the number of atoms at the start

λ = the decay constant

$t_{½}$ = half life

t = time

Nuclear Energy

Mass defect

Take a **proton** and a **neutron** - find their total mass - combine them via nuclear fusion - take their new mass - and some has **disappeared.** !!??!!! We call it **the mass defect**. This mass has been turned into **energy.**

Consider matter as a solid form of energy.

Binding energy

"The energy released when the nucleus is assembled from its constituent parts."

Note: the value is often given per nucleon !!!

The **most stable elements** are those whose atoms need the **most energy** to separate them, i.e. those with the greatest binding energy.

Fusion and Fission

Because iron is the most stable nucleus, it makes sense (in energy terms) for other nuclei to try to become more like iron.

So smaller nuclei will combine (and give out energy in doing so) to produce larger nuclei - more like iron! This process is called **Nuclear Fusion.**

Larger nuclei will split up to produce smaller nuclei (more like iron) and give out energy in doing so. This is **Nuclear Fission.**

Finding nuclear radius

You cannot simply look inside an atom in order to find how large the nucleus is. Instead high-energy particles are directed at atoms and arrays of detectors surround the target to find what sort of particles are scattered and where to. By looking closely at the data from the detectors physicists can discover much about the targets in question.

Symbols

Nuclear Physics

E = energy, J

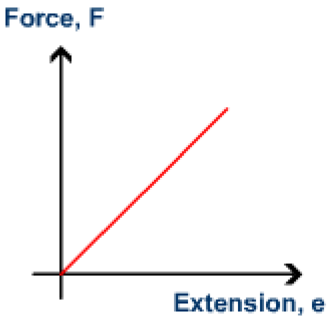
m = mass defect, kg

c = speed of light, ms^{-2}

Deformation of Solids

Hooke's Law

Measure how a spring stretches as you apply an increasing force to it and you get:



Note: Because the force acting on the spring (or any object) causes stretching; it is sometimes called tension or tensile force.

This shows that Force is proportional to extension. This is **Hooke's law. It can be written as:**

F = ke

Where:

F = tension acting on the spring

e is extension = (l-lo); l is the stretched length and lo is original length, and;

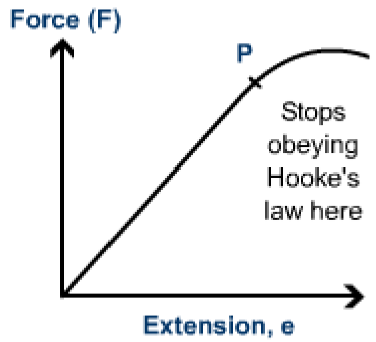
k is the gradient of the graph above. It is known as the spring constant.

The above equation can be rearranged as:

$$k = \frac{F}{e}$$

Spring constant = Applied force/extension

If you continue to stretch a spring it eventually comes to a point where it stops obeying Hooke's Law.



The point on the graph where it stops obeying Hooke's Law is often called the '**limit of proportionality**' because it is the last point at which the deformation of the material is proportional to the force acting on the material.

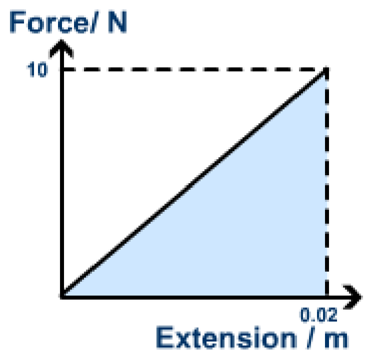
At about the same moment as it stops obeying Hooke's law; you will notice that if you unload the spring it won't return to its original shape. It has been permanently deformed. We call this point the **elastic limit** - the **limit of elastic behaviour**.

If a material returns to its original size and shape when you remove the forces stretching or deforming it, we say that the material is **demonstrating elastic behaviour**.

Permanent deformation is a sign of plastic behaviour.

Energy in deformations

To calculate the energy stored in a deformed object, find the area under the force - extension graph.



In this example:

Work = ½ force x extension = ½ x 10 x 0.02 = 0.1J

Equations

Deformation of solids

F = **ke** - Hooke's Law

Work (or energy Stored) = ½ force x extension

Symbols

Deformation of solids

F - Force, N

k - spring constant (or the spring stiffness). Nm^{-1}

e - extension, m

Glossary

Breaking Stress	Stress at which material breaks
Deformation	Change of size (dimension) under the action of a force
Deformation (elastic)	Non-permanent deformation. It disappears when the force casing it are removed i.e. object returns to zero strain condition (reversible deformation)
Deformation (plastic)	Permanent deformation; material does not go its original shape after the forces causing it are removed (irreversible deformation).
Density (r)	Weight per unit volume (units:kgm^{-3})
Elastic Behaviour	a behaviour of a material exhibiting return to its original size and shape when the forces deforming it are removed (see deformation (elastic)).
Elastic Limit	A limit (of stress/strain) within which a material will regain its original shape (zero strain position) after the deforming force is removed. a material will acquire a permanent deformation if stretched beyond elastic limit
Hooke's Law	Law describing behaviour of elastic solids: Force is proportional to extension.
Hysteresis	Phenomenon of lagging behind of any effect when the forces acting on a body are changed. Some substances like rubber show hysteresis when they are subjected to forces deforming them.
Hysteresis Loop	Loop formed by two branches (loading and unloading) in force-extension and stress-strain graphs of some materials (e.g. rubber). Area of the hysteresis loop represents the energy lost during a

loading unloading cycle.

Stress and Strain

Stress and Strain

The problem with force - extension graphs is that they only give information about the exact object and material that you are examining.

Stress and strain are measurements that allow us to compare behaviour of materials and objects no matter what size or shape they are because the force and extension are multiplied up or down to find out what the force would be if it was spread over 1 m^2 or what the extension would be per metre of the original material.

Stress and Strain, Definitions

Stress is defined as the force per unit area of a material.

Stress = force / area

$$\sigma = \frac{F}{A}$$

Units: Nm^{-2} or Pa.

Strain is defined as extension per unit length.

Strain = extension / original length.

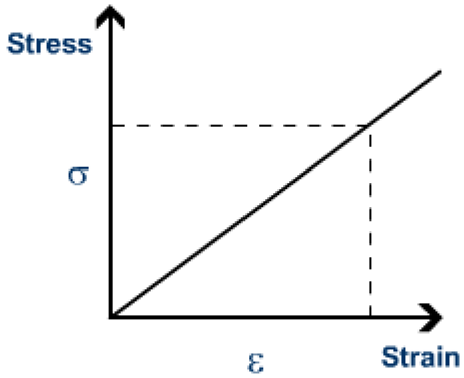
$$\varepsilon = \frac{e}{lo}$$

Strain has no units.

A useful tip: In calculations stress is usually a very large number and strain is usually a very small number. If it comes out much different than that, you've done it wrong!

Young Modulus

Instead of drawing a force - extension graph, if you plot stress against strain for an object showing (linear) elastic behaviour, you get a straight line.



This is because stress is proportional to strain. The gradient of the straight-line graph is the Young's modulus, E

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon} \quad \text{and} \quad E = \frac{\sigma}{\varepsilon} = \frac{F/A}{e/l_o} = \frac{F\,l_o}{e\,A}$$

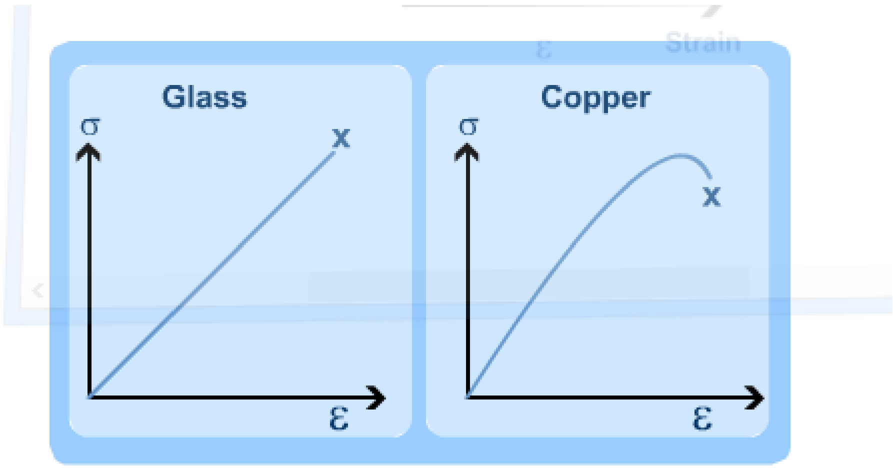
Units of the Young modulus E: Nm^{-2} or Pa.

Note: The value of E in Pa can turn out to be a very large number. It is for this reason that, some times the value of E may be given MNm^{-2}.

Note: Because 'stress' and 'strain' are (uniquely) related to force and extension, it is not surprising that the two graphs, stress v/s strain and force v extension, have similar shapes and characteristics. (Of course, there is a quantitative difference because the units of plots on the two graphs are different.).

Stress - strain graph beyond elastic behaviour

In this 'quick learn' so far, we have drawn stress-strain graphs for the elastic behaviour of a material. In the elastic region the stress-strain graph is a straight line. We can, however draw a stress-strain graph beyond the elastic region. The graph then becomes non-linear because Hooke's law is not obeyed and stress is not proportional to strain. **Here are schematic stress-strain graphs of copper and glass.**



Note: the gradient of a stress - strain graph = stress / strain.

Density

We know that some materials are light while some are very heavy. For instance, a cube of polythene will weigh a lot less than the same size cube of steel.

We can systematically compare the amount of matter in of different materials by defining a property called **density (ρ).**

Density = mass per unit volume

$$\rho = \frac{M}{V}$$

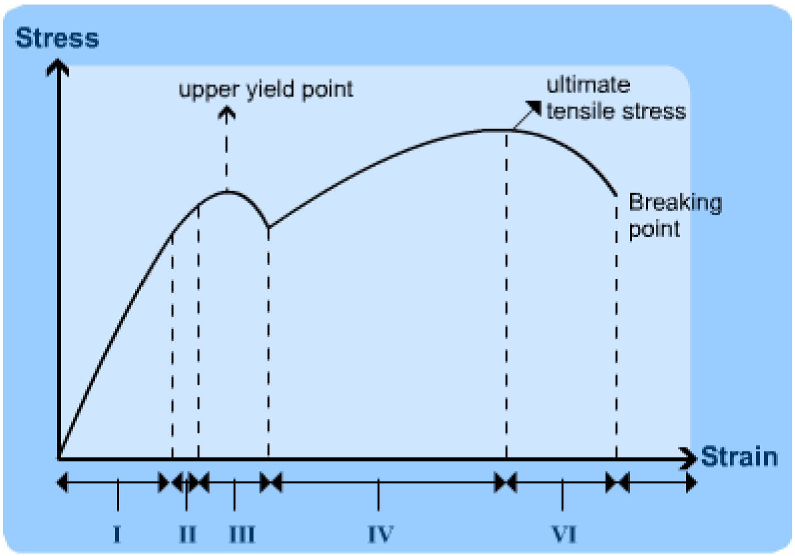
Where:

M is the mass of an object, and V is its volume.

Units of ρ : kgm^{-3}.

Deformation and fracture

When looking at different materials for mechanical purposes we use **'stress-strain'** curves. We saw that for materials obeying Hooke's law the stress strain graph is a straight line. However, this straight line forms just a part of the stress strain curve. The whole of the stress-strain curve of a material is an invaluable aid to describing its mechanical behaviour.



1. **Linear elastic region (region I)**
2. **Non-linear elastic region (region II)**
3. **Yield region (region III)**
4. **Beyond the lower yield point (region IV)**
5. **If the material is stretched further beyond the UTS (region V)**

Equations

Stress/ Strain

$$\sigma = \frac{F}{A} = \text{stress equation}$$

$$\varepsilon = \frac{e}{l} = \text{strain equation}$$

$$E = \frac{\sigma}{\varepsilon} = \text{Young's Modulus}$$

$$W = \frac{1}{2}Fe = \text{Energy per } m^3$$

Symbols

Stress/ Strain

E - Young Modulus, Nm^{-2} or Pa

F - Force, N

A - Area, m^2

σ - stress, Nm^{-2} or Pa

ε - strain, no units

e - extension, m

l - original length of material, m

Molecular volume ($V_{molecule}$)	Average volume occupied by each molecule in a substance by using the following formula
Molar mass	mass of one mole of the material.

Mole	amount of material containing 6.023×10^{23} molecules
Plastic behaviour	Behaviour of a material where deformation remains after the forces are removed (irreversible deformation)
Resilience	Ability of a material to be repeatedly stressed without plastic deformation and without losing strength
Spring constant	Force per unit extension (a constant of proportionality in Hooke's law)
Strain	Extension per unit length.
Strain energy density (ρ_ε)	Energy stored per unit volume in a material when elastically deformed. (units: Jm^{-3})
Stress	Force per unit area of a material (units: Nm^{-2} or Pa)
Strain energy density (ρ_ε)	Strain energy stored per unit volume (units:Jm^{-3})
Ultimate tensile strength (UTS)	The maximum tensile stress a material can stand
Yield	Suddenly increased deformation
Young's Modulus (E)	A constant indicating stiffness of a material, given by the ratio: stress/strain (units: Nm^{-2} or P)

Temperature and Thermal Properties

Thermometric properties

To measure the temperature of an object you first need to find something that varies with temperature. This is called a **Thermometric property.**

For example, the volume of mercury, the resistance of a piece of wire and the pressure of a gas in a fixed volume.

The Centigrade scale

To measure the temperature of an object:

1. Measure the changes to a thermometric property of a substance in thermal equilibrium with the object.
2. Find the value of the thermometric property when it is at two known temperatures, called **Fixed Points** e.g. the ice point and the steam point.
3. Assume that the thermometric property varies in a linear (straight line) way with temperature and you've got a centigrade scale.
4. Use this equation to calculate the temperature, t, in the centigrade scale:

$$t = \frac{(x_t - x_0)}{(x_{100} - x_0)} \times 100$$

Where:

t = temperature

X_t = the thermometric property at unknown temperature t

X_0 = the thermometric property at the ice point

X_{100} = the thermometric property at the steam point.

Absolute or Thermodynamic Temperature Scale

This is also known as the **Absolute Scale** or even the **Kelvin Scale** of temperature.

Always use thermodynamic temperatures when doing calculations involving temperature.

It is an imaginary, perfect temperature scale that has two fixed points - absolute zero and the triple point of water.

Temperatures are measured in Kelvin, K. 1K ≡ 1°C

The Celsius Scale

The thermodynamic scale is not used every day because the numbers are too difficult. For example, water freezes at 273.15K.

The Celsius scale is exactly the same as the thermodynamic scale except that the freezing point of water is called zero degrees Celsius.

Temperature in Celsius = Temperature in Kelvin - 273.15

Remember: in calculations, always use the kelvin value.

Internal Energy

Internal energy of a body has two components:

- **kinetic** (i.e. vibration, rotation and translation)
- **potential** (as a result of forces between particles -atoms or molecules)
  There are only two ways that you can change the internal energy of a body
- Heat it (or cool it)
- Squash it (compress or expand it)

Hence the **First Law of Thermodynamics.**

"The increase in internal energy of a body (ΔU) is equal to the sum of the heat flowing **into** the body (ΔQ) and the work done by the body (ΔW)."

or

$\Delta U = \Delta Q - \Delta W$

and

$\Delta W = p\Delta V$

Specific Heat Capacity

The definition of Specific Heat Capacity is:

"The amount of energy required to raise the temperature of 1 kg (a unit mass) of the substance by 1°C (a unit temperature rise)"

Symbol: **c**

Unit: **$Jkg^{-1}K^{-1}$**

$$c = \frac{\Delta Q}{m\Delta\theta}$$

Where:

ΔQ is the heat energy added (or removed)

m is the mass of the substance you are heating (or cooling)

$\Delta\theta$ is the change in temperature.

Specific Latent Heat

It takes a certain amount of energy to change the state of 1kg of water from solid to liquid. This amount of energy is called the **Specific Latent Heat**, l_f, of water

The definition:

"The amount of energy per kg (unit mass) required to change ice to water."

Units: Jkg^{-1}

$$\ell_f = \frac{\Delta Q}{m}$$

Where:

ΔQ is the heat energy added

m is the mass of the substance involved.

There is no temperature term involved in this equation as it all takes place at the same temperature.

Note: that there are two occasions when you change state and both of these require different amounts of energy (as different things are happening to the atoms during the state changes). So there are two symbols.

l_f - latent heat of fusion - solid to liquid and back.

l_v - latent heat of vaporisation - liquid to gas and back.

Equations

$c = \Delta Q/m\Delta T$	$pV = nRT$
$I = \Delta Q/m$	$pV = N k T$
$\Delta U = \Delta Q - \Delta W$	$p = 1/3\ \frac{Nm}{V}\langle c^2\rangle$

$\Delta W = p\Delta V$ $p = 1/3\ \rho\ \langle c^2 \rangle$

$$\frac{pV}{T} = \text{a constant} \quad t = \frac{(x_t - x_0)}{(x_{100} - x_0)} \times 100$$

Symbols

c = specific heat capacity, $Jkg^{-1}K^{-1}$

U = internal energy, J

l_v = specific latent heat of vaporisation (liquid to gas and back), Jkg^{-1}

Q = thermal energy, J

l_f = specific latent heat of fusion (solid to liquid and back), Jkg^{-1}

W = work done, J

Q = thermal energy, J

ΔV = change in volume, m^3

m = mass, kg

p = pressure, Pa

ΔT = change in temperature, K or °C

T = temperature, K

t = temperature, °C

R = universal molar gas constant

T = thermodynamic temperature, K

n = number of moles

X_t = value of thermometric property at temperature 't'

N = number of molecules

X_o = value of thermometric property at the ice point, 0°C

k = Boltzmann constant

X_{100} = value of thermometric property at the steam point, 100°C

ρ = density, kgm^{-3}

$\langle c^2 \rangle$ = mean square speed, ms^{-1}

Thermodynamics and Ideal Gases

First law of thermodynamics

There are only 2 ways that you can change the internal energy, U of the gas. (without adding or removing any atoms).

1. **Heat it or cool** it i.e. ΔQ or heat transferred.
2. **Compress it or expand** it i.e. ΔW or work done.

This leads us to the **first law of Thermodynamics** but first let's just look at the two more closely.

Heat

If you heat up gas, you pass energy to the atoms. (It appears as E_k).

Heat flowing into the gas is positive.

Work

If gas expands it has to push back the stuff that was around it. It has to do work (use energy) to do this. This is related to its internal energy.

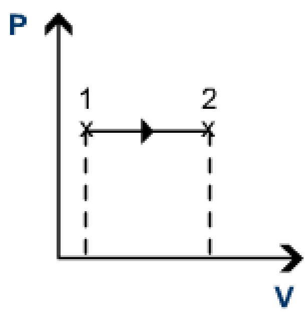
We define work done by the gas pushing back its surroundings as positive.

Equation for work done by a gas.

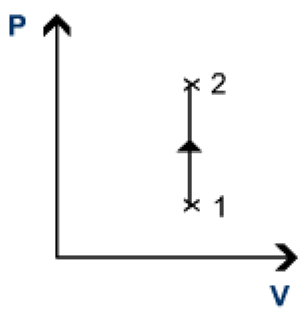
p-V or Indicator diagrams

We sketch graphs showing how pressure and volume vary when we do certain things to a gas.

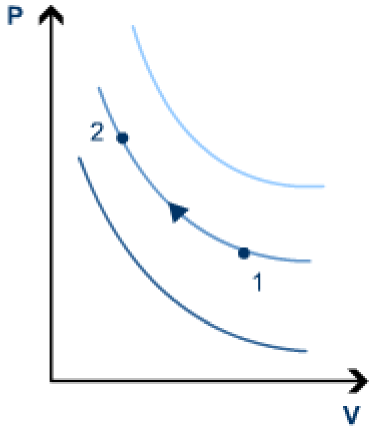
Here are the three you need to understand:



Constant pressure (isobaric) process.



Constant volume (isovolumetric) process.



Constant temperature (isothermal) process.

Adiabatic process.

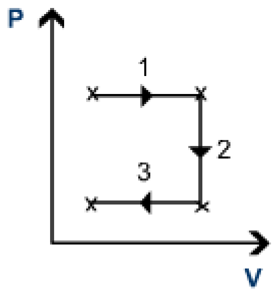
Note temperature increases, pressure increases and volume reduces, so none of these is unchanged. So why is this **special**?

Well in the processes that we've looked at so far we've had U = O and W = O but not Q = O. Well, this is it. In an adiabatic process →**Q = O**!

What does that mean? No heat can be transferred to or from the gas!!

Cycles

If you do a number of things to a sample of gas, one after the other you could end up with a graph like this:



To deal with this and work out what's going on, consider each process separately.

For example:

Process 1 is constant pressure expansion (as its volume goes from small to large).

Process 2 is constant volume cooling (its temperature drops - see constant temperature lines).

Process 3 is constant pressure contraction (volume decrease).

Kinetic Theory

Kinetic Theory

Large numbers of particles moving in continuous random motion.

Evidence: Brownian motion, diffusion.

Assumptions

- large numbers

- elastic collisions

- no intermolecular forces

- negligible collision time

- negligible volume.

Note: ideal gases have no E_p component to their internal energy

$$p = 1/3\ \frac{Nm}{V}\langle c^2 \rangle$$

but...

$$\frac{Nm}{V} = \text{density, } \rho$$

so...

$p = 1/3\rho\ \langle c^2 \rangle$

Root mean square speed, rms speed

The speed term in the equation above is the average of the square speed which has a different value from the square of the average speed - do you see the difference? The root mean square speed is the square root of the mean square speed.

The Gas Laws

The three gas laws this ideal gas obeys perfectly are:

pV = constant (at constant temperature)

$\frac{p}{T} =$ constant (at constant volume)

$\frac{V}{T} =$ constant (at constant pressure)

Note: T stands for absolute temperature (in kelvin), not temperature in °C.

Boltzmann constant and E_k

The Boltzmann constant, k, is the universal molar gas constant for 1 atom or molecule.

Use it to derive:

$1/2m \langle c^2 \rangle = 3/2\ NkT$

This shows that the temperature of a gas sample depends only on the kinetic energy of the particles (atoms or molecules) that make it up.

Equations

$c = Q/m\Delta T$	$pV = nrt$
$l = Q/m$	$p\,V = N\,k\,T$
$\Delta U = \Delta Q - \Delta W$	$p = 1/3\ \frac{Nm}{V}\langle c^2 \rangle$
$W = p\Delta V$	$p = 1/3\ \rho\ \langle c^2 \rangle$
$\frac{pV}{T} = \text{a constant}$	$t = \frac{(x_t - x_0)}{(x_{100} - x_0)} \times 100$

Symbols

c = specific heat capacity, $Jkg^{-1}K^{-1}$

U = internal energy, J

l_v = specific latent heat of vaporisation (liquid to gas and back), Jkg^{-1}

Q = thermal energy, J

l_f = specific latent heat of fusion (solid to liquid and back), Jkg^{-1}

Q = thermal energy, J

m = mass, kg

ΔT = change in temperature, K or °C

t = temperature, °C

T = thermodynamic temperature, K

X_t = value of thermometric property at temperature 't'

X_o = value of thermometric property at the ice point, 0°C

X_{100} = value of thermometric property at the steam point, 100°C

$\langle c^2 \rangle$ = mean square speed, ms^{-1}

W = work done, J

ΔV = change in volume, m^3

p = pressure, Pa

T = temperature, K

R = universal molar gas constant

n = number of moles

N = number of molecules

k = Boltzmann constant

ρ = density, kgm^{-3}

Quantum Physics

The Photoelectric Effect

The wave model of light can't explain the **photoelectric effect** i.e.:

- the threshold frequency.

- the maximum E_k of the photoelectrons.

- no. of electrons is proportional to intensity, not frequency.

- the instantaneous production of photoelectrons.

Einstein explained this using Quantum Theory:-

- light comes in packets of **energy (photons)**.

- each photon has energy that depends on the frequency of the light:

$E = h f$

- each photon interacts with only one electron (and vice versa).

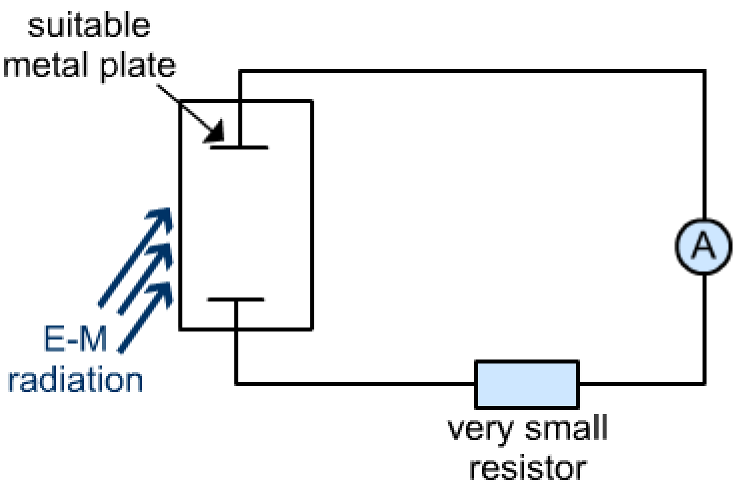
Higher frequency, shorter wavelength radiation is more energetic.

The **work function, Φ,** is the energy needed for an electron to leave the **surface** of the material.

$h f = \Phi + 1/2\ m\ v^2_{max}$

This is **Einstein's photoelectric equation.**

Photoelectric Current

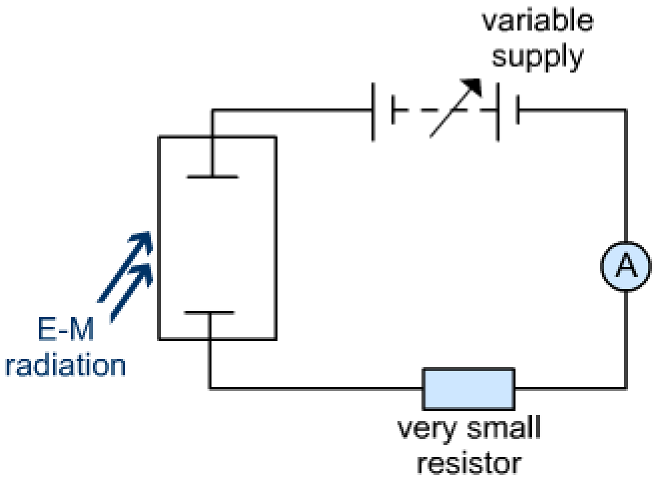


- The plate is called the **"emitter"**.

- The electrons that cross the gap are collected at the other metal plate - called **"the collector"**

- The flow of electrons across the gap sets up an emf between the plates that causes a current to flow around the rest of the circuit. That's **a photoelectric cell producing a photoelectric current.**

Stopping Potential, V_s



The emitter **gives out** electrons. So we call it a **cathode.**

If you remember, work done moving a charge through a pd is W = QV and in this case charge, Q = e, the charge on an electron,

then:

$$eV_s = E_{kmax} = \frac{1}{2}mv^2_{max}$$

Using this information you can calculate the maximum energy of the photoelectrons emitted from the metal.

Rewrite the photoelectric equation (from about 3 screens above this point) as

$$eV_s = h(f - f_o)$$

or

$$V_s = \frac{h}{e}(f - f_o)$$

Equations

E = hf

$h f = \Phi + 1/2\ m\ v^2_{max}$

Symbols

h = Planck's constant, Js

f = frequency, Hz

λ = wavelength, m

m = mass, kg

v = velocity, ms^{-1}

Φ = work function, J

E = energy, J

Wave Particle Duality and Electron Energy Levels

Wave Particle duality

Electrons, protons, α -particles can be **diffracted**! That's a wave thing!

de Broglie found the equivalent (de Broglie) wavelength for particles:

$\lambda = h/p$

where p = momentum of the particle.

E-M radiation:-

- propagates as a wave.

- interacts with surfaces as a particle.

Electron Energy Levels

Look at the Sun (Don't actually look at it though!) It doesn't have a complete white light spectrum. There are tiny gaps (**lines**) of **no light**! This light has been **absorbed** by gas around the Sun. Why are only certain lines (which relate to certain frequencies) absorbed?

The Answer:

Electrons can only exist in **discrete energy levels** around nuclei.

When jumping from low to high levels, they **absorb** energy in lumps.

When jumping from high to low levels, they **emit** energy in lumps.

The lumps have energy value calculated using:

$\mathbf{h\,f = E_1 - E_2}$

The lines on the spectra are the frequencies of light that exactly match the energy required to make the jumps between energy levels.

Absorption spectra

Dark lines on coloured background.

Emission spectra

Lines of colour on a dark background.

Equations

$E = hf$

$\lambda = h/p$

$h f = E_1 - E_2$

Symbols

h = Planck's constant, Js

f = frequency, Hz

λ =wavelength, m

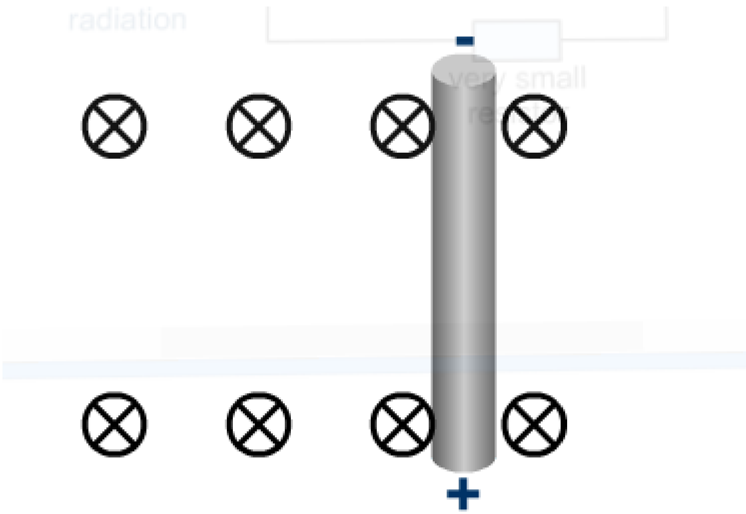
Electric Fields and Forces

Inducing EMFs

Method 1:

Pick up a metal rod and swing it about in a magnetic field - for example, the Earth's magnetic field. Although you won't realise it, you have just induced an emf across the ends of the rod.

A simple version would be this:



Note: The rod is not part of any circuit

As you swipe the metal bar to the left (as shown above) you sweep through the area of field shown by the crosses.

It's this movement through a field that induces (produces) an emf across the bar ends.

Factors Affecting the Amount of Induced EMF

Any of the following would mean that you induced more emf:

- A **longer** bar would **'sweep'** out more area of field.

- A **stronger** field would mean you swept through more field lines when moving the same distance.

- A **faster** swipe would mean you swept out more area of the field per second.

So the induced emf depends on the length of the conductor, the strength of the magnetic field and the speed at which the conductor cuts the field.

Magnetic Flux

The magnetic field strength, B, multiplied by the area swept out by a conductor, A, is called the magnetic flux, Φ.

$\Phi = BA$

Units of flux: weber, Wb.

Magnetic Flux Linkage, F

This is the magnetic flux for a coil. It is also measured in weber and has the symbol Φ. The difference is that a coil has more wire in the field, so for a coil, the equation becomes

'n' x the Magnetic Flux

where 'n' is the number of turns in the coil.

Faraday's Law

For a conductor in a changing magnetic field, the factors affecting the size of the induced emf are:

- How quickly the magnetic field is changing;

- The number of turns or loops of the conductor in the field.

This leads to **Faraday's Law,** which is that:

The emf induced is equal to the rate of change of magnetic flux linkage or the rate of flux cutting.

$$E = N\frac{\Delta BA}{t} = N\frac{\Delta \varphi}{\Delta t} = \frac{\Delta \Phi}{\Delta t}$$

Do you induce a Current or do you induce an EMF?

If you move a conductor through a magnetic field, you always induce an emf!

If there is a **circuit** available, the emf will push a current through it.

If there is **no circuit** you will still get an emf, but you won't get a current.

Symbols

Φ = magnetic flux, Wb

B = magnetic field strength, T

A = area of the field swept out or area of the coil, m^2

n = number of turns in a coil

E = induced e.m.f.

t = time, s Δ = change in...

Gravitational Fields and Forces

Gravitational Field

A gravitational field is **"a region in which masses will experience a force".**

All masses attract - but unless you're huge it's a tiny force.

Radial Field

A non-uniform field. The further you are from the object at the centre of the field, the weaker the field.

Use **Newton's Law of Gravitation** to solve problems.

Always consider objects as point masses, all their mass concentrated at their centre.

Gravitational field strength, g

The strength of a gravitational field is defined as the force, F, acting on a unit mass, m, in the field which in an equation is:

Symbol: g. *Units:* newtons per kilogram, Nkg^{-1}, which is the same as ms^{-2}.

$$g = \frac{F}{m}$$

Uniform field

In a uniform field, g will remain constant.

Radial Field

In a radial field, the field strength reduces as you move away from the centre.

Newton was the first person to fully explain gravitational fields. He came up with the following equation for field strength in a radial field:

$$g = \frac{Gm}{r^2}$$

where:

g = field strength at a point

G = the universal gravitational constant, value 6.7×10^{-11} $Nkg^{-2}m^2$

m =the mass of the object which causes the field

r = the separation between that point and the centre of the object causing the field.

Force in a gravitational Field

If the field strength at a point in a field is the force per unit mass, it doesn't take a huge leap to realise that the total force acting on an object of mass, M, in a gravitational field will be

$$F = M.g$$

Apply that to the equation for field strength in a radial field to get:

$$F = \frac{GMm}{r^2}$$

Electro-magnetic Waves

Electro-magnetic Waves

All the waves in the electromagnetic spectrum...

- travel the same speed in a vacuum;

- can be reflected, refracted, diffracted and polarised;

- are transverse waves.

It is important that you are able to remember the different parts of the electromagnetic spectrum and their properties.

A list of the spectrum is shown below:

Type of ray:	**Gamma rays:**	**X-rays:**	**Ultraviolet:**	**Visible light:**
Production:	Emitted during radioactive decay	Produced by firing electrons at a metal target	Emitted by the Sun	Emitted by the Sun
Uses:	Medicine in chemotherapy	Medicine for looking at bones	Tanning	Seeing
Hazards:	Causes cancer by damaging cells	Causes cancer by damaging cells	Can cause skin cancer	Intense light can damage your sight
Wavelength (m):	$x10^{-12}$	$x10^{-10}$	$x10^{-8}$	$7x10^{-7}$ to $4x10^{-7}$
Frequency (Hz):	$x10^{20}$	$x10^{18}$	$x10^{15}$	$x10^{14}$
Photon Energies (eV):	400 k	4 k	4	0.4

Type of ray:	**Infra-red:**	**Micro-waves:**	**Radio-waves:**
Production:	Emitted by hot objects	Produced by changing currents in a conductor	Produced by changing currents in a conductor
Uses:	Conventional cooking	Microwave cooking and communications	Communication and media

Hazards:	Can burn	Can burn	Currently not considered to be hazardous
Wavelength (m):	$x10^{-5}$	$x10^{-3}$ to $x10^{-2}$	x 1
Frequency (Hz):	$x10^{12}$	$x10^{10}$	$x10^{8}$ to $x10^{10}$
Photon Energies (eV):	4 μ	40 μ	4

All of the waves in the electromagnetic spectrum are oscillating electric and magnetic fields. These fields are perpendicular to each other.

Terms and conditions