AS Physics - Unit 1

Section 1.1 - Basic Physics

Systeme Internationale or 'SI' units

All quantities in physics have an unit which has been agreed on internationally. For example:

charge - coulomb, C　　force - newton, N　　energy - joule, J

In addition, there are about 6 fundamental quantities that can be used to define or derive any other quantity. These are known as **base quantities**, and their units are therefore **base SI units.** Here are 6 **base quantities:**

mass (kg)　　length (m)　　time (s)　　temperature (K)　　current (A)　　amount (mol)

Since all derived quantities, like 'energy' or 'force' are based upon base quantities, it must be possible to express their units in terms of base quantity units (kg , m , s , K , A or mol).

To change **SI units** into **base SI units**, you simply need to think of an equation containing base quantities, e.g. changing the 'newton, N' into **base** SI units:

In this section the square brackets around a quantity are used to denote "the units of" that quantity, e.g. **[m]** denotes **"the units of mass".**

Simple equation for 'force' ➔ $\Sigma F = \underset{\downarrow}{m} \times \underset{\downarrow}{a}$

Hence 'the units of force' , $[F] = kg \times ms^{-2}$

∴ If the SI unit for force is the newton, the equivalent unit in terms of **base** SI units is **$kgms^{-2}$**

Example

Electrical current, I is defined by the equation, $I = \frac{Q}{t}$ *where* Q = *charge,* t = *time.*

The SI unit for charge is the ***coulomb, C****. Express this unit in terms of* ***base SI units****.*

Re-arranging the equation to make 'Q' the subject:

$Q = I \times t$ ∴ $[Q] = [I] \times [t] = A \times s$ ∴ Answer = As (Amps seconds)

Quantity	SI units	BASE SI units
Spring constant, k = F / x	Nm^{-1}	$kg\ s^{-2}$
Pressure (= Force/Area)	Pa or N/m^2	$kg\ m^{-1}\ s^{-2}$
Energy or Work done (Work = Force x distance)	J	$kg\ m^2\ s^{-2}$
Voltage (V=Energy/charge)	V	$kg\ m^2\ A^{-1}\ s^{-3}$

You are NOT expected to remember these BASE SI units, but you may be expected to derive them as shown in the example box above.

Why not try to use the equations given in the first column to see if you can derive the BASE SI units shown in the last column?

This information can be used to check equations for **homogeneity. An equation is said to be homogenous** if both sides have identical base SI units.
(Note : This does not check whether any constants in an equation have the correct values).

Example

Show that the following equation is homogenous : $\mathbf{E = \dfrac{Y\,A\,e^2}{2\,L}}$

where , E = *energy stored in a stretched wire (unit = joule = kg* $m^2\,s^{-2}$ *)*
Y = *modulus of elasticity (Pascal = unit of pressure,* $P = F/A$*)*
A = *Area*
e = *extension*
L = *original length of wire*

Answer

First, we must find the SI units for each expression in the equation :

LHS

[E] = $\mathbf{kg\,m^2 s^{-2}}$ (given)

RHS

[Y] = [Pressure] = [F / A] = [m a / A] = $kg\,ms^{-2}$ / m^2 = $\mathbf{kg\,m^{-1}s^{-2}}$
[A] = $\mathbf{m^2}$
[e] = m
∴ [e^2] = $\mathbf{m^2}$
[L] = **m**
[2] = No units

$$\therefore \left[\frac{Y\,A\,e^2}{2\;L}\right] = \frac{kg\,s^{-2}}{\cancel{m}} \cdot \frac{\cancel{m^2}}{\cancel{m}} \cdot m^2 = \mathbf{kg\,m^2\,s^{-2}}$$

Since the units are identical on both sides of the equation, this equation is **homogenous.**

Scalars & Vectors

Scalar = **A scalar is a quantity that has magnitude only.**

Vector = A vector quantity has magnitude and direction.

Examples of scalars are: mass , distance , volume , density , time , speed , pressure

Examples of vectors are: displacement , velocity , acceleration , momentum , force , current

Displacement

Displacement is the vector equivalent of distance. However, displacement is measured in a different way to distance - displacement is akin to the 'distance as the crow flies'. See the example below:

A cyclist travels from Bangor (North Wales) to Betws-y-Coed.
A device attached to the wheel measures the distance travelled as the wheel turns. The reading by the end of the journey was 80km.

However, the displacement is shown by the dotted (red) line.
The displacement was 27km at a bearing of S 50° E.

Note : Since displacement is a vector it requires a direction too.

Speed & Velocity

Velocity is the vector equivalent of speed. However, we must be careful! Velocity is defined as 'displacement per unit time', and so displacement values must be used to calculate velocity, whereas distance values are used to calculate speed.

Adding vectors

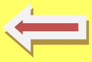
When adding vectors we must take their direction into consideration. If the vectors are 'in line', then it is a simple calculation (as seen at GCSE level). See the example below.

Example

A woman is rowing against the flow in a slow moving river and wants to estimate how long the journey will take. To do this she needs an idea of her speed relative to the river bank. She knows her usual rowing speed is 3.2 m/s. The speed of the water in the river is approximately 0.8 m/s in the opposite direction. Calculate her resultant velocity (relative to the river bank).

Answer :

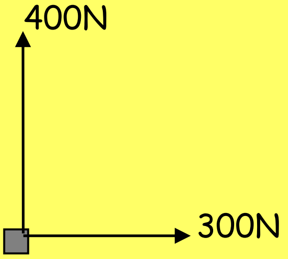
3.2m/s + 0.8m/s Resultant velocity, v = 3.2 - 0.8 = **2.4 m/s ➔**

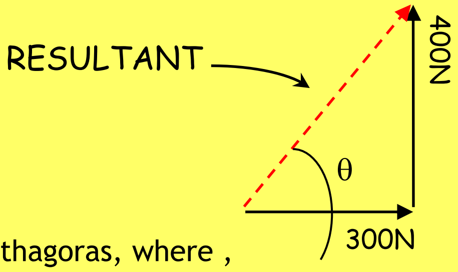


We can also add vectors that are not 'in line', i.e. are at an angle to each other. This can be done by scale drawing, but a more accurate method is by using trigonometry. **You will only be expected to do calculations with vectors that are at 90° to each other.**

Example

Imagine a heavy block being pulled by two people simultaneously. Person A pulls with a force of 300N due East; person B pulls with a force of 400N due North. What is the resultant force on the block?





The forces are added by placing them **"tip to tail"**, as shown, or alternatively by the parallelogram rule.

The resultant is then the line that joins the tail of one to the tip of the other.

The magnitude of the resultant, |R| can be found using pythagoras, where ,

$$R^2 = 300^2 + 400^2 \qquad \therefore \quad R = \sqrt{300^2 + 400^2}$$

$$\therefore \quad |R| = \mathbf{500\ N}$$

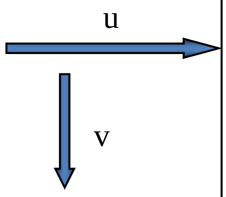
The direction of the resultant is given by "Soh, Cah and <u>Toa</u>" :

$$\tan\theta = 400 / 300 \qquad \therefore \quad \theta = \tan^{-1}(400 / 300)$$

$$\therefore \quad \theta = \mathbf{53.1}\ ^\circ$$

Subtracting vectors

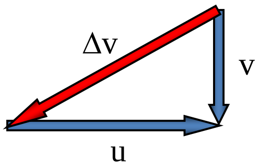
Sometimes it is necessary to calculate the 'change' in a certain quantity. A change in a quantity is always the final value minus the initial value, and hence this requires vector subtraction. For example, when calculating acceleration, we need to find the **change in velocity**.



If a particle is initially travelling to the right with a velocity, u, of 25 m/s,

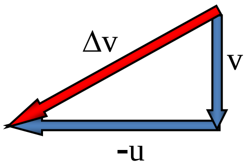
but that some time later, has a final velocity, v, of 10m/s downwards,

we would calculate the **change** in velocity like this:



This is: $\Delta v = v - (+u) = v - u$

Alternatively :



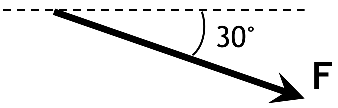
This is: $\Delta v = v + (-u) = v - u$

Either way the resultant is 'v - u'

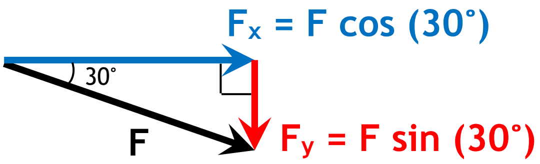
Resolving vectors

When a vector is **resolved** it is split up into vectors that have the same effect as the original. The two new vectors, called **components**, are chosen to be at 90° to each other so that the two components can be treated **independently.**

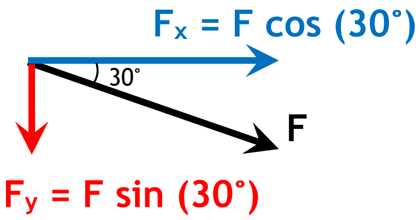
Consider a force, F, acting at 30° to the horizontal:



This force vector can be resolved into two perpendicular components:



The components are found by simply applying '**S**oh, **C**ah, **T**oa' !

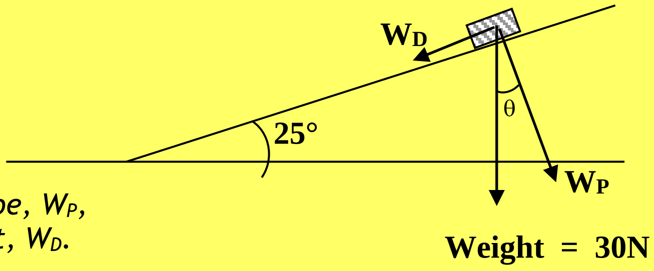


Alternatively, we can set all the 'tails' together, and just remember that the component linked to the original by the angle is always the 'cos' component.

Example

A box is placed on a (rough) slope.
The weight of the box is 30N.

Calculate
(i) the component perpendicular to the slope, W_P,
(ii) the downslope component of the weight, W_D.



Firstly, we identify the angle, θ, as 25°. (Look at any right-angled triangle in the diagram).
We now see that the 'W_P' component is linked to the original via the angle, and hence,

(i) $W_P = W\cos(25°) = 30 \times \cos(25°) =$ **27.2 N**
(ii) $W_D = W\sin(25°) = 30 \times \sin(25°) =$ **12.7 N**

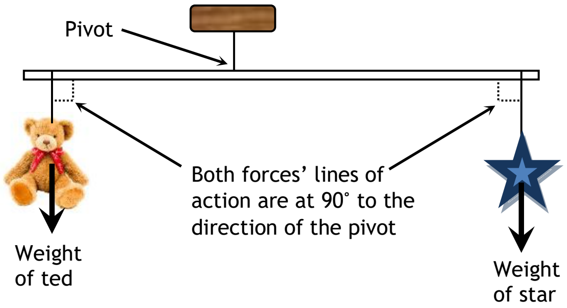
Remember : The original vector always forms the hypotenuse of the new triangle formed with the 2 components.

Moment (turning effect/torque)

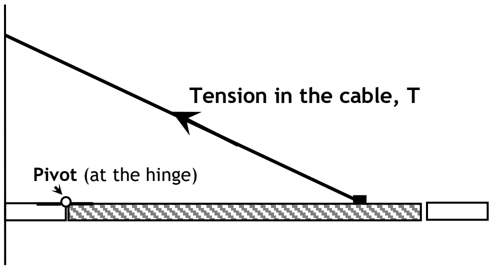
Moment is defined as the product of force and the perpendicular distance between the line of action of the force and the pivot. Here's the equation:

Moment = Force x distance $M = F\ d$

In many cases the forces will naturally act in a direction that's perpendicular to the pivot direction, e.g. a toy mobile.

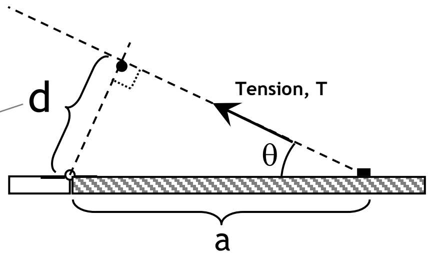


However, in some cases, you may need to use some trigonometry to find the perpendicular distance before you attempt to take moments, e.g. a trap door in the attic



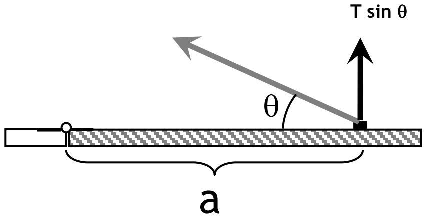
There are two ways to do this:

1) Look along the line of action of the tension force - put a dot at the point along this line that is closest to the pivot. The line joining this dot to the pivot (hinge) is now the perpendicular distance, d, and can be found by basic geometry.
   ($\sin\theta = d / a$, $\therefore\ d = a \sin\theta$,
   hence, Moment = $T \times a \sin\theta$)



2) Resolve the tension.
   The horizontal component acts towards the pivot, and hence creates no moment.

   The vertical component is at 90° to the direction of the pivot, and hence , moment,
   $M = T \sin\theta \times a$



Notice that the final equation used to calculate moment is identical in both cases!

The Conditions needed for equilibrium

There are two conditions that must be satisfied if an object can be said to be in equilibrium:

1. The resultant force (in any given line) is zero.

2. The net moment (about any pivot) is zero.

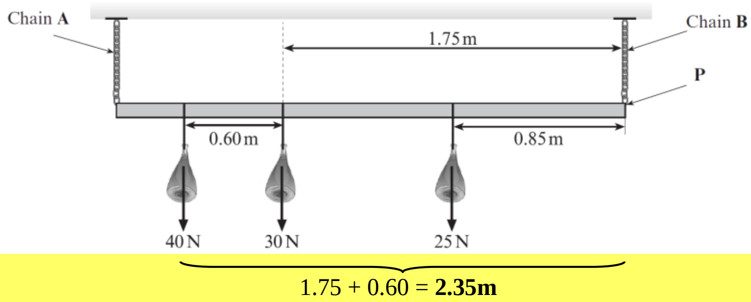
The second condition is also known as the "Principle of moments":

If an object is in equilibrium, then the resultant (or 'net') moment about any pivot is zero.

This is in effect like stating that if an object is 'balanced' on a pivot, **then the total clockwise moment must equal the total anticlockwise moment.** This idea is used to calculate unknown distances or forces.

Example

By taking moments about a suitable pivot, find the tension in both chains, A and B. The horizontal bar's length is 3.0m; assume its weight is negligible.



Strategy

1. **Choose a pivot** (In this case we've chosen the base of chain B, thus eliminating the tension here, T_B from the moments equation).
2. Find the perpendicular distance from each force to the chosen pivot.
3. Take moments : M = M

Taking T_A as the tension in chain A, $T_A \times 3 = (40 \times 2.35) + (30 \times 1.75) + (25 \times 0.85)$

$\therefore$ $T_A \times 3 = 167.75$ Nm

$\therefore$ $T_A = 167.75 / 3 = \mathbf{55.9\ N}$

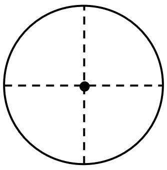
To find the tension in chain B, we could repeat the above with a pivot chosen at the base of chain A, however, we can now apply the 1st condition of equilibrium (no net force) :

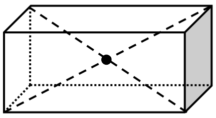
$$T_A + T_B = 40 + 30 + 25$$

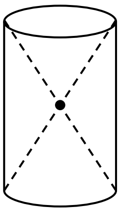
$$\therefore \quad T_B = 95 - T_A = 95 - 55.9 = \mathbf{39.1\ N}$$

Centre of gravity

This is the point at which all the weight of the object is considered to act, and makes calculations like those seen above much easier. You should memorise the following 3 examples:



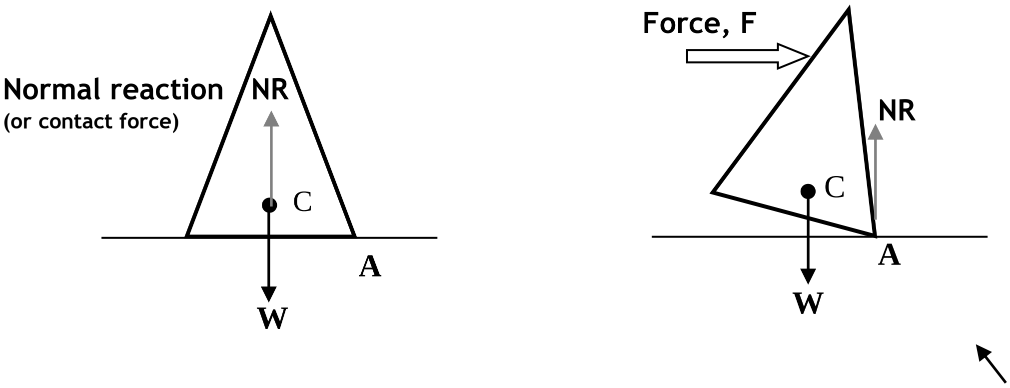




Centre of gravity and toppling angles

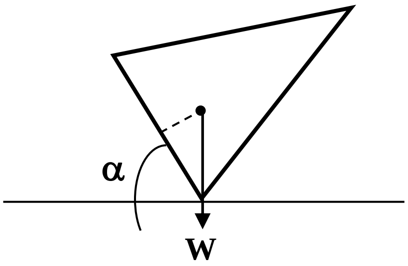
One example of the usefulness of the idea of a centre of gravity is when trying to evaluate the stability of an object, i.e. its toppling angle.

A tilted object will topple over when its weight (acting from the centre of gravity) acts just outside the corner of the object. This is explained in terms of moments.



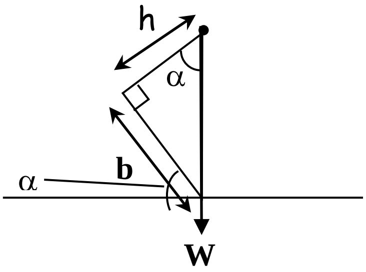
Once a force is applied, the object starts tilting. If it is held in the position shown, and then the force is removed, the object will fall back to its upright position. Why ?
Once tilted, the normal reaction then acts from the pivot (at A), and hence creates no moment. The weight now creates an anticlockwise moment about point A, and hence the object rotates back upright.

The toppling angle is shown (➔). At a slightly higher value of the angle, α, the weight would then act outside the corner, and start creating a clockwise moment, which would cause the object to topple over.



Taking a closer look at a small triangle inside the cone, we get this diagram:

$\alpha = \tan^{-1}(b / h)$



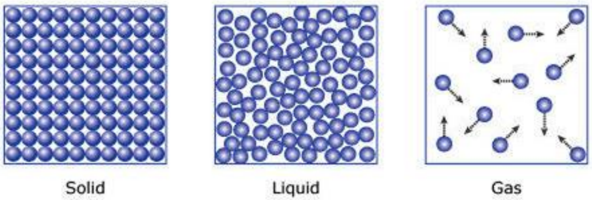
Density

Density is defined as the mass per unit volume:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

So, if mass, m, is measured in **kg**, and volume, V, is measured in **m^3**, then density, ρ , is measured in **kgm^{-3}.**

In general, solids have high density values whereas gases have very low values:



Section 1.2 - Kinematics

First, some basic definitions that you'll need to learn :

Quantity	Definition	Symbol	Unit	Equation
Displacement	The displacement of a particle is defined as the (straight line) distance it travels in a given direction.	x	m	
Velocity	Rate of change of displacement.	v	ms^{-1}	$v = x / t$
Speed	**Distance** travelled per unit time.	v	ms^{-1}	$v = x / t$
Acceleration	Rate of change of velocity.	a	ms^{-2}	$a = \Delta v/t$

In addition, the words 'mean' and 'instantaneous' are applied to both speed and velocity.

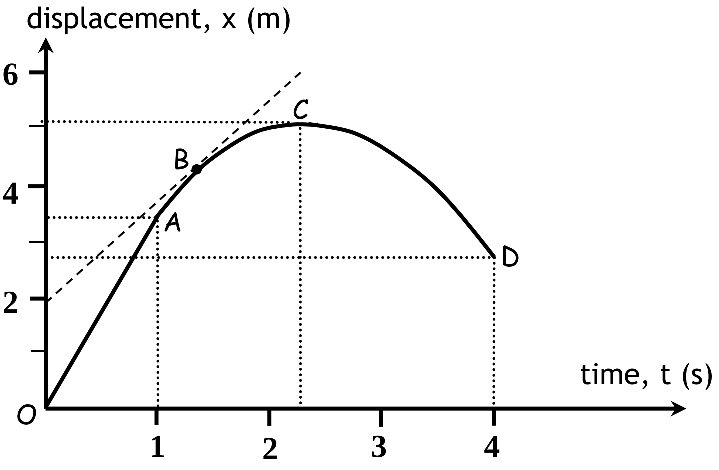
Mean is obviously the average measured over a significant amount of time. If calculated over a whole journey, then velocity = total displacement / total time.

'Instantaneous' is the speed or velocity at any one instant, and is calculated by taking a very small time interval (or by taking a tangent to the curve on a displacement-time graph – see later).

Displacement-time graphs

The graph opposite shows how the displacement of a particle travelling in a **straight line** changes with time.

This curve is a complete description of the motion of the particle.



There's just one 'rule' that applies to this type of graph :

The gradient of the graph at any point gives a value for the velocity at that point.

Hence, to calculate the **instantaneous** velocity at a point in time, we need to find the gradient of the tangent to the graph at that point.

To calculate the **average** velocity between two points, we divide the change in displacement between those two points by the time between them, e.g.

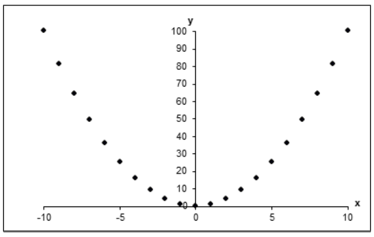
The average velocity between points A and C is $v_{AC} = \Delta x / t = 5.1 - 3.5 / 1.3 = 1.23\ ms^{-1}$

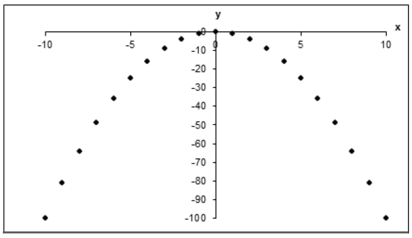
The instantaneous velocity at point B is v_B = gradient = $(6 - 2) / 2.3 = 1.74\ ms^{-1}$

For a situation where the velocity is changing (i.e. a curve), it is very difficult to judge just by looking whether or not the acceleration/deceleration is constant.

An examination question may ask you to calculate the gradient several times in order for you to make a judgment if the velocity is changing in regular increments, i.e. constant acceleration.

It may be useful to remember that if the acceleration is constant, then the curve on a displacement-time graph would be **parabolic**, i.e., it will look like a graph of $y = x^2$ (or $y = -x^2$), as follows:





Velocity-time graphs

There are two ‘rules’ for this type of graph:

1) The gradient of the velocity–time graph represents the acceleration.

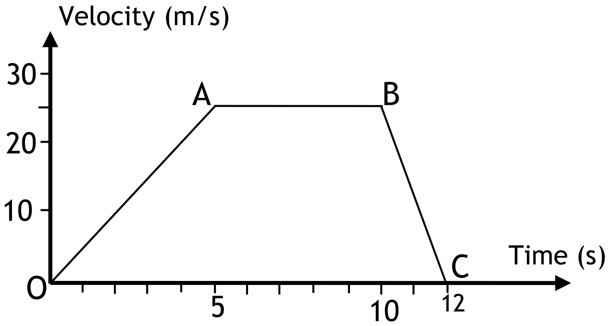
If the line is curved, then to find the **instantaneous acceleration** find the gradient of the **tangent** to the line at that point.

2) The AREA under the velocity-time graph represents the displacement travelled.

The graph (➔) shows an object accelerating from rest.
In section OA, it accelerates up to a velocity of 25 m/s. Since the gradient is constant, the acceleration must be constant also (rule 1, above).

The gradient in section AB is zero, hence the acceleration is zero, i.e. constant velocity.

From B to C the object has constant deceleration (constant negative gradient).



The displacement in any section (or the whole journey) can be found by applying rule 2:

$$\left.\begin{array}{l} \text{Area under section OA} = 62.5\text{m} \\ \text{Area under section AB} = 125\text{m} \\ \text{Area under section OA} = 25\text{m} \end{array}\right\} \quad \text{Total} = 212.5\text{m}$$

Uniformly accelerated motion - kinematic equations

This whole section relies upon the fact that we can assume the **acceleration is constant**. So, for example, when considering the motion of an object we must assume air-resistance is negligible. This approximation applies for many practical cases.

Think about a particle moving along a straight line with constant acceleration, **a**. Suppose that its initial velocity, at time **t** = 0, is **u**. After a further time t, its velocity has increased to **v**. From the definition of acceleration as (change in velocity) / (time taken), we have:

$a = \frac{(v - u)}{t}$ or, re-arranging $\boxed{\mathbf{v = u + at}}$ ------------- ①

Since the change in velocity is **UNIFORM,** we can define the average velocity as, $v_{av} = \frac{v + u}{2}$

The correct symbol for displacement is, "x", and the equation for displacement is , $x = v_{av}\ t$
(re-arrange velocity = displacement / time)

So, substituting for v_{av} we get: $\boxed{\mathbf{x = \left(\frac{v + u}{2}\right) t}}$ ------------- ②

We can get a third equation by substituting for the "v" in this equation from eq. ① like this:

$$x = \left(\frac{v + u}{2}\right) t = \frac{(u + at + u)\ t}{2} = \frac{(2u + at)\ t}{2} = \frac{(2ut + at^2)}{2}$$

$\boxed{\mathbf{x = ut + \tfrac{1}{2} a t^2}}$ ------------- ③

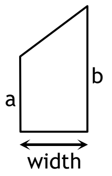
Finally , the fourth equation is obtained by substituting for "t" in eq. ② (from eq. 1)

$$x = \left(\frac{v + u}{2}\right) t = \left(\frac{v + u}{2}\right) \cdot \frac{v - u}{a} = \frac{(v^2 - u^2)}{2a}$$

$\therefore \quad 2ax = v^2 - u^2 \qquad \therefore \quad \boxed{\mathbf{v^2 = u^2 + 2ax}}$ ------------- ④

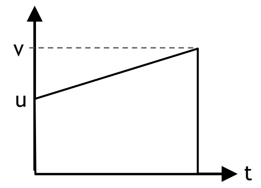
Equations 2 & 3 can also be derived by using a velocity-time graph, as follows:

The displacement is calculated from a v-t graph by the area between the line/curve and the t axis, therefore, using the formula for the area of a trapezium,



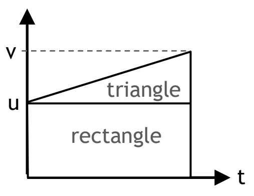
$$\text{Area} = \frac{(a + b)}{2} \times \text{width}$$

$$x = \frac{(v + u)}{2} \times t \qquad (= \text{Equation 2 !!})$$



If we split the trapezium into a rectangle and a triangle then the displacement is now given by the sum of the area of these two sections:

$$x = \underbrace{ut}_{\text{Area of rectangle}} + \underbrace{\left(\frac{v - u}{2}\right) \times t}_{\text{Area of triangle}}$$



This equation then becomes equation 3 if we substitute for "v – u" with "at" (equation 1).

Therefore, the four equations for the motion of the particle in uniformly accelerated motion are:

$$\boxed{v = u + at} \qquad \boxed{x = \left(\frac{v + u}{2}\right) t} \qquad \boxed{x = u\,t + \tfrac{1}{2} a\, t^2} \qquad \boxed{v^2 = u^2 + 2\,a\,x}$$

Example

A car in a land speed record attempt can maintain an acceleration of 7.2 m/s^2. The car's speed at the start of the run is 5 m/s. If the target speed at the end of the run needs to be 340 m/s, how much distance is needed to attain this speed?

We need to find 'x' but are not given 't', therefore, we need to choose an equation that does **not** contain 't'. Hence, we must use $v^2 = u^2 + 2\,a\,x$

Re-arranging ➔ $x = \dfrac{v^2 - u^2}{2\,a} = \dfrac{340^2 - 5^2}{(2 \times 7.2)} = \mathbf{8026\ m}$

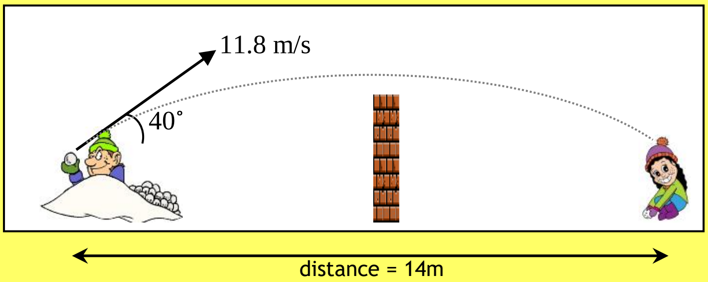
Two dimensional motion

In most cases, the situation given is for an object moving in a gravitational field, where it is assumed that the air resistance is negligible, or where there is no air, e.g. the Moon's surface. In such situations there is a resultant force, and hence acceleration, in the vertical direction only, although the object's velocity may have both vertical and horizontal components. The kinematic equations can be applied to the vertical component, but the horizontal component has no acceleration, and hence we can only apply $v = x / t$.

Example

A snowball is launched at a velocity of 11.8 ms^{-1} as shown in the diagram ➔. Calculate,

(a) the time it takes to hit it's target,
(b) the maximum height of the wall, if it is 7m from the man (1/2 way).



Strategy - a good setup !

Taking **up** as positive,

x_x = 14m	x_y =
u_x = 9.04 ms^{-1}	u_y = 7.58 ms^{-1}
t =	v_y =
	a_y = - 9.81 ms^{-2}
	t =

(a) Using, $v = x / t$, $\quad t = \dfrac{x_x}{u_x} = \dfrac{14}{9.04} = \mathbf{1.55\ s}$

(b) Now that we also have the time in the 'y' direction, we have the necessary minimum of 3 quantities in order to calculate the others.

We must remember that the time to reach the wall will be **half** of the time calculated in part (a), since we assume there's no air-resistance, hence, t = 0.775 s :

$$x_y = u_y t + \tfrac{1}{2} a_y t^2 = (7.58 \times 0.775) + (0.5 \times -9.81 \times 0.775^2) = 5.875 - 2.946$$

$\therefore \quad x_y = \mathbf{2.93\ m}$ (above the height at which it is launched !)

Note that in the data book, the symbol for displacement is '**x**' not 's' !!

Note that some quantities given are not immediately obvious. Here's an example.

A rock is thrown horizontally from the top of a cliff at a speed of 8 m/s. If it takes 4.2 s to hit the sea below, how high is the cliff above sea level?

Strategy – a good setup !

Choosing **down** as positive.

x_x =	x_y =
$u_x = 8.0\ \text{ms}^{-1}$	u_y =
t = 4.2 s	v_y =
	a_y =
	t = 4.2 s

At 1st glance, it seems that only x_x can be calculated, however, we know the acceleration is 'g' = $9.81\ \text{ms}^{-2}$.

Also, if the stone is launched horizontally, then the initial vertical velocity must be zero, i.e. $u_y = 0$. So, in fact, we already have 3 quantities out of the 5 in the vertical direction, and hence we can calculate any of the remaining quantities with one of the relevant equations. (BTW : $x_y = 86.5\text{m}$)

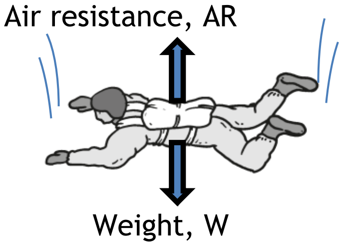
Other similar quantities :
An object 'dropped from rest' : $u_x = 0$ and/or $u_y = 0$
For projectiles starting and ending at the same height, $x_y = 0$
For an object thrown up, and at its greatest height, $v_y = 0$

However, for an object ending up at rest on the ground $v_y \neq 0$!!!!

This is because the kinematic equations only work if the acceleration is constant. The acceleration changes as soon as a falling object makes contact with the ground, and hence we can only apply the equations to the point **just** before it hits the ground.

Terminal velocity

All the work above on kinematic equations is done under the assumption that the acceleration is constant. Strictly, this is only true where there is no air resistance. When we take air resistance into account, the acceleration is non-uniform, and reduces to zero as the object gains speed.



For an object moving vertically downwards, there are usually just two forces, as shown.

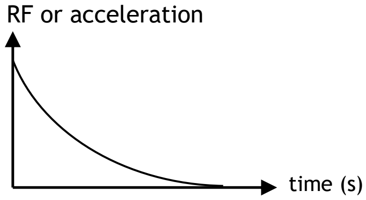
At the beginning, the sky diver's vertical speed is zero (or very close to zero), and hence there's no air resistance.

There's therefore a downward resultant force created by the weight. This causes the skydiver to accelerate downwards.

As the skydiver's speed increases, he/she pushes downwards on the air molecules with an increasing force, since the air's momentum is changing at a greater rate.

Hence the air molecules, by newton's 3rd law, are creating an upward force on the skydiver (air resistance) that increases with speed.

Eventually, the air resistance becomes equal to the weight, and terminal velocity is reached. A graph of resultant force or acceleration would look like this ➔



Section 1.3 - Dynamics

Newton's 3 'Laws of Motion'

The first law states that if the resultant force on an object is zero then the object will either remain stationary, or if it was already moving, then it will continue to move with uniform motion.

Newton's 2^{nd} law states that the rate of change of momentum (= mass x velocity) is directly proportional to the applied (resultant) force and occurs in the same direction as the force :

$$F = \frac{\text{change in } (mv)}{\text{Change in } (t)} = \frac{d\,(mv)}{d\,(t)}$$

The 3^{rd} law states that if body A exerts a force on body B, then body B exerts an equal but opposite force on body A. (To every action there is an equal and opposite reaction).

Newton's 2^{nd} Law can be simplified in the case where the mass is constant:

$$F = m\,\frac{d\,(v)}{d\,(t)} = m\,\frac{(v - u)}{t} \qquad \text{but} \quad \frac{v - u}{t} = \text{acceleration}$$

$$\therefore \quad \boxed{\Sigma F = m\,a}$$

F is measured in NEWTONS , N.
m is measured in kilograms , kg.
a is measured in m /s ^{2}.

Note : 'F' in this equation is ALWAYS the RESULTANT force.

Since weight is a type of force, we can apply the force equation to calculate it:

$$F = m \times a \quad \text{hence} \rightarrow \quad \boxed{W = m\,g}$$

where W = weight, m = mass, g = acceleration due to gravity / gravitational field strength. The value of 'g' is given in the data book as: $g = 9.81\ ms^{-2}$, which is the value close to the Earth's surface.

It's important to remember the distinction between **mass** and **weight.**

Mass is a measure of how much 'matter' or material an object has. It's measured in **kg.**

Weight is a measure of how large the force of gravity is on an object. It is measured in **N.**

Newton’s 3rd law

In order to accelerate at the start of a race a formula one car’s engine must create a large force. This force is transmitted to the back wheels.

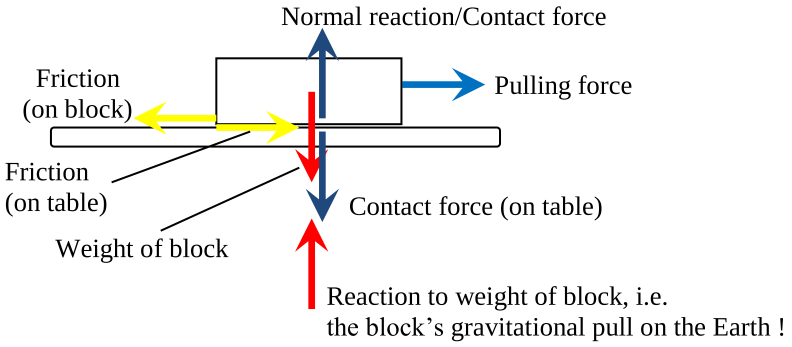
The wheel pushes backward onto the road.

The road pushes with an equal but opposite force onto the wheel.

The effect of the force of the road on the wheel is of course to accelerate the car forwards. The effect of the wheel on the road is to accelerate the Earth backwards!

> Although the two forces are **always** equal and **always** opposite, they never ‘cancel out’ since they always act on **DIFFERENT OBJECTS.**

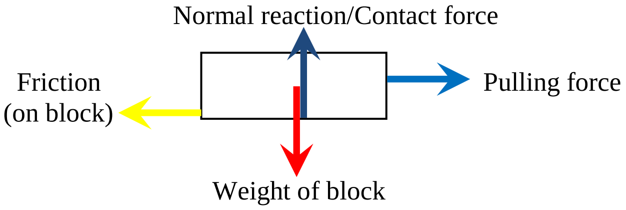
Situations in real life can therefore get very complicated! Look at this relatively simple situation where a block is being pulled along the surface of a table, assuming there’s no air-resistance (!):



Note : The (newton’s 3rd law) reaction to the pulling force, acting on the object that’s doing the pulling, has not been shown !

Some of the forces shown above are acting on the block, some on the Earth, and some on the table. In order to calculate the effect on the motion of the block, we must consider only those forces acting on the block itself.

Thus we draw a **free body diagram,** i.e. a diagram that shows only one object, and any forces acting on it. Here’s the free body diagram **for the block:**



This makes the situation must simpler. It can be further simplified by grouping the left and right forces together, the up and down forces together, and then considering the vertical and horizontal motions separately.

Momentum

Momentum is the product of mass and velocity. $p = m v$

The units for momentum are **kg ms^{-1}**

When interactions and collisions between 2 or more objects are studied it is seen that the total momentum before the interaction/collision and after is the same (even if some energy is 'lost' from the system of colliding objects). This is known as the conservation of momentum:

The Principle of Conservation of Momentum

"The total momentum of a system of interacting bodies will remain constant if there are no external forces acting".

Momentum is a **vector**, and hence we must remember to state its **direction**, especially when applying the conservation of momentum as shown by the following example.

Example

A 'bumper' car in a fairground of mass 95kg is travelling at a speed of 2.8 ms^{-1} when it collides with another car (initially not moving) of mass 140kg. If the speed of the 1st car after collision is 0.4ms^{-1} in the opposite direction, calculate the velocity of the 2nd car.

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

$$(95\text{x}2.8) + 0 = (95 \text{ x } -0.4) + (140 \text{ x } v_2)$$
$$266 = -38 + 140v_2$$
$$\therefore \quad 266 + 38 = 140\, v_2$$
$$\therefore \quad v_2 = \mathbf{2.17\ ms^{-1}}$$

Always a good way to start !!

Notice the negative sign before the "0.4" - the forwards direction of the 1st car is taken as positive, hence the backwards motion is negative.

Elastic and inelastic collisions

If you calculate the kinetic energy ($E_k = 0.5mv^2$) in the example above you will see that the E_k before is 372.4 J, but that after the collision, the total E_k of both cars is 337.7 J. This is an example of an **inelastic collision**, where some of the kinetic energy of the 'system' is lost to the surroundings.

If you try to calculate the kinetic energy, remember that 'energy' is a **scalar**, and hence the direction of the car is irrelevant !

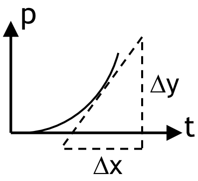
In an **elastic collision,** no kinetic energy is lost.

Elastic collisions can only realistically occur when individual particles are interacting, e.g. an alpha particle approaching another alpha particle - most everyday collisions incur a significant kinetic energy loss, but remember that we can still apply the conservation of **momentum!**

Also remember that newton's 2nd law refers to momentum: F = Rate of change of momentum

This means that if we plot a graph of momentum against time, then,

Force is equal to the gradient of the momentum-time graph.



Section 1.4 - Energy concepts

Work done

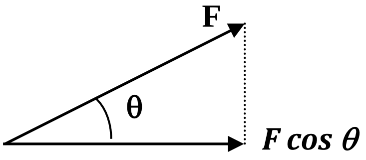
If a body moves as a result of a force being applied to it, the force is said to be doing work on the body. The work done is given by ➔ where 'x' = **distance moved in the direction of the force.**

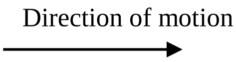
$$\boxed{W = F\,x}$$

Remember that: **Work done is always equal to the energy transferred.**

Hence the unit for work done is the joule, J.

If the force on an object, F, causes it to move in a direction other than its own, as shown below, then we take only the **component** of the force that acts in the direction of movement:





So, work done ,

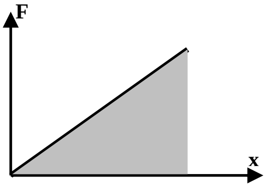
W = F. cos θ . x = F x cos θ

Force - distance graphs (Also seen in next section)

If a graph is plotted of the applied force against distance, then the area under the graph is equal to the work done by the force on the object. **This is true whether the force is constant or not.**

Hooke's law states that the force exerted on a material is directly proportional to the extension. Thus, **F = k x ,** where k = the spring constant (see next section for more details).

Therefore, a graph of force against extension for a material obeying Hooke's law looks like this:



Hence, the energy stored in this material (in the form of elastic potential energy, EPE) is :

ΔEPE = Work = area of triangle = **½ F x**

since F = kx (Hookes' law), **$\Delta EPE = ½\,kx^2$**

Kinetic and potential energy

These equations are given in the data book in the examination:

$$\boxed{E_k = ½\,mv^2} \qquad \boxed{\Delta E_p = mg\Delta h} \qquad \boxed{E_{elastic} = ½\,kx^2}$$

where E_k = kinetic energy, ΔE_p = change in gravitational potential energy, and
$E_{elastic}$ = elastic potential energy

Work-energy theorem

From page 11, we have the kinematic equation, $v^2 = u^2 + 2ax$.
If we substitute for 'a' from F = ma, the kinematic equation above becomes:

$$\boxed{Fx = \frac{1}{2}mv^2 - \frac{1}{2}mu^2}$$

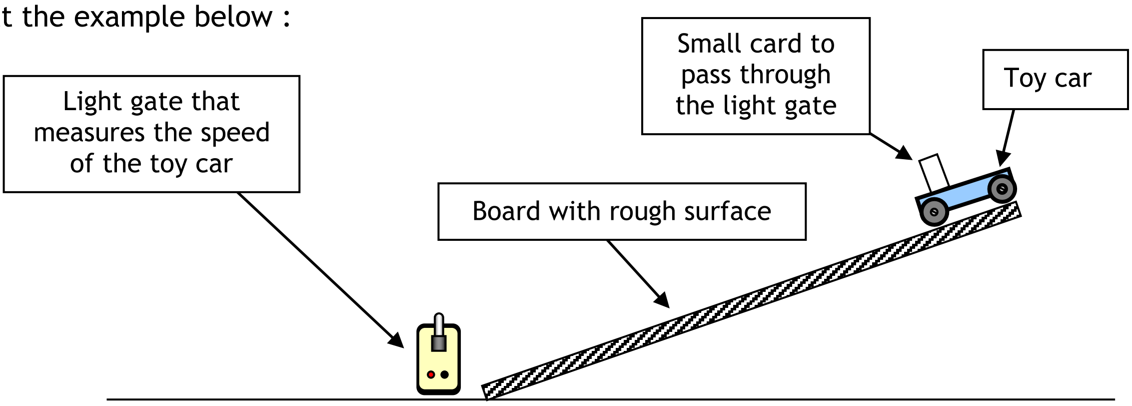
So, a force pushing an object horizontally does work on the object equal to "F x", and in the absence of friction etc, this work translates to a gain in kinetic energy. This relates directly to the 4th line on the previous page ("Work = energy transferred").

Conservation of energy

The work-energy theorem above assumes there are no dissipative/resistive forces involved, i.e. that the work done on an object transfers perfectly to kinetic energy. In most real situations here on earth, there's always some friction, and usually air-resistance too. These forces transfer some of the energy into wasted forms of energy like heat and sound.
Even if some energy is 'lost' from the system of objects we're looking at, the total energy is always conserved – this is the conservation of energy:

Energy cannot be created or destroyed, only transferred from one form to another.

Look at the example below :



If we assume that no friction or air-resistance are acting on the toy car, the gravitational potential energy, E_p , would transfer perfectly into kinetic energy, E_k. The speed **calculated** would be the 'theoretical maximum'.

$$\boxed{\Delta E_p = E_{k\,gain}}$$

However, when we also consider frictional forces, we then write ➔

$$\boxed{\Delta E_p = E_{k\,gain} + W}$$

where 'W' is the work done by the frictional forces (W = F x).
The speed **measured** would be significantly less than the 'theoretical maximum' calculated with no frictional forces.

Power

Power is defined as the rate of doing work. It is therefore also the rate of transferring energy, and hence the equation for power is either $\boxed{P = \frac{W}{t}}$ or $\boxed{P = \frac{E}{t}}$

Another useful expression is given by substituting for 'W' as 'force x distance' or 'Fx' :

$P = \frac{F\,x}{t}$ but since x / t = speed, this becomes $\boxed{P = F\,v}$

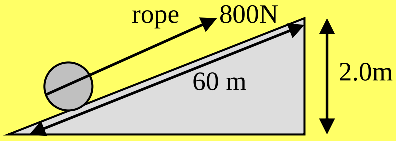
P = F v applies to situation where an object has a force exerted on it that is trying to accelerated it, but is being balanced by another force, e.g. friction, which means that the resultant force is zero, and hence the object is moving at a **constant speed.**

Efficiency

Efficiency is a quantity used to describe how much useful energy a device or machine produces as compared to the amount of input energy, and is usually expressed as a percentage. Thus,

$$\boxed{\text{Efficiency (\%)} = \frac{\text{Useful energy transfer}}{\text{Total input energy}} \times 100\ (\%)}$$

Example



*A rock of mass 150kg is being pulled up a rough incline at a **steady speed** of 0.8 m/s by applying a steady force of 800N to a rope attached to it, as shown ➔. Calculate,*

(a)the gravitational potential energy acquired by the rock at the top of the slope,
(b) the efficiency of this pulling system,
(c)the friction acting on the rock,
(d) the power developed by the person pulling the rope.

(a) $\Delta E_p = mg\,\Delta h = 150 \times 9.81 \times 2 = \mathbf{2943\ J}$

(b) Total input energy = W = F x = 800 x 60 = **48 000 J**

$\text{Efficiency} = \frac{\text{Useful out}}{\text{Total input}} \times 100 = \frac{2943}{48\,000} \times 100 = \mathbf{6.1\%}$

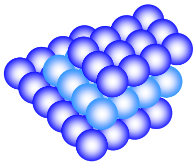
(c) Work done by friction, W_{FR} = 48 000 - 2943 = **45 057 J**

Hence, friction, FR = W_{FR} / x = 45 057 / 60 = **751N**

(d) P = F v = 800 x 0.8 = **640 W**

Section 1.5 - Solids under stress

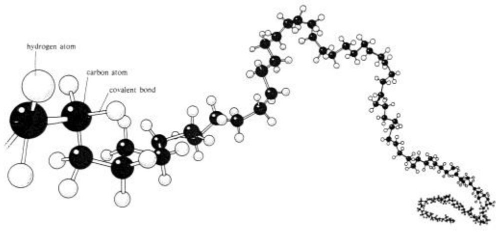
3 types of solid



1) **Crystalline** : These solids have short and long-range order i.e. there is a regular pattern of atoms (or sometimes molecules) over a distance of at least 100 atomic diameters. Almost all metals are examples of **poly**crystalline solids, as well as many minerals e.g. salt, where there are many small crystals called **grains.** Each grain has a different orientation. This makes the structure very strong. The line between each grain is known as the **grain boundary**.

2) **Amorphous** : The term amorphous (meaning 'without shape or form') is used to describe solid substances in which there is little or no long-range order in the arrangement of the particles. It can be likened to an instantaneous or 'frozen' picture of the internal structure of a liquid. In practice there are few examples of solids with such totally random structures, however, glass or brick are given as examples in which there may be ordered clusters of atoms (much smaller than the 'small' crystals found in polycrystalline materials like metals).

3) **Polymeric** : Polymers consist of very long chains of carbon atoms (commonly in excess of 1000 atoms !) bonded to hydrogen and other atoms. Polymers can be natural (e.g. cellulose, protein, rubber, etc.) or synthetic (e.g. polyethane [shown ➔] , polythene, polystyrene, nylon, etc.).



The effect of external forces on solids

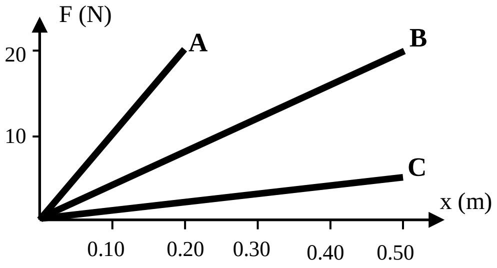
Many materials that are crystalline or amorphous will extend under tension in a linear way, at least for a limited range of force. They are said to follow **Hooke's law** :

Provided, the elastic limit is not exceeded, the extension of a body is proportional to the applied load.

$$F = k x$$

Where, F = force (N) ; k = spring constant (Nm^{-1}) ; x = extension (m)

This leads to force-extension graphs like this ➔.



Material 'A' would feel 'stiffer' than material 'C', since with the same force, 'A' extends much less. 'A' would have a higher value for 'k' as seen in the equation representing Hooke's law, above.
In fact **'k' is equal to the gradient** of this graph.

Remember !!! The area under the graph is equal to the work done by the force on the object. Hence, the energy stored in a material (in the form of elastic potential energy, EPE) is :

$$\Delta EPE = \text{Work done} = \text{area of triangle} = \tfrac{1}{2} F x$$

since F = kx (Hookes' law), $E = \tfrac{1}{2} kx^2$

Stress & Strain

The problem with using the elastic constant is that its value is different for each specimen of a material that has a different shape or size. A more useful quantity is the **Young's Modulus**, which is **independent** of the material's length and width. This enables a fair comparison of the stiffness of different materials. The **Young's Modulus** is defined as follows:

$$\boxed{\text{Young's Modulus, } E = \frac{\text{Stress}}{\text{Strain}}} \qquad \boxed{E = \frac{\sigma}{\varepsilon}}$$

stress, σ = Force / Area → σ = F/A units : **Nm^{-2}** or Pascal, **Pa**

strain, ε = extension / original length $\varepsilon = l / \Delta l$ units : **None !**

Hence the unit for Young's Modulus is **Nm^{-2}** (or Pascal, Pa) – the same as the unit for stress.

So, substituting these two definitions for stress and strain into the young's modulus equation (not given in data booklet):

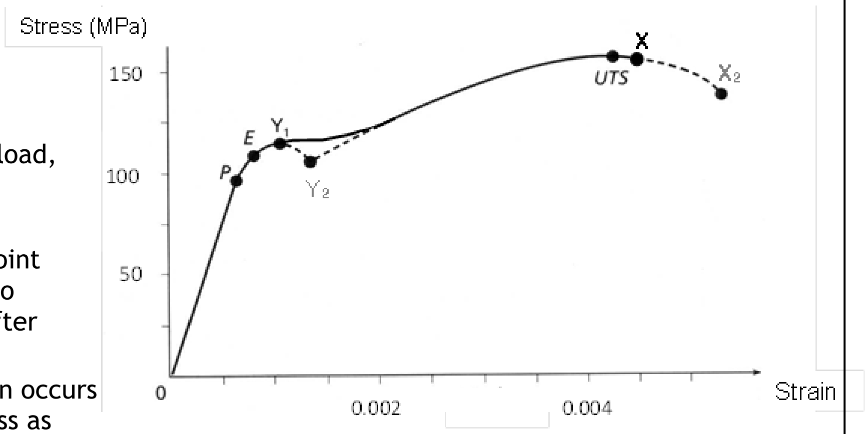
$$\boxed{E = \frac{F / A}{\Delta l / l}}$$

or, if you prefer

$$\boxed{E = \frac{F\ l}{\Delta l\ A}}$$

Stress & Strain graphs for different materials

1) Crystalline



Analysis

OP - extension proportional to load, i.e. follows Hooke's law.

Point P - limit of proportionality.

Point E - elastic limit; up to this point the material will return to original shape and size after force is removed.

Y_1 - yield point; large extension occurs with little or no extra stress as planes of atoms start to slip past each other.

Y_2 - material stretches so much in some materials, e.g. copper, that the stress is actually reduced for a while.

EX - plastic region; material will not return to original size once it's entered this region.

X - material breaks; signifies the UTS (ultimate tensile strength) for most materials.

X_2 - Some very ductile metals like copper become narrower and extend rapidly just before breaking (known as necking).

Explaining the behaviour of the material in different parts of the graph

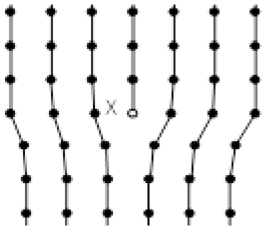
Metals (and minerals like salt) have a regular atomic pattern. Any force exerted on a crystalline material will therefore be transmitted equally to each bond because of the long range order. So, for small extensions, the behaviour of the material as a whole is very similar to the behaviour of a single bond, where, $F \alpha x$, and hence the graph is straight from O to P.

Plastic behaviour occurs when a solid is extended beyond its elastic limit. The atoms in one plane can slip over the atoms in the other plane, if the forces are great enough.

A more detailed look at the 'slipping' of planes brings in the idea of **dislocations** to explain the relative ease with which a ductile material extends in the plastic region.

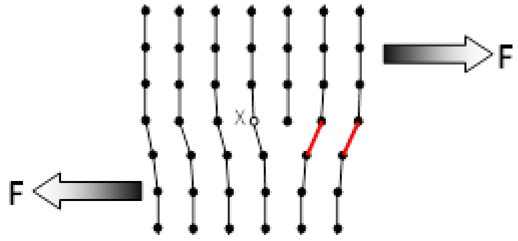
Sometimes, as molten metal cools down when it is smelted, mistakes happen as the metal ions join the crystal. A frequent mistake — one every million atomic planes or so — is that half a plane of atoms is missed out. This is known as an edge dislocation.

Edge dislocations are the key to plastic deformation.
The secret is in the bonds around the ion X.
These bonds are all under strain (they're longer than usual), so they are places of weakness.



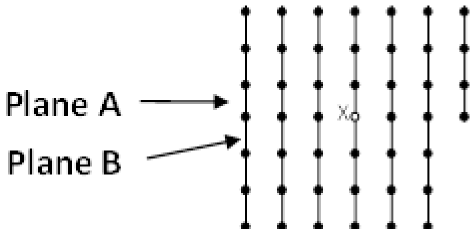
Suppose the structure to the right is put under tension.
If the forces, F, are small, the horizontal bonds are stretched reversibly (if the force is removed, they contract again) and the material behaves elastically.

If the forces become larger, the already strained bonds below and to the right of X [shown in red] are stretched even more and at some point, the Yield Point of the material, they snap making the dislocation migrate to the right.



If the same force that causes this movement continues to be applied, the dislocation carries on moving, through the snapping and reformation of bonds, until it reaches the edge of the crystal.

In this way, the dislocation has moved from left to right through the crystal. It appears as if plane A and plane B have slipped over each other. However, it has been achieved more easily since only one (short) line of bonds, rather than a whole plane, has been broken at a time.

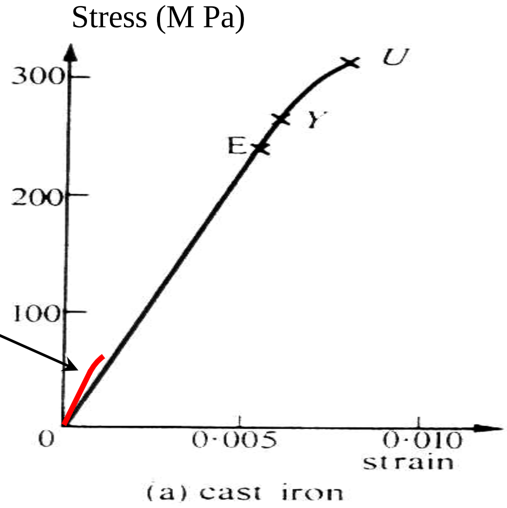


Metals can therefore be strengthened (by making plastic deformation less likely) by :

1) Having smaller 'grains' – this restricts the movement of dislocations.
2) Introducing foreign atoms. In effect this creates a point dislocation that inhibits the movement of dislocations as described above.

2) Amorphous

Glass is categorised as an amorphous material, and is very brittle. Cast Iron is also a brittle material. Shown right is the stress-strain curve for cast iron, and added in red, the curve for glass.



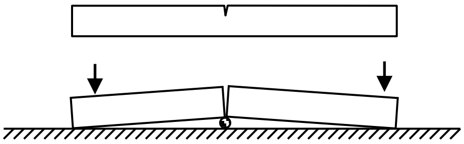
Neither curve has a ‘plastic’ region since both are for brittle materials.

Notice that although glass has a similar value for its Young’s Modulus to that of cast iron (similar gradient), i.e. similar **stiffness**, it has a significantly lower value for its ultimate breaking stress of about 70 M Pa, meaning it has less **strength** than iron.

Analysis and explanation

Glasses have the stiffness and brittleness of crystal without their large-scale regularity of structure or planes of weakness. They have an **amorphous** structure, with no regularity in the way that their molecules are locked together in the solid.
The lack of crystalline structure makes dislocation slip impossible – there isn’t enough long or short range order for dislocations to move. This means that stress which builds up on a surface crack is not ‘relieved’ by the movement of dislocations, as would happen in a ductile material. This means that the material will not have a plastic region. Hence, glass may be stiff, but it certainly isn’t strong.

Cracks



Glasses are brittle because cracks can travel through them easily. A relatively small stress can make a microscopic crack on the surface grow uncontrollably through the solid until it snaps in two.
This is used to shape sheets of glass, and for cutting tiles, as shown in the diagram above.

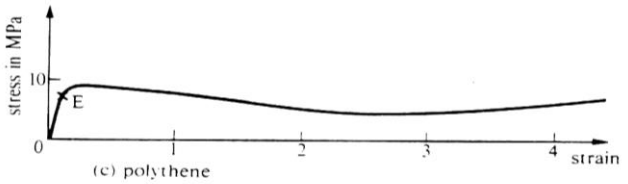
Firstly, a small crack is scored on the surface of the glass with a sharp instrument. Then a modest stress is applied to the glass in such a way as to force the crack open. The result is (usually) a clean fracture along the line of weakness defined by the original crack.

The initial crack does not have to be very deep, simply sharp. A short but narrow crack can result in a large local increase in stress. So the material at the crack tip will reach its ultimate tensile stress well before the rest of the material does. The crack will therefore be able to grow even though the average stress on the sample is well below the material’s tensile strength. Of course, once the crack has started to grow, the crack becomes sharper : the stress increase as the tip becomes larger, etc. The crack tip propagates through the sample at roughly the speed of sound until it reaches the other side!

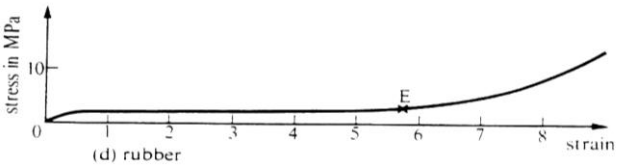
3) Polymeric

Analysis and explanation

The main factor that dictates the behaviour of a polymer is the **cross-links.** These are strong (covalent) bonds that form between adjacent / overlapping molecules, or even between different parts of the same molecule. If the molecules don't have many cross-links then they can slide over each other quite easily i.e. the polymer is stretchy, like rubber (latex). If you increase the number of cross-links by adding impurities like sulphur to the latex, the polymer then becomes more rigid. The 'latex' is then given a different name – 'vulcanite'.



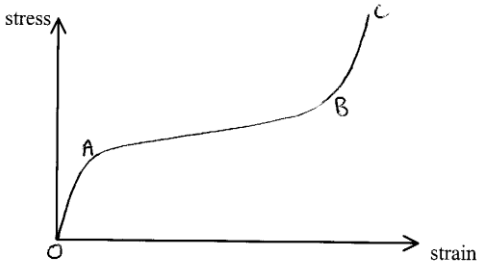
(c) polythene



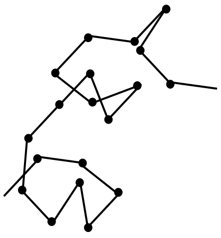
(d) rubber

We need to take a closer look at a typical stress-strain curve for rubber. You must be able to explain, on the **molecular level,** why it has three distinct sections :

The curve can be related easily to party balloons :
first blow hard (OA), then much easier (AB), then harder again (BC) – finally BANG (C).

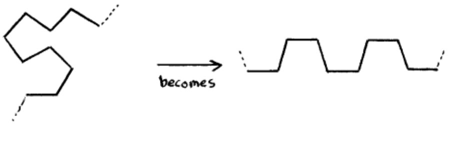


Rubber molecules are long and thin, resembling rods with swivel joints at periodic intervals (**one** molecule is shown ➔).



The cross-links are strong covalent bonds (in addition to the strong covalent bonds in between each molecule) but as already mentioned, are quite scarce in natural rubber (latex). Hence, there aren't enough cross-links to keep the molecules in a tangled, knotted mess.

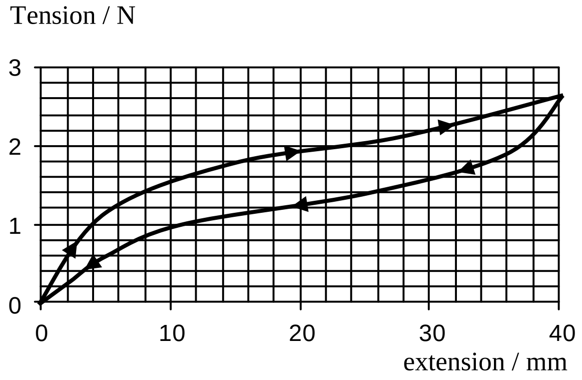
Weaker bonds are formed in the tangled mess of molecules known as a **van der Waals** forces. Every time one part of a molecule comes very close to another molecule (or a different part of the same molecule) a van der Waals force can occur – think of it as a weak bond that acts only over very short distances. Many of these are produced between the rubber molecules, that tend to keep the molecules stuck together. This explains the section **OA** of the graph i.e. the initial 'stiffness' of the rubber material.



The strength of these van der Waal deceases very rapidly with distance, and hence suddenly, at point **A,** the molecules begin untangling from themselves and from each other.This is why section **AB** of the graph is quite 'flat' i.e. there is a large extension of the rubber material without much extra effort. In this way, quite modest stresses can achieve strains of up to 5.

Once the molecule has been straightened out (point **B**), stretching the rubber any further requires that the strong covalent bonds in between each **molecule** are lengthened, as well as lengthening or breaking the strong covalent **cross-links**. This is much more difficult than simply unravelling the molecules, and so the graph becomes much steeper from this point on. The rubber **behaves** much like any other covalently bonded solid in section **B** to **C**, i.e. it is stiff and strong.

Hysteresis



The curve for the extension of a material is often different to the curve for the contraction. This is especially true for a polymeric material, again because of those cross-links.

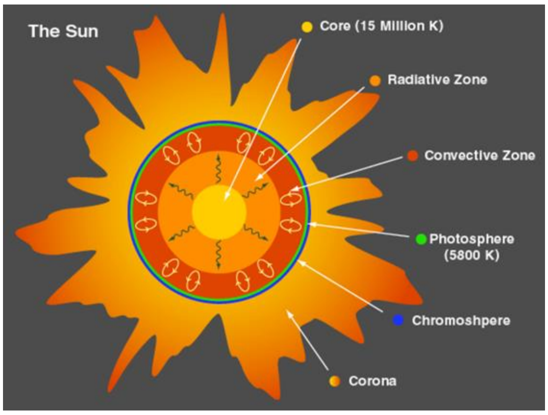
Looking at the force-extension graph (➔) for a rubber band, the extension curve has little extension at the start. This is because all those cross-links between the molecules are making it difficult to stretch.

Once fully stretched, these cross-links have re-attached at new positions, and when the tension is now slowly decreased, they again make it harder for the molecules to (initially) pass over each other, i.e. rubber band doesn't contract as easily as expected.

The net effect is that there's work done internally, a bit like friction. This work done over one extension-contraction cycle is released as heat, and its value is equal to the area between the two curves.

This is an example of hysteresis, and is the reason an elastic band will become hot if it is repeatedly stretched and released several times in quick succession.

Section 1.6 - Using radiation to investigate the stars



Stellar spectra

Stars don't have a definite surface; the light we see from a star comes from a layer of gas several hundreds of km thick, known as the **photosphere.**

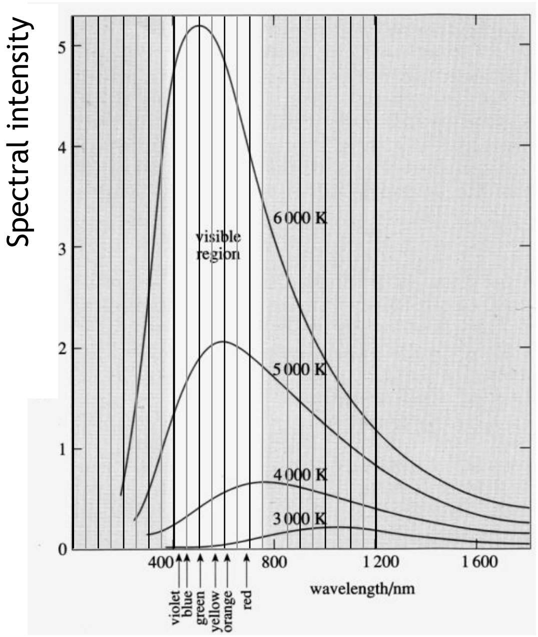
When light is emitted by a hot object like a star, we expect the light to have a wide range of wavelengths similar to the spectrum of a black body! A black body is defined like this:

> **A black body is a body (or surface) which absorbs all the electromagnetic radiation that falls upon it. Nothing is a better emitter of radiation at any wavelength than a black body at the same temperature.**

Although stars are obviously not black, they are almost perfect 'emitters', and so when we look at the light emitted by a star, we should get a continuous spectrum as shown opposite (i.e. all colours, all wavelengths).

However, some specific colours/wavelengths can be absorbed by the atoms in a star's atmosphere (and upper photosphere !), and so what arrives at our telescopes is an absorption spectrum, as shown ➔.

When the intensity of each small section of this is studied carefully, it is found to follow **Wien's law:**

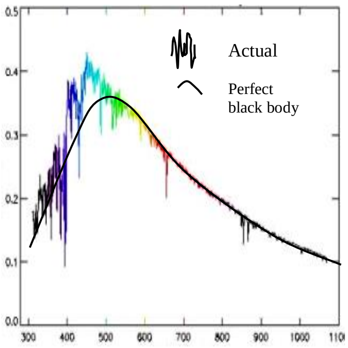


$$\lambda_{max} = \frac{W}{T}$$

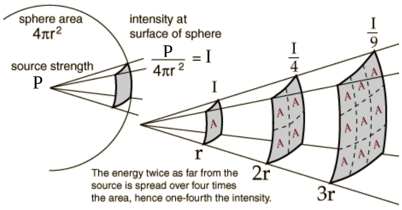
where, λ_{max} = the peak wavelength (m)
W = Wien's constant = 2.90×10^{-3} mK
T = the surface temperature of the star (K)

Notice how closely the black body curve agrees with the actual spectrum for our sun ➔.

The downward 'dips' are the absorption lines.



The inverse square law of light and Stefan's law



As you go further from a light source the amount of light energy striking each square metre each second decreases. This is because the light initially emitted is spread out over a larger and larger 'surface area' as it travels away from the source.

The 'amount of light energy striking each metre square per second' is known as the spectral intensity, I, sometimes known as 'flux density' or just 'flux'. It is given by the equation opposite ➔,

$$\boxed{I = \frac{P}{4\pi x^2}}$$

where, I = intensity (Wm^{-2}) ,
P = total power (luminosity) produced by the star (W),
x = distance from the source (m).

Note that $4\pi x^2$ is the surface area of an 'imaginary' sphere of radius 'x'; units = m^2.

It is found that the intensity of the light (that is, the power per metre square), **at the surface of a star**, is directly proportional to the fourth power of the surface temperature. This is known as **Stefan's law**:

$$\boxed{P = \sigma A T^4}$$

Dividing both sides by the area, A, the left side becomes "P/A" and is the intensity again (I=P/A), except this time,

A = surface area of the star = $4 \pi R^2$, where R = radius of star.

σ = Stefan's constant = 5.67×10^{-8} $Wm^{-2}K^{-4}$

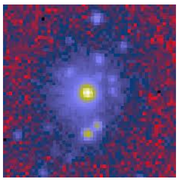
T = surface temperature of the star (K)

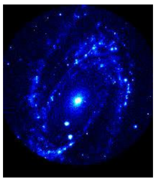
So, Stefan's law is the application of the intensity equation at a specific distance (the radius of the star), where x = R.

Multiwavelength astronomy

We can learn different things about an object in space, e.g. a galaxy or nebula, by studying it with different telescopes (sensitive to different wavelengths of the EM spectrum). Here's an example:

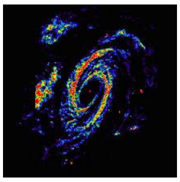
The visible light image (c) is the familiar image seen of a galaxy known as M81, and shows much detail, e.g. the spiral arms can be seen clearly.


(a) X-ray


(b) UV


(c) Visible


(d) IR


(e) 21.2cm

Conversely, the UV image picks out hotter regions and it shows knots of young giant stars well away from the galactic centre.

The x-ray image only displays very high temperature regions. The bright spot in the centre is matter heated up as it spirals in towards the black hole at the galactic centre.

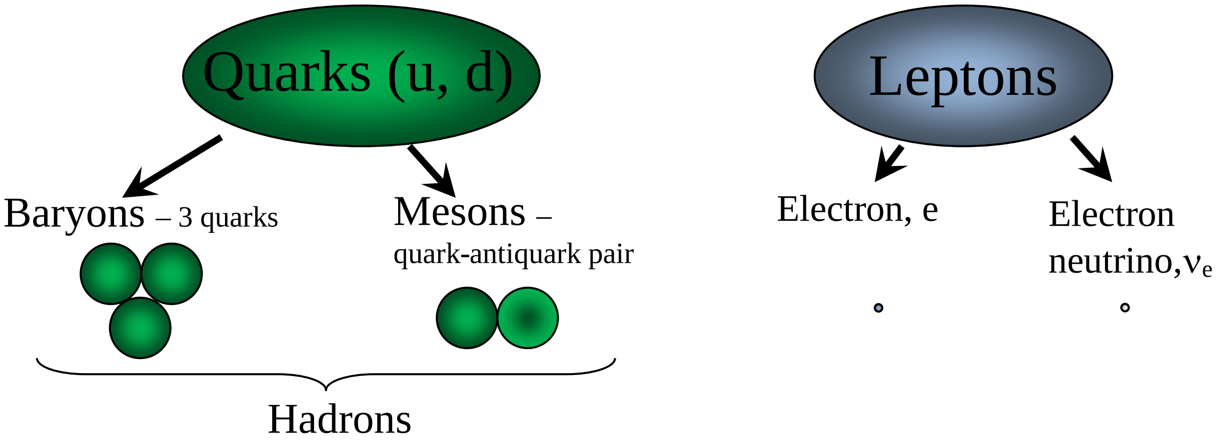
The Image (e) shows neutral hydrogen by its 21.1cm signature emission. It is clearly missing from the galactic centre region!

Section 1.7 - Particles and Nuclear Structure

Scientists have found that there are two groups of elementary particles : **quarks** and **leptons**. They are splits into two groups based on which force (strong or weak) they interact with.
NOTE : Only 1st generation particles are dealt with here.

Quarks are relatively high mass particles, are either 'up' type or 'down' type, and have never been directly seen on their own. These particles are affected by the strong force. (Protons and neutrons are made of three quarks each).

Leptons are lightweight particles, and have two types – the 'electron' and the 'electron neutrino'. These are affected by the weak force.



In addition, it has been found that for each particle, there exists an 'antiparticle'. Antiparticles have the same mass but the opposite charge to their counterpart.

'The rules' for quarks!

Quarks have only been detected in a group. By considering the charge on particles like protons and neutrons, it is believed that quarks have the following charge values:

Quark	**up**	**down**	**anti-up**	**anti-down**
Charge / e	**+2/3**	**-1/3**	**-2/3**	**+1/3**

When quarks form in a group of 3, they are known as **Baryons**.
There are only four possible ways to combine up and down quarks to form a group of 3:

uud	proton	p	charge = +2/3 +2/3 -1/3 = **+1**
udd	neutron	n	charge = +2/3 -1/3 -1/3 = 0
uuu	delta plus plus	Δ++	charge = +2/3 +2/3 +2/3 = **+2**
ddd	delta minus	Δ-	charge = -1/3 -1/3 -1/3 = **-1**

There are also 'excited' versions of the uud and udd baryons (protons and neutrons) that are also classed as 'delta' particles : the excited proton (uud) is Δ^+ and the excited neutron (udd) is Δ^0.

There are also anti-particles for these baryons, e.g. the anti-proton, $\bar{p}$ which is made from the following anti-quarks : $\bar{u}\bar{u}\bar{d}$. (It doesn't seem that there are any **baryons** that have a mixture of particles and antiparticles).

Antiparticles are represented by a small bar above the symbol.

Quarks can also form in pairs. **Mesons** must be a quark and an antiquark. For 1st generation particles, they are known as **pi mesons**, or **pions**. Again, there are only 4 combinations that can exist :

$u\bar{d}$	pi plus	π^+	charge = +2/3 +1/3 = +1
$\bar{u}d$	pi minus	π^-	charge = -2/3 -1/3 = -1
$u\bar{u}$	pi zero	π^0	charge = +2/3 -2/3 = 0
$d\bar{d}$	pi zero	π^0	charge = -1/3 +1/3 = 0

'The rules' for leptons!

Since leptons can exist on their own, there are none of the rules seen for combining baryons. However, each lepton is given a 'lepton number':

	electron	electron neutrino	anti-electron **(positron)**	electron anti-neutrino
symbol ➔	e^-	ν_e	e^+	$\bar{\nu}_e$
lepton number ➔	**1**	**1**	**-1**	**-1**
charge / e ➔	-1	0	+1	0

Note : The anti-electron or 'positron' has its own symbol, e^+ , i.e. no bar above the symbol
Any particles that are not leptons have a lepton number of zero!

Conservation laws

The following conservation laws apply to any decay reactions or collision-type interactions:

(1) Conservation of momentum : In any interaction between particles in a system, the total momentum must stay constant.

(2) Conservation of mass-energy : In any interaction between particles in a system, mass-energy must neither be created nor destroyed.

(3) Conservation of charge : In any interaction between particles in a system, the total charge in the system must not change.

You have seen these three several times before in Physics GCSE!

Cons. of charge is used to calculate the current in series and parallel circuits.

(4) Conservation of baryon number:

In any interaction between particles in a system, the total baryon number in the system must not change.

Example

The following interaction has been observed:

$\pi^+ + {}^2_1H^+ \rightarrow p + p$

Which conservation laws are being illustrated by this reaction?

Firstly, we can see that conservation of charge is being observed - there is a charge of 2+ on the left, and since each proton has a charge of 1+, there is also a charge of 2+ on the right.

Secondly, the baryon number is being conserved. There are two baryons on the left (the deuterium nucleus contains one proton and one neutron), and obviously the two protons are the two baryons on the right.
However, we can take this a step further, down to the level of quarks:

$$\pi^+ \quad + \quad {}^2_1H^+ \quad \rightarrow \quad p \; + \; p$$

$$u\bar{d} \quad + \quad (uud + udd) \quad \rightarrow \quad uud + uud$$

So, there are 4 'up' quarks on the left, and four on the right. There are 3 'down' quarks and one 'anti-down' quark on the left, which means, overall, just 2 'down' quarks. There are also 2 'down' quarks on the right.

Note : If the weak force is involved (see next page), one up quark can change to one down quark, or vice versa. (The baryon number is unchanged).

(5) Conservation of lepton number

In any interaction between particles in a system, the total lepton number in the system must not change.

Example

In a special laboratory in Canada neutrinos from the Sun are detected by looking for electrons released in the interaction:

$$\nu_e + {}^2_1H \rightarrow p + p + e^-$$

Explain whether lepton number is conserved in this interaction.

The electron neutrino (left) and the electron (right) both have a lepton number of +1; all the other particles are baryons, and so have a lepton number of zero. Hence, lepton number is conserved.

The following interaction is suggested: $\nu_e + {}^2_1H \rightarrow p + p + \pi^-$
Is this possible?

No ! Although charge is conserved (as before), the lepton number is no longer conserved, as the pion on the right has a lepton number of zero (it's a meson). Hence, this reaction would not be possible.

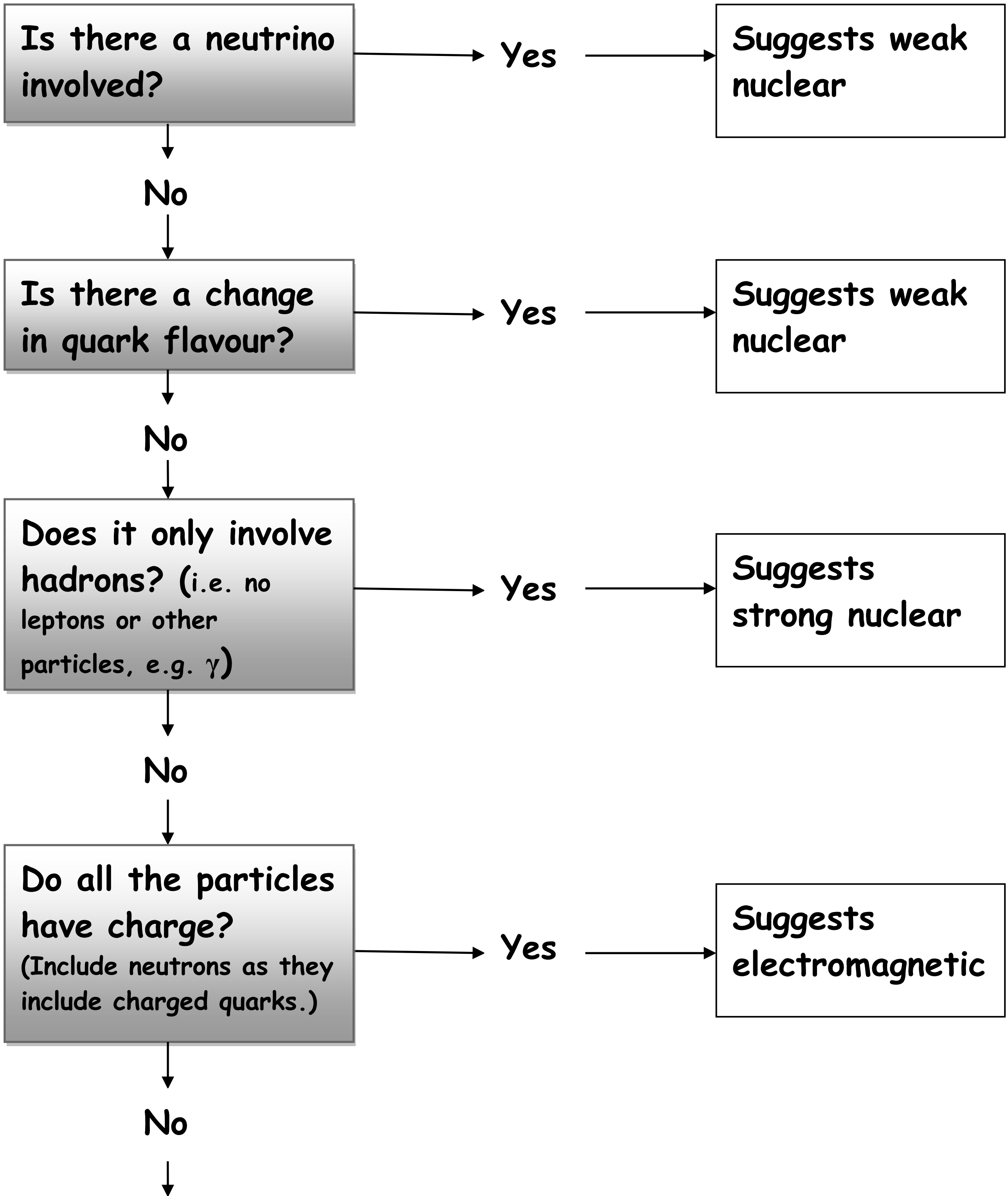
Which forces are involved in interactions?

All the forces in the Universe and all particle interactions are the result of just 4 fundamental forces. A key to identifying the differences between particles are the way they are affected by different forces.

The force of gravity acts between any two masses, no matter how small, or how far apart they are (!), however, it is only significant for large masses like planets and stars and hence is not applicable to interactions between subatomic particles. The other 3 forces are summarized below:

Interaction	Range	Experienced by …	Notes
The strong force	Short range	Quarks	Only experienced by quarks and particles composed of quarks. (i.e. hadrons). Doesn't act on leptons. Associated with the re-grouping of quarks.
The electromagnetic force	Infinite	Charged particles	Much stronger (and therefore more likely/shorter lifetime) than the weak force. Governs interactions composed entirely of charged particles and photons. Also experienced by neutral hadrons because they are composed of quarks.
The weak force	Very short range	All particles	Only significant in cases where the electromagnetic and strong interactions do not operate. Interaction governed by this are of low probability (in the case of collisions), or of long lifetime (in the case of decays). Governs any interactions that include both hadrons and leptons e.g. β decay. Neutrino usually involved.

Which interaction (fundamental force)?



Look for other clues:

- Includes any photons – electromagnetic.
- Very short lifetime – strong nuclear.
- Long lifetime (i.e. more than a second) – weak nuclear.

UNIT 2

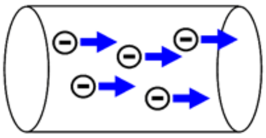
1.Conduction of electricity

Charge on an electron: The unit of charge is the **Coulomb (C)**. It enables us measure the amount of electrical charge an object has (e.g. an electron).

1 C Coulomb = charge on 6,240,000,000,000,000,000 (6.24 billion-billion) electrons.

Charge on each electron 'e' = -1.6×10^{-19}C

'Electric Current' is the flow of electrons in an electric circuit. Flowing water is a good analogy of electricity. When water flows through a pipe, or down a stream, there is a current.



Conventional Current: We say that the current flows from positive to negative (+ → -). This is due to conventions established a long time ago.

Electron Flow: this occurs in the opposite direction. From - to +

Definition of ELECTRIC CURRENT: The rate of flow of charge

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

Units of electrical current – Ampere – A which is equivalent to Cs^{-1}.

Current-time graphs. - *If the current is constant as it is for a bulb in a DC circuit then the current-time graph looks like the graph below.*

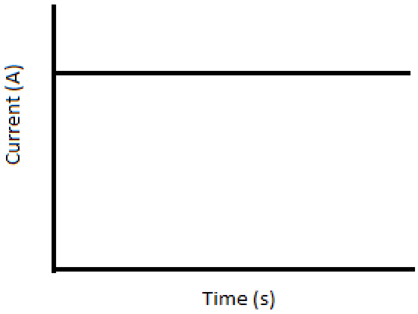
The area under the graph gives you the total charge - Q.

This is because Q= It.

e.g. So if a current of 3A flows for a time of 30s

then the total charge which flowed in this time.

$Q = It = 3 \times 30 = 90$ C



Mechanism of conduction - Drift velocity

All metals have a lattice structure of atoms. Some of the outer electrons are only loosely bound and are not required for bonding. On average about one electron in each atom is not required for bonding. This electron is free to move around the lattice and is called the ‘**FREE ELECTRON**’.

If no current is flowing then these free electrons will move randomly throughout the structure (1×10^6 ms^{-1}). This is known as the ‘**THERMAL VELOCITY**’ of the free electrons. The magnitude of the thermal velocity depends on the temperature of the metal.

When a potential difference (voltage) is applied across the ends of a metal an electric field is produced in the metal. The electric field exerts a force on the free electrons, causing them to accelerate towards the highest potential (voltage). However, before they get very far they collide with an atom and lose some of their kinetic energy. As a result they tend to ‘drift’ towards the positive end, bouncing around from atom to atom on the way.

The mean ‘***DRIFT VELOCITY*** ‘is proportional to the applied electric field. Hence the current we get is proportional to the applied voltage. It also explains why we have to supply energy to maintain the current. We have to give the electrons kinetic energy to move them along. This keeps being ‘lost’ every time they collide with the metal ions. It is given to the atoms, making them jiggle around more furiously — i.e. it warms up the resistor. As a result, electrical energy is turned into internal energy (thermal energy) of the ions.

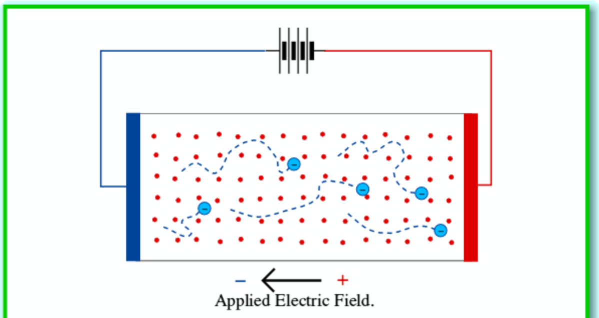
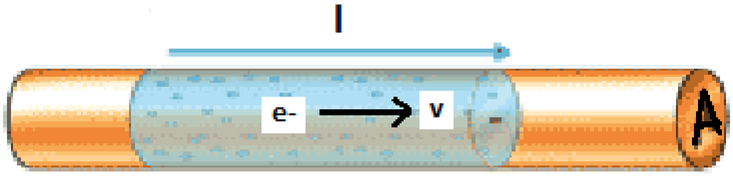


Figure 2.2 Electrons squeezing their way through a resistor.

For example, in a copper conductor of radius 1 mm, carrying 1 Amp, the electron drift velocity 0.0001ms^{-1}. This opposition to electron movement results in resistance and heat.

Derivation of I = nAve

We need to be able to calculate a value for the drift velocity of the electrons relating it to the current flowing.



The wire has; Cross sectional area = **A**, Length = **l**, Number of free electrons per m^3 = **n**
The electrons are moving through the wire with a drift velocity ‘**v**’ .If they travel the length **l** in a time, **t** then we can write:

Volume of the length of wire = A l (Volume of a cylinder)

Number of free electrons (in cylinder) = nAl

Total charge on electrons in wire - Q = nAle

Distance moved by free electrons - l = vt so, Q = nAvte

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

substitute $I = \frac{nAv\cancel{t}e}{\cancel{t}}$ the t’s cancel to give I = nAve

Units of: I – (A), n - (m^{-3}) v - ms^{-1} e - 1.6×10^{-19}C

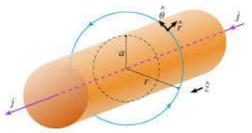
Using I = nAve

Worked example.
A wire of radius 2 mm, can carry a current of up to 20 A. Given that n = $4.8 \times 10^{29}\ m^{-3}$, what is the maximum value for the drift velocity in this wire?

First you must calculate the cross sectional area 'A' = $\pi r^2 = \pi \times (2\times10^{-3})^2$

$= 1.26 \times10^{-5}\ m^2$

rearrange to give; $v = \dfrac{I}{nAe} = \dfrac{20}{4.81\times10^{29} \times 1.26\times10^{-5} \times 1.6\times10^{-19}} = 2.07\times10^{-5}\ ms^{-1}$



What effect does doubling the drift velocity have on the current?

If the drift velocity doubles then the current also doubles.

What can be said about the value of 'n' and 'e' for a certain metal/material?

These are constants and so do not change (for a specific material)

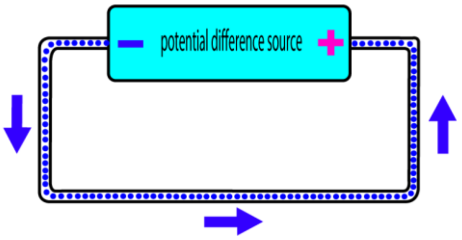
If the radius of a wire doubles what effect does this have on the current?

Since area is calculated using 'A' = πr^2, then doubling the radius means the area increases by a factor of 4 (quadruples). So the drift velocity decreases by a factor of 4.

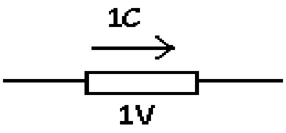
Potential difference

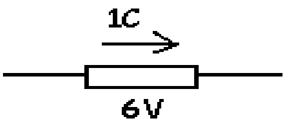
Definition

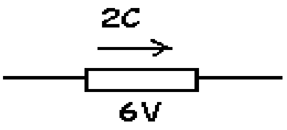
The p.d. between two points is the amount of electrical energy transferred to other forms of energy when 1 Coulomb of charge flows between the points.



Unit of p.d. is the Volt, V.
The p.d. between 2 points is 6V, what does this mean? 6J of electrical energy is transferred to other forms of energy when 1 Coulomb of charge flows between the two points.
How much electrical energy is transferred to other forms of energy in each case?







Answers = 1J 6J 12J

The Volt

So 1 Volt is 1 Joule per coulomb of charge. In equation form:

Remember (not given in exam)

$$\boxed{\begin{gathered}\textbf{Energy transferred } W \textbf{ or } \Delta E = V\,Q \\ V = \frac{W}{Q}\end{gathered}}$$

V = Volt (V) **or JC^{-1}**　W= electrical energy (work done) (J)　Q = charge passed (C)

We know that Q= It

So we can substitute this into the equation to give

Electrical energy transferred **$W = VIt$**

Resistance

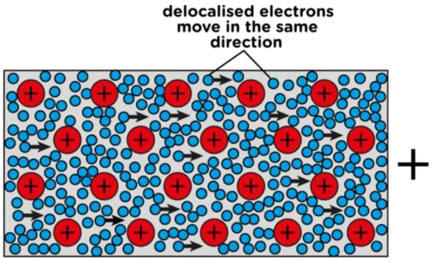
The resistance of a conductor is the p.d. (*V*) placed across it divided by the resulting current (*I*) through it.

$$\boxed{\text{Resistance} = \frac{\text{potential difference}}{\text{Current}} \qquad R = \frac{V}{I}}$$

The units of resistance are : Ohms, Ω　or VA^{-1}

What causes electrical resistance?

Collisions between free electrons which are moving through a metal conductor and positive ions of the metal lattice (structure) give rise to electrical resistance. In the collision energy is transferred from the electrons to the ions. This increases the **random vibrational energy** of the ions leading to an increase in the temperature of the metal.



In Summary

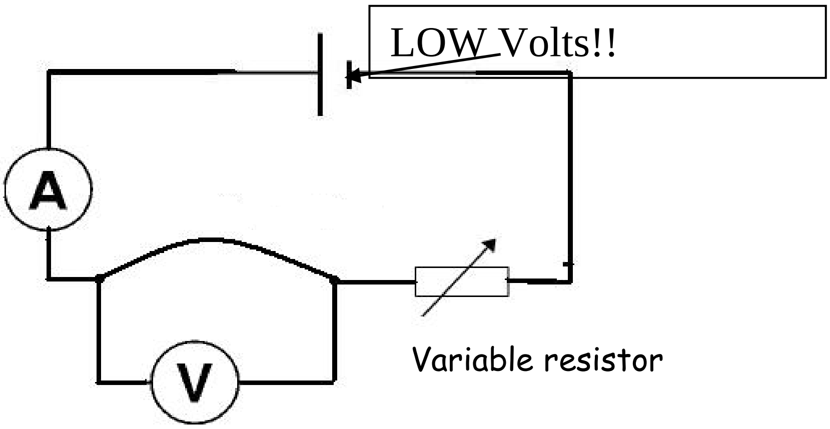
- Free electrons
- collide with atoms / ions of metal
- in the conductor / lattice

If the current is constant then so the drift velocity will be constant since I = nAve
So the drift velocity will remain steady under a given p.d.

Remember if the resistance increases the drift velocity of the electrons decreases.

I-V, Voltage and Current Investigations

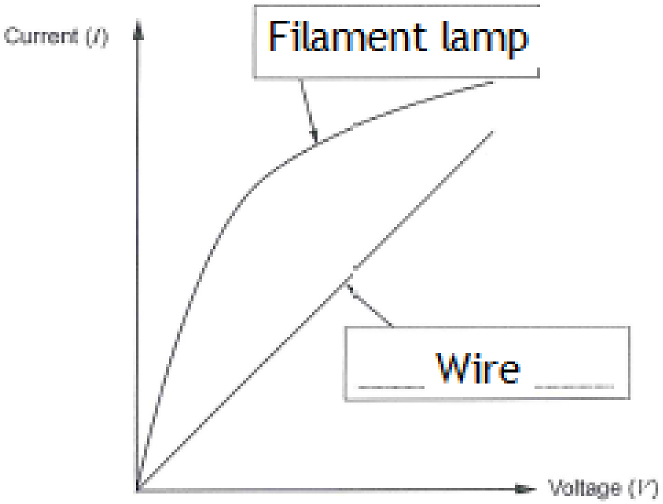
1. Resistor/wire at constant temperature.
The circuit below can be used to see how p.d. and current change for a wire at constant temperature.



It is important to keep the current to a low value so any heating effect in the wire is kept to a minimum. Take recordings of both voltage and current at regular intervals.

2. Filament lamp/bulb. The same experiment can be replicated for a filament lamp. Just replace the wire with a filament lamp.

A graph is plotted of current and voltage.



Metal wire at constant temperature	Filament of lamp
Directly proportional The Straight line shows that *resistance is* constant throughout [or *V*/*I* constant] because the temperature is constant throughout.	Curved line. Initially *the resistance is* constant [or *V*/*I* constant] as since the line is straight Then *the temperature* increases so resistance increases. Collisions between free electrons and ions in metals increase the **random vibration energy** of the ions, so the temperature of the metal increases.

OHM’s LAW

Definition. The current flowing through a metal wire at constant temperature is proportional to the p.d. across it.

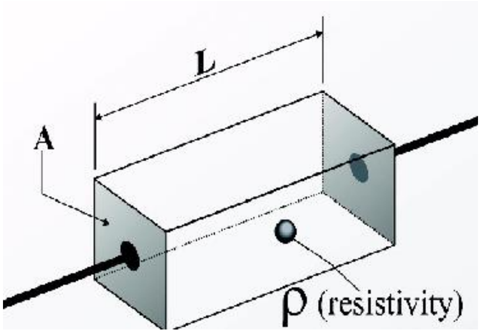
$$I \, \alpha \, V \qquad\qquad \frac{V}{I} = \text{constant}$$

So the filament bulb is a non-linear or NON-OHMIC device. The reason being that as the p.d. increases the filament becomes much hotter and so the resistance will increase i.e. temperature does not remain constant. So a metallic conductor is called a linear device or an OHMIC device.

Resistivity – ρ

The resistance of a wire depends upon 3 factors

- ***the length - l; double the length, the resistance doubles.***
- ***the area - A; double the area, the resistance halves.***
- ***the material that the wire is made of.***



Resistivity is a property of the material. It is defined as the **resistance of a wire of the material of unit length.**

Resistivity remains unchanged (constant) for a specific material regardless of changing length or area. e.g. it is constant for copper at a certain temp.

Resistivity is defined by the equation.

$$R = \frac{\rho l}{A} \qquad \text{or} \qquad \rho = \frac{RA}{l}$$

Units **R- Ohms, (Ω), A - (m^2), l - (m), ρ - (Ωm)**

What effect does doubling the radius or diameter have on the resistance of the material if the length and material remain constant?

Since area is calculated using ‘A’ = πr^2, then doubling the radius means the area increases by a factor of 4 (quadruples). So the resistance decreases by a factor of 4.

Resistivity - ρ

Values for resistivity for some common materials.

Material	Resistivity at 20˚C (Ωm)
Copper	1.7×10^{-8}
Aluminium	2.8×10^{-8}
Constantan	4.9×10^{-7}
Germanium	4.2×10^{-1}
Silicon	2.6×10^{3}
Polythene	2.0×10^{11}
Glass	10×10^{11}

Very good conductors such as copper and aluminium have very small values of resistivity whereas very good insulator such as polythene have a very high value. Semiconductors such as germanium have values in between.

Worked example
Calculate the length of constantan wire radius 5.0×10^{-2}cm needed to make a 3ohm resistor.

1st step: $\rho = \frac{RA}{l}$ rearrange $l = \frac{RA}{\rho}$

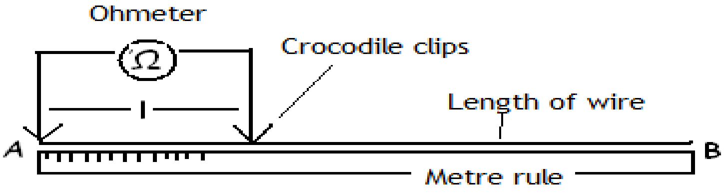
Change from cm to m.

2nd step: Calculate the cross sectional area, $A = \pi r^2 = \pi \times (5.0\times10^{-4})^2 = 7.85\times10^{-7}\ m^2$

3rd step: $l = \frac{3 \times 7.85\times10^{-7}}{4.9\times10^{-7}}$ **Answer = 4.81m**

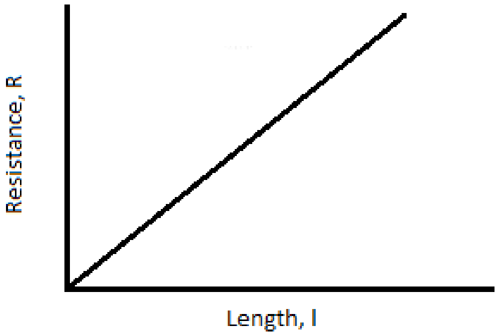
Investigation - Calculating Resistivity

Diagram of the apparatus.



1. Using a micrometer screw gauge measure the diameter of the wire at 3 different places along the length of the wire. Determine the average diameter of the wire. You must ensure that there are no kinks in the wire. Use the formula ($A = \pi r^2$) to calculate the cross sectional area.
2. The sliding contact is then touched at several points along the wire. At each point the distance from A to the sliding contact is measured (l) by means of the ruler and the resistance R is measured by means of the ohmmeter (resistance of the leads is subtracted). Repeat to measure the resistance as the length is decreasing.

Plot a graph of your results (length on x-axis) (Resistance on y-axis)



Calculate the gradient of the graph = R/l

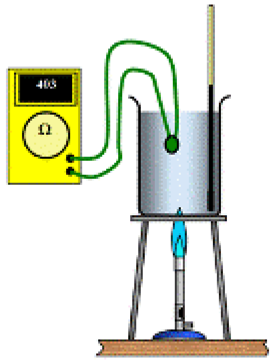
Resistivity, $\rho = \frac{RA}{l}$ = gradient of graph x A

Variation of resistance of a metal with temperature

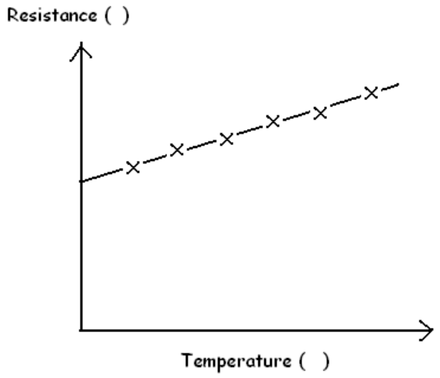
The greater the temperature the greater the vibrational energy of the lattice / metal ions producing a greater or rate of collisions between free electrons and metal ions.

Investigation to determine the variation of resistance with temperature of a metal wire.

The ohmmeter is used to measure the resistance of the coil. The thermometer is used to measure the temperature of the liquid surrounding the coil. The leads can be very thick wires so that their resistance is very small compared to the resistance of the copper wire. Measure the resistance of the copper wire at 10˚C intervals from 20˚C to 100˚C. The value of resistance can also be determined as the liquid is cooled.



(Diagram: resourcefulphysics.org)



The resistance of metals varies almost linearly with the temperature over a wide range of temperatures.

When the temperature of the metal increases the amplitude of vibrations of the positive ions increases. This means that the electrons collide more often, leading to a drop in drift velocity which results in a decrease in the current for the same p.d.

Since resistance = p.d./current, resistance will increase.

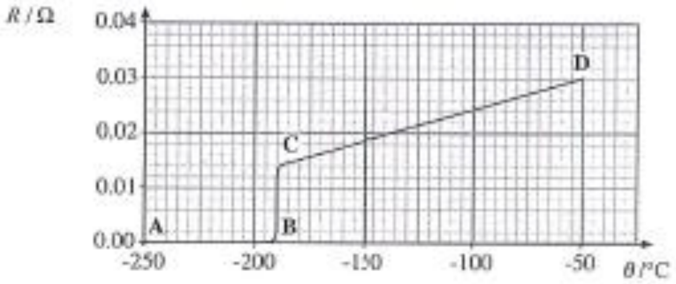
Superconductivity

When metals are cooled down to extremely low temperatures – approaching absolute zero 0 K (-273.15˚C) their resistance disappears. The temperature at which resistance disappears is called the critical temperature – T_c.

Transition temperatures (critical temperature): The temperature at which a material, when cooled, loses all its electrical resistance, and becomes *super-conducting*.

We cool down these metals to these low temperatures using liquid Nitrogen or Helium

In a superconducting circuit a p.d. is needed to start the current flowing but then no p.d. is needed to keep the current flowing since there is no resistance.This is the region A→B of the graph.
Transition temperature = -190°C



Uses of Superconductivity

Many metals/materials exhibit superconductivity e.g. Zinc T_c = 0.87 K, Lead T_c = 7.19 K, Mercury T_c = 4.15 K

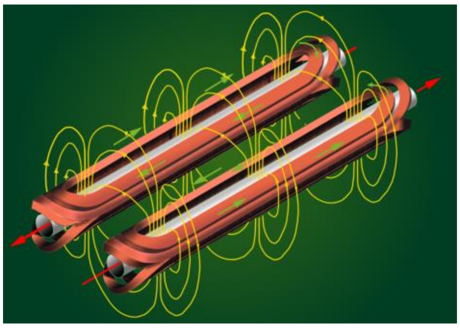
High temperature superconductors.

Certain materials (high temperature superconductors) having transition temperatures above the boiling point of nitrogen (-196 ˚C) (clearly this is still very cold). They are developing more and more high temperature superconductors e.g. $YBa_2Cu_3O_7$ which has a transition temperature of 92K or -181 ˚C.

The advantage of superconductivity is that there is no resistance so no heat loss which means that large currents can be maintained from zero p.d. (no power dissipated)

Applicatons/uses:
Nuclear fusion / tokamaks, Large Hadron Collider CERN/ *Particle accelerators*, MRI *(magnetic resonance imaging)* scanners, large motors or generators.

Electric generators made with superconducting wire are far more efficient, and about half the size, than conventional generators wound with copper wire.



Disadvantages: The limitations of superconductors include the technical difficulties of achieving and reliably sustaining the extremely low temperatures required to achieve superconductivity. The materials, of which they are made, are often brittle, are hard to manufacture and they are difficult to make into wire.

Electrical Power

Power is defined as the energy transferred per second. We need an expression for the amount of electrical energy transferred to other forms of energy in a certain time.

$$\text{Power} = \frac{\text{Energy transferred}}{\text{Time}} \qquad P = \frac{W}{t}$$

Unit of power – Watt, W or Js^{-1}

The p.d. (V) between 2 points is the work done in moving a charge of 1C between the 2 points so if a charge Q moves between the 2 points the work done or energy transferred is VQ

$W = VQ$ which can be combined with the above equation to give

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

However, $Q = It$ so we can substitute for Q in this equation giving,

$P = \frac{VIt}{t}$ the t's cancel to give $P = VI$

continued….

If the component is ohmic it can be useful to substitute for the voltage as V = I R which gives

$P = VI$ so, $P = IRI$ which becomes $P = I^2R$

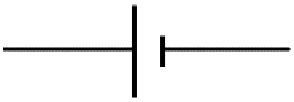
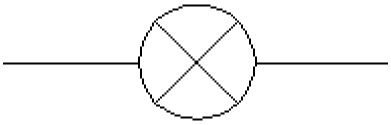
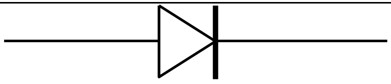
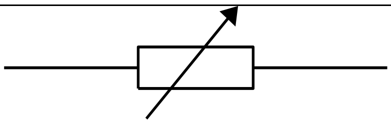
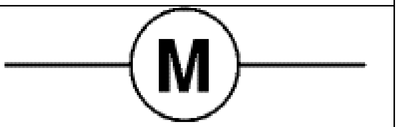
Use this for any questions that ask you to calculate the energy or power dissipated as heat in a resistor.

Or/

$P=VI$, and since $I = V/R$ then we can write, $P = \frac{VV}{R}$ which becomes $P = \frac{V^2}{R}$

You need to know how to derive the 2 equations above.

3. D.C. Circuits

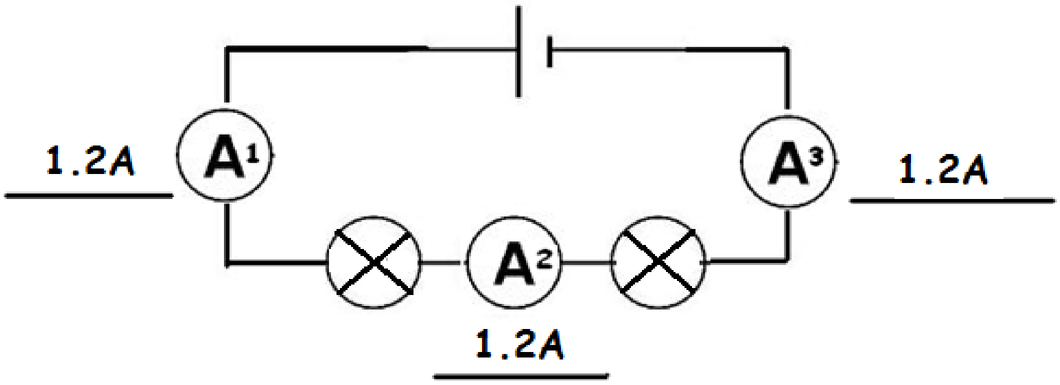
Device	**Symbol**	**Device**	**Symbol**
Wire		**Cell / Battery**	
Power Supply		**Bulb**	
Open switch (Off)		**Closed switch (On)**	
Diode		**Resistor**	
Variable resistor		**Motor**	

Current

Current is measured in **Amperes, A**
It is measured using an **Ammeter in series.**

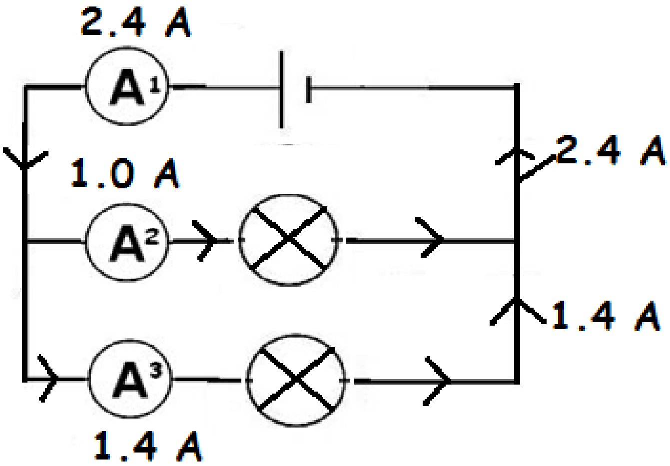
To avoid the ammeter affecting the current it must be connected in series and have negligible (almost no) resistance.

Current in series circuits: ammeters must be connected in series i.e. in the circuit.



The value of the current is the same at all points ($I_1 = I_2 = I_3$) in the circuit since there is only one path for the current to flow.

Current in parallel circuits: the ammeter in this parallel circuit is connected in series.



The value of the current in the two branches adds up to the total current flowing,
i.e. ($I_1 = I_2 + I_3$) or (2.4 = 1.0 + 1.4).

The amount of electrons/charge leaving the battery and entering the battery at the positive terminal are equal. This is due to the fact that you don't destroy the electrons and so gives rise to the ***conservation of charge***.

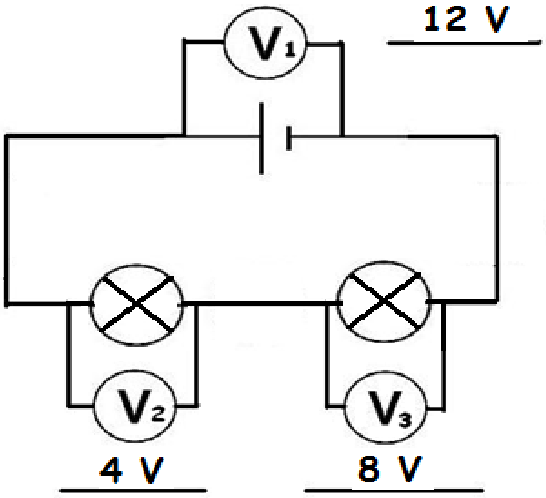
The sum of the currents entering a junction is equal to the currents leaving the junction. This is due to the conservation of charge.

Potential difference p.d.

Potential difference is measured in **Volts, V.**

It is measured using a **Voltmeter connected in parallel.**

Potential difference in series circuit: the voltmeters are connected across the component e.g. bulb or battery.

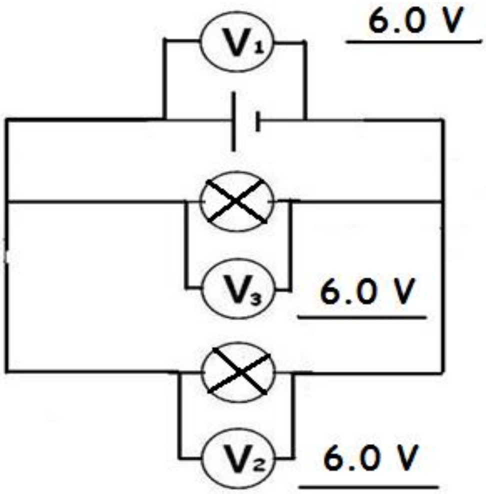


The p.d. across both components/bulbs here adds up to the p.d. across the supply/battery i.e. ($V_1 = V_2 + V_3$) or (12 = 4 + 8). Since energy cannot be created nor destroyed the same reasoning can be applied to potential difference which is defined in terms of work or energy.

The sum of the p.d's across components in a series circuit is equal to the p.d. across the supply. This is a consequence of the conservation of energy.

Potential difference in parallel circuit: the p.d. across all components in parallel is the same.

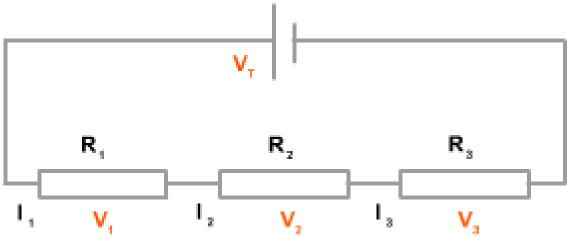
i.e. ($V_1 = V_2 = V_3$)



The p.d.'s across components in a parallel circuit are equal.

Resistors in series and parallel.

Series. Since the resistors are connected in series, they must all have the same current flowing through each one ‘I’ (conservation of charge). The sum of the pd.’s across the individual resistors must be equal to the total p.d. across all resistors.

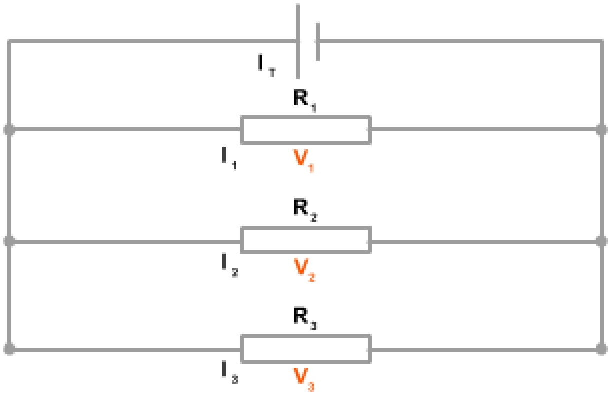


Total resistance, $R_T = R_1 + R_2 + R_3$ (Must Remember)

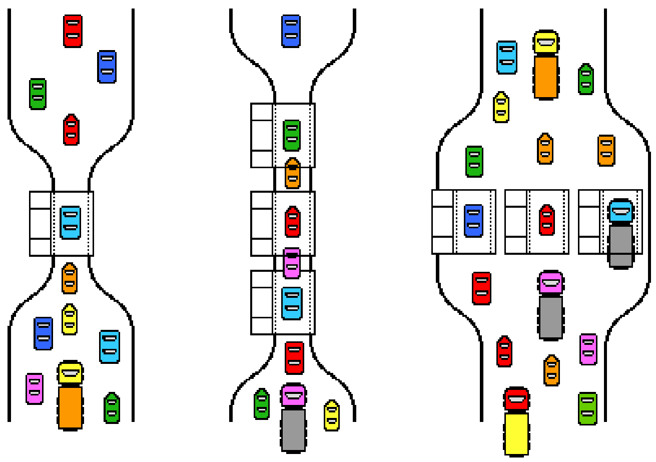
Parallel. In this case all of the resistors are in parallel and they must have the same potential difference ‘V’ across them. By the conservation of charge the main current ‘I’ is equal to the sum of the currents in each resistor. The total resistance of all components in parallel must always be smaller than the smallest individual component resistance. Why? Adding more components draws more current so a smaller resistance.

Total resistance,

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$ (Must Remember)



Influencing the Flow Rate on a Tollway



A Single Resistor

Three Resistors Placed in Series

Three Resistors Placed in Parallel

e.g. A 5Ω, 3Ω and a 10Ω are connected in parallel. Calculate the total resistance.

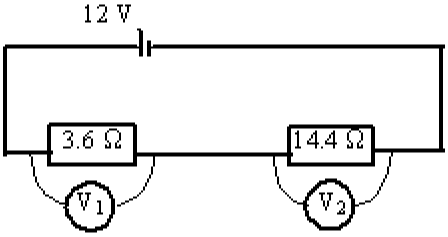
$$\frac{1}{R_T} = \frac{1}{5} + \frac{1}{3} + \frac{1}{10}$$

$$\frac{1}{R_T} = \frac{1}{5} + \frac{1}{3} + \frac{1}{10}$$

$$\frac{1}{R_T} = \frac{19}{30} \quad \text{so} \quad R_T = \frac{30}{19} = 1.58\ \Omega$$

Potential Divider

It is often useful to be able to control the p.d. precisely. For example, a car radio may need exactly 9.6V D.C. However, the only source available is the car's own battery, V = 12 V. The easiest way to control the voltage is by simply using two resistors in series. Each resistor takes some fraction of the total voltage. If the first resistor is twice the size of the second, the voltage across the first resistor will be twice that of the second resistor.



What is the total resistance, R_T? 18Ω

What is the current in/out of the battery, I_T? I = V/R = 12/18 = 0.67A

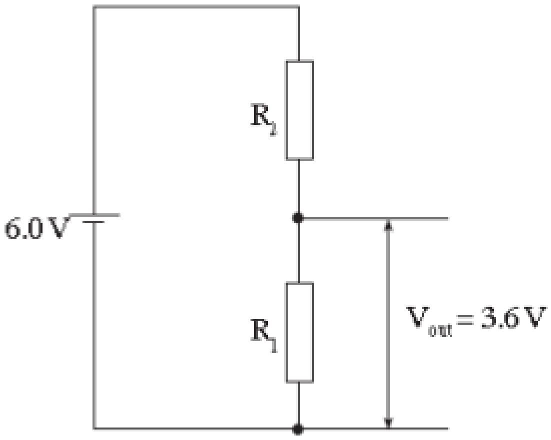
Use V=IR to calculate, $V_1 = 0.67 \times 3.6 = 2.4V$ What is the value on $V_2 = 0.67 \times 14.4 = 9.6V$

Therefore, we can divide the voltage into any values we choose by changing the ratio of R_1 to R_2.

Adding any components in parallel to a resistor will alter the overall resistance.
The equation for a potential divider is:

$$\frac{V}{V_{total}} = \frac{R}{R_{total}} \quad \text{or} \quad \frac{V_{OUT}}{V_{IN}} = \frac{R}{R_{total}}$$

Worked Example
The value of R_1 is given as 225Ω.



You should be able to see that the p.d. across R_2 is 2.4V since the p.d. across both must add up to 6V.

To calculate the value of R_2 using the potential divider equation. Considering R_1 is easier.

$$\frac{V}{V_{total}} = \frac{R}{R_{total}}$$

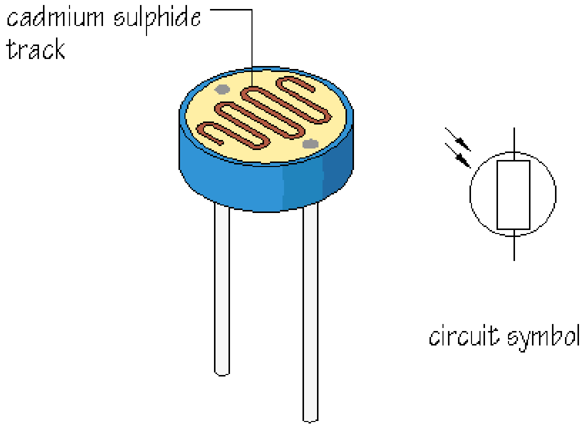
$$\frac{3.6}{6} = \frac{225}{225+R_2} \rightarrow 3.6\,(225+R_2) = 225 \times 6$$

$$225+R_2 = \frac{1350}{3.6} \rightarrow 225+R_2 = 375 \rightarrow R_2 = 375-225 = 150\ \Omega$$

There is an easier way using V= IR!!! I = V/R = 3.6/225 = 0.016A
Since this is a series circuit the current is the same and we know the p.d. across R_2, so R=V/I = 2.4/0.016 = 150 Ω

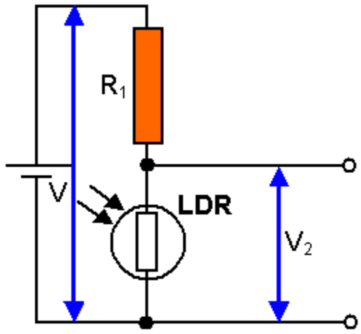
Potential Divider with LDR and Thermistor.

Light dependent resistor, or LDR



The LDR is a component that has a resistance that changes when light falls on it. As the intensity of the light is increased so the resistance of the LDR falls.

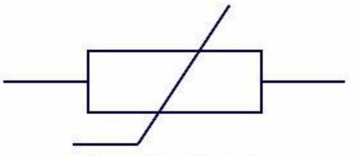
If the LDR is connected as part of a potential divider as shown in the diagram then as the light level is increased its resistance falls and the proportion of the input voltage dropped across it will also fall.



So in the light V_2 is low and in the dark V_2 is high.

Temperature sensors

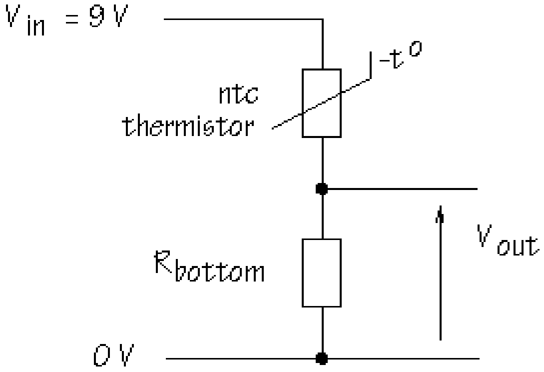
A temperature-sensitive resistor is called a **thermistor**. There are several different types:



Thermistor Symbol

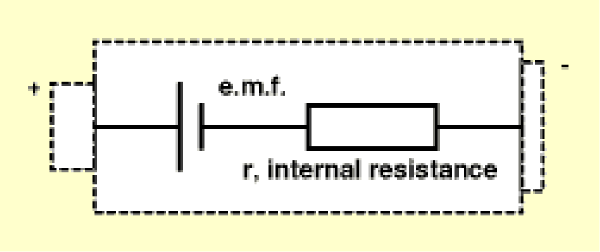
The resistance of most common types of thermistor *decreases* as the temperature rises. As the temperature rises, more charge carriers become available and the resistance falls.

How could you make a sensor circuit for use in a fire alarm? You want a circuit which will deliver a HIGH voltage when hot conditions are detected. You need a voltage divider with the ntc thermistor in the R_{top} position:



You will be expected to calculate V_{OUT} using the potential divider equation.

Electro Motive Force - emf



The cell has to use up part of its energy to drive the current through its own internal resistance since some is converted into non-useful forms e.g. heat. This resistance is called the **internal resistance** (very low but typically around 0.01'Ω) of the cell. This is called the lost volts.

Lost Volts = I r

A cell can be thought of as a source of e.m.f. with a resistor connected in series.

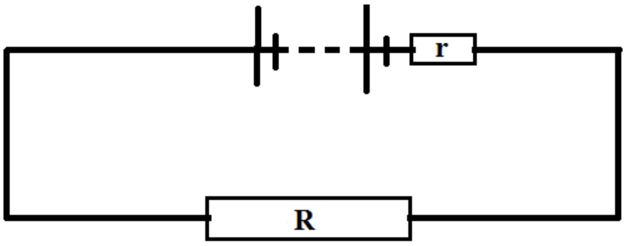
<u>EMF Definition</u> – The emf of a source is the energy converted from some other form (e.g. chemical) to electrical potential energy per coulomb of charge flowing through the source.

$$\text{e.m.f of the source} = \frac{\text{Energy transferred by the supply}}{\text{charge}}$$

e.m.f. = W/Q

units of e.m.f. – Volt, V

Emf is the total energy supplied to the circuit per unit charge, while p.d. is the electrical energy per unit charge converted to other energies by the components.



By the conservation of energy

V = E - Ir

or E = V + Ir

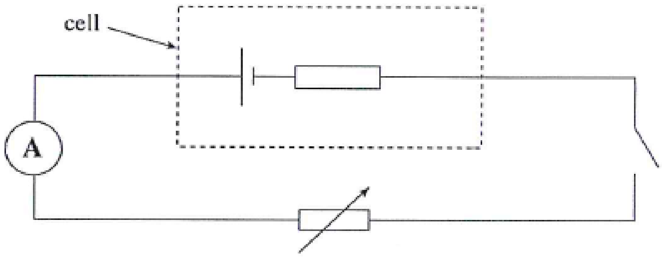
or E = IR + Ir since V= IR

or E = I (R + r)

E is emf – Units(V) V is the terminal p.d. – Units (V) Ir is the lost volts – Units (V)

Investigation to determine the internal resistance

The following circuit is set up to determine the emf and internal resistance of a cell. The following readings are recorded.



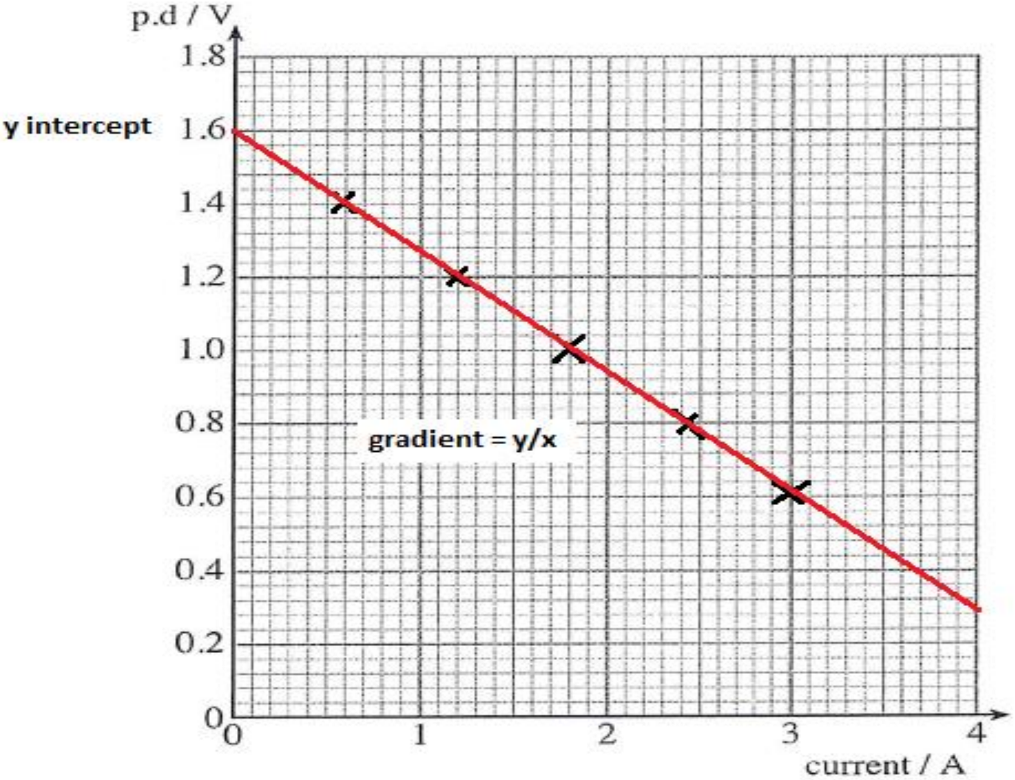
p.d. across cell terminals /V	Current /A
1.4	0.6
1.2	1.2
1.0	1.8
0.8	2.4
0.6	3.0

A graph is plotted of the results. p.d. on the y-axis and current on the x-axis.

Using the equation:

$$V = E - Ir \text{ and comparing with } y = mx + c,$$

y is V, I is x, m(gradient) is r (internal resistance) and c (intercept) is the emf.



So the intercept is 1.6V which is the emf.

Make a triangle as large as possible. Gradient of the graph is y/x = 1.2/3.6 = 0.33Ω, which is the internal resistance (r).

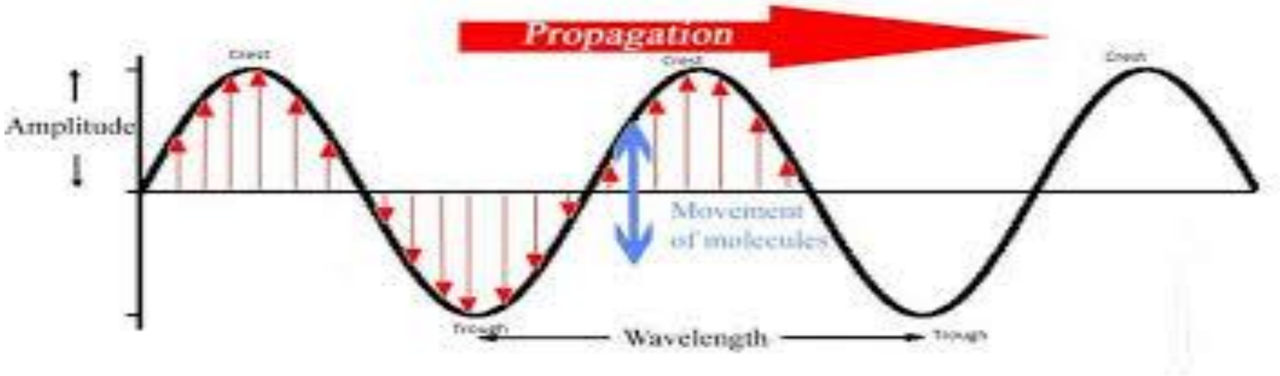
4. The nature of waves.

Progressive wave: A pattern of disturbances travelling through a medium and carrying energy with it, involving the particles of the medium oscillating about their equilibrium position. It does not involve the transfer matter.

There are two main groups of waves. These are transverse waves and progressive longitudinal

Transverse

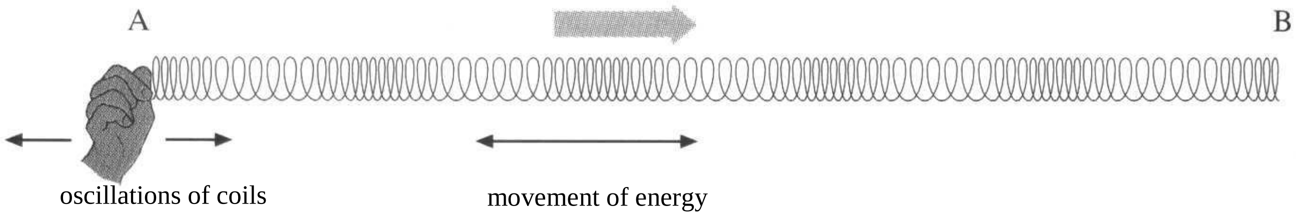
The oscillations of the particles are at right angles to the direction of travel of the wave. Diagram of transverse wave.



Examples of transverse waves: Light (all e-m waves, s-seismic waves)

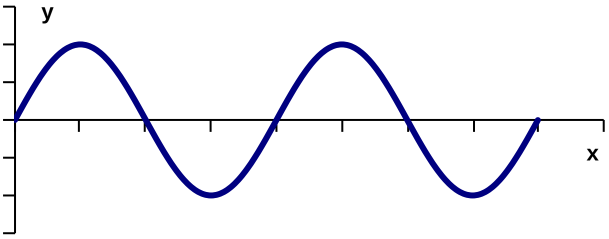
Longitudinal waves

The oscillations of the particles are in line with (or parallel) to the direction of travel of the wave.



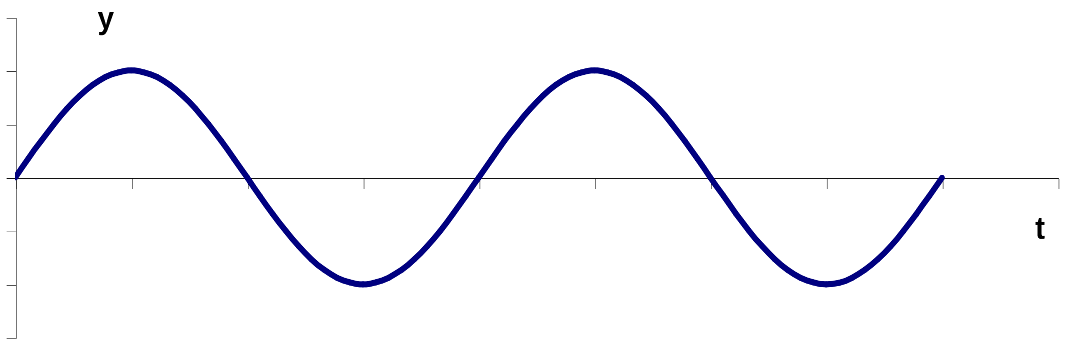
Examples of longitudinal waves: sound waves and p-seismic waves.

Graphical representation of waves. Displacement is a vector quantity, and can be positive or negative. A transverse wave may be represented by plotting displacement **y** on the y-axis against distance **x** along the wave, on the x-axis. It can be seen from the diagram below that the graph is a snapshot (basically, a picture or snapshot of the wave at a particular time) of what is actually observed to be a transverse wave.

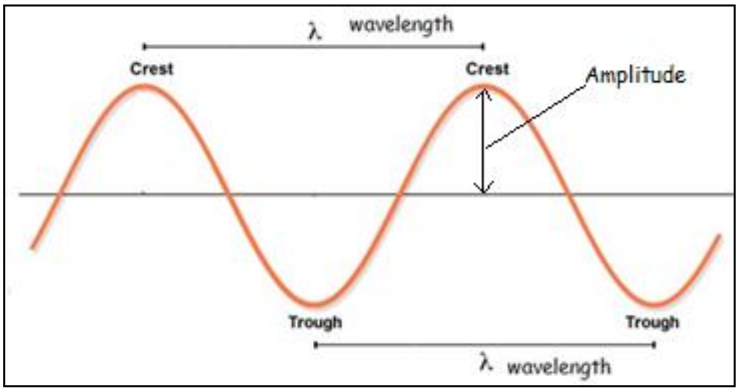


Characteristics of waves.

Another way to represent both waves is to plot a graph of displacement **y** of any **one particle** or part of the wave, against **time t**. This is shown in the diagram below.



Characteristics	What is it?	Units
1.Wavelength **λ**	The wavelength of a progressive wave is the minimum distance (measured along the direction of propagation) between two points on the wave oscillating in phase. If there are 10 waves in 5 metres then the wavelength is 0.5m	Metres, m
2. Frequency **f**	The frequency of a wave is the number of cycles of a wave that pass a given point in one second. 1 Hz is 1waves per second. If there are 40 waves in 10 seconds then the frequency is 4 Hz.	Hertz, Hz or s^{-1}
3. Amplitude	Distance from the middle of the wave to the crest/top. The greater the amplitude the more energy the wave is carrying.	Metres, m
4. Speed **c**	The distance travelled by the wave in 1 second. Or/ **Velocity of a wave is the distance that the wave profile moves per unit time.**	Metres per second, ms^{-1}



Relationship between time period and frequency.

$$\mathbf{T = \frac{1}{f}} \qquad \mathbf{f = \frac{1}{T}}$$

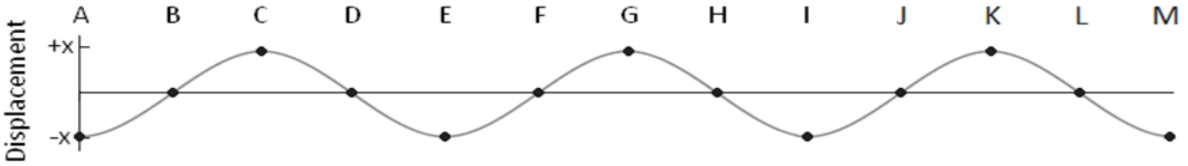
e.g. 10 waves in 50 seconds. Calculate f and hence T.
f= 10/50 = 0.2 Hz so T=1/0.2 = 5s

Phase

Phase is the term used to describe ***the relationship between the pattern of vibration of two points on a wave***. Phase difference is the difference in position of 2 points within a cycle of oscillation. It is given as a fraction of the cycle or as an angle, where one whole cycle is 2π or 360°], together with a statement of which point is ahead in the cycle.

Points which are oscillating **in phase** will be multiples of 360˚or 2π radians e.g. A and E

Points which are oscillating in **antiphase** are 180° or π radians out of phase e.g. A and C



	B	C	D	E	F	G	H	I	J	K	L	M
Phase Difference from A (radians)	½π	1π	1½π	2π	2½π	3π	3½π	4π	4½π	5π	5½π	6π
Phase Difference from A (degrees)	90	180	270	360	450	540	630	720	810	900	990	1080

All points on wavefronts oscillate in phase, and that wave propagation directions (rays) are at right angles to wavefronts.

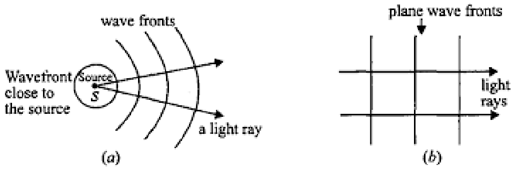


Fig. 20.1

Wave equation

If a wave moves a distance, x, in a time, t,

Speed = distance/time

However if we consider the specific case when the distance moved by the wave is exactly equal to one wavelength, λ , then the time elapsed **must** be equal to the period, T.

Speed = wavelength/Time period but we know that T=1/f

So we can substitute $\boxed{c = f\lambda}$

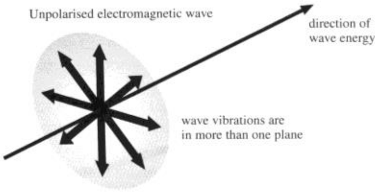
Where c - wave speed (ms^{-1}) f - frequency (Hz) and λ - wavelength (m)

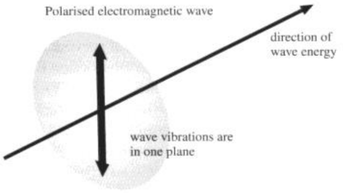
If we are talking about any region of e-m radiation then c = $3\text{x}10^{8}$ ms^{-1} in a vacuum.

The speed of light is $3.0 \text{ x } 10^{8}$ ms^{-1}. Calculate the frequency of red light when it has a wavelength $6.5 \text{ x } 10^{-7}$ m.

$f = c/\lambda \quad 3.0\text{x}10^{8}/ 6.5\text{x}10^{-7} = 4.61\text{x}10^{14}$ Hz

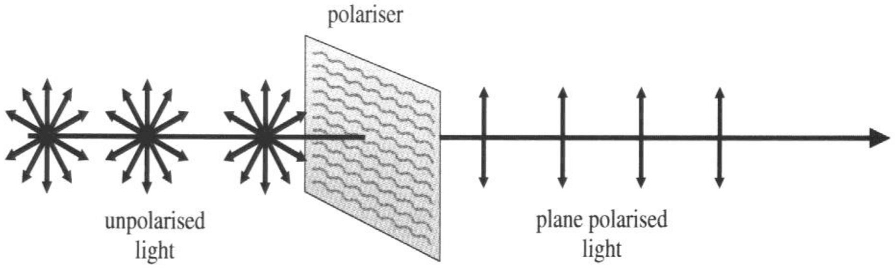
Polarisation





A polarised wave is a transverse wave in which particle oscillations occur in only one of the directions at right angles to the direction of wave propagation.

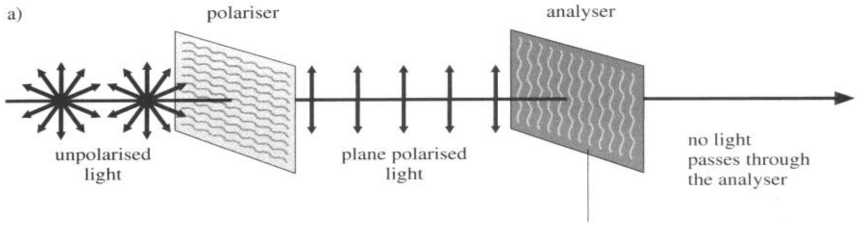
It is not possible to polarise longitudinal waves. The Sun and domestic light bulbs emit unpolarised light, that is the vibrations take place in many directions at once, instead of in the single plane associated with plane-polarised radiation.



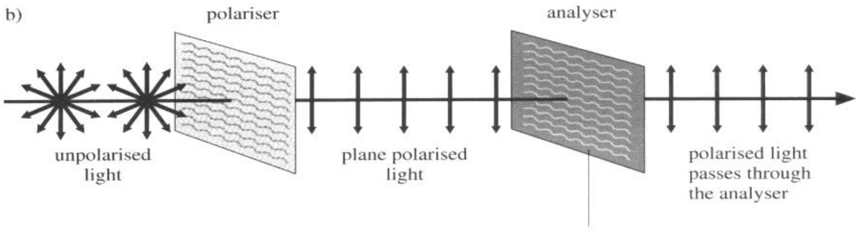
The Polaroid sheet acts as a polariser, producing plane polarised light from light which was originally unpolarised.

If you try to view plane-polarised light through a second sheet of Polaroid that is placed so that its polarising direction is at right angles to the polarising direction of the first sheet, it will be found that no light is transmitted. In this arrangement, the Polaroids are said to be crossed. The second Polaroid sheet is acting as an **analyser**. If the two Polaroids have their polarising directions parallel, then plane-polarised light from the first Polaroid can pass through the second. So rotating the analyser through 180˚, we move from light (0˚) to dark (90˚), to light again (180˚)

a)

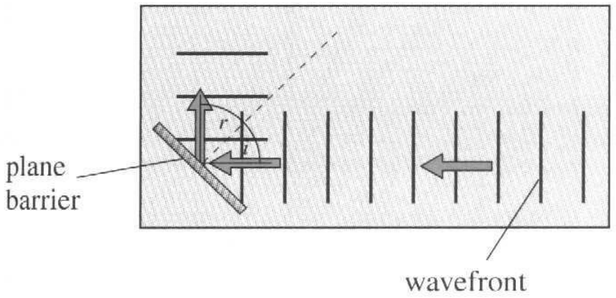


b)

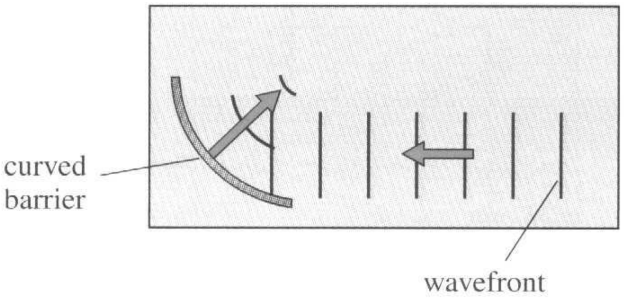


Wave properties

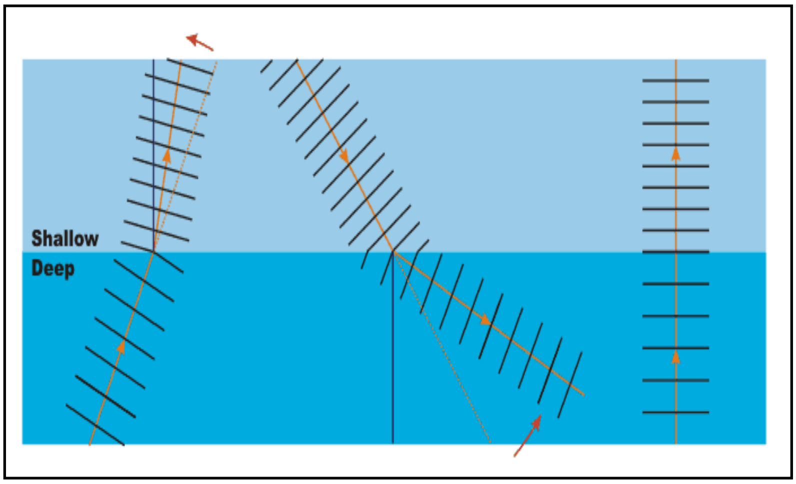
Reflection. As the waves strike a plane (flat) barrier they are reflected. This is very similar for a beam of light reflecting on a plane mirror. If a curved (concave) barrier such as a satellite dish is used, the waves can be made to converge (concentrate) at a point. The angle of incidence and reflection will be equal.



Reflection on a satellite dish.



Refraction: Refraction is the change in direction of a wave at the boundary between two materials. This is caused by a change in speed.

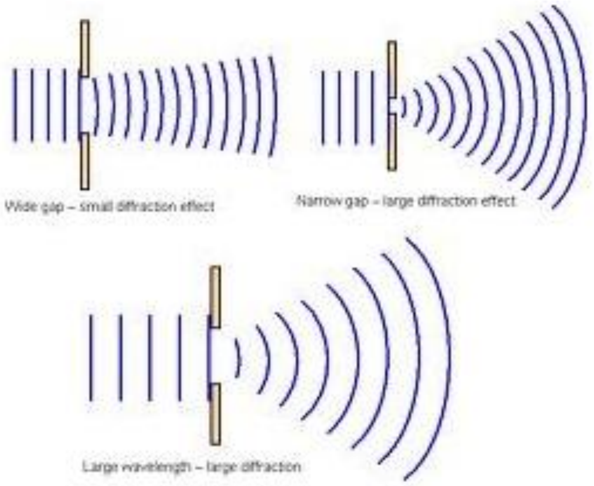


Water. This occurs when water waves pass between deep and shallow water. The waves move more slowly in shallow water. The ***frequency of the waves remain constant*** and so the wavelength decreases. When the waves move from shallow to deeper water, their speed increase and they change direction away from the normal

Diffraction

Diffraction is defined as the spreading of a wave when it meets an obstacle into regions where it would not be seen if it moved only in straight lines.

There is little diffraction when λ is much smaller than the dimensions of the obstacle or slit. If λ is equal to or greater than the width of a slit, waves spread as roughly semicircular wavefronts, but if λ is less than the slit width the main beam spreads. The wavelength remains unchanged.



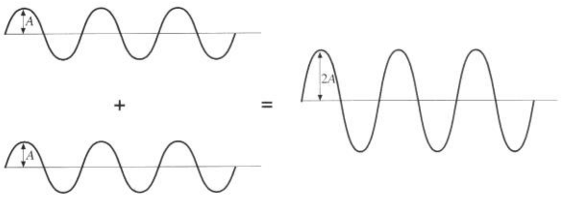
Principle of Superposition.

***The principle of superposition states if the waves from two sources occupy the same region then the total displacement at a point is the vector sum of the displacements of the individual waves at that point*.**

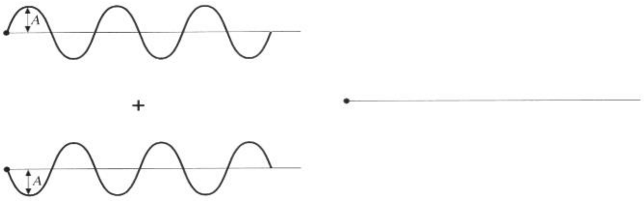
Interference

There are two types of interference. **Constructive and destructive.**

The diagram below shows two waves arriving together. If they arrive at a point in phase, that is if their crests arrive at exactly the same time, they will interfere **constructively**. If the two incoming waves have the same frequency and equal amplitude A, the resultant wave produced by **constructive** interference has an amplitude 2A. The frequency of the resultant wave is the same as that as the incoming waves.



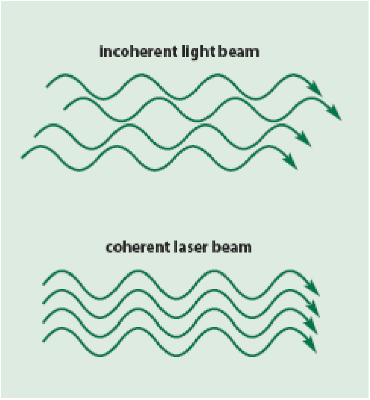
If the two waves are out of phase that is, if the peaks of one wave arrive at the same time as the troughs from the other, they will interfere **destructively.** The resultant wave will have smaller amplitude. This is shown in the diagram below, where the incoming waves have equal amplitude, the resultant wave has zero amplitude.



Coherence

To observe interference then the two wave sources must be coherent and get a meaningful resultant wave by using the principle of superposition.

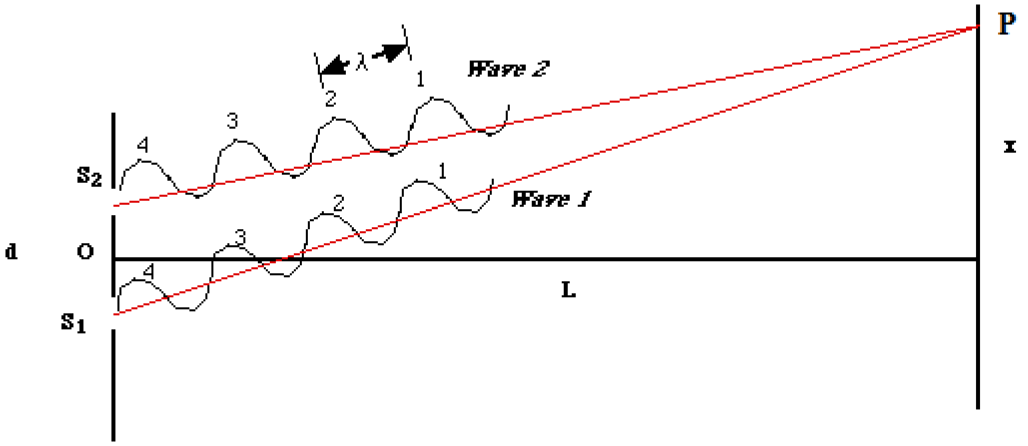
Coherent:* means that there is a constant phase difference*. (They must therefore have the same frequency)



A laser is an example of a coherent light source. Examples of incoherent light source are car headlights, normal light bulb. Coherent sources are monochromatic with wavefronts continuous across the width of the beam and, (when comparing more than one source) with a constant phase relationship.

Path difference and Young’s double slit experiment.

The path difference is a measure of the distance between two waves arriving at a point in terms of their wavelength. If we consider the effect of superposition at a number of points in space, we can build up an interference pattern - a pattern showing some areas where there is constructive interference, and hence a large wave disturbance, and other areas where the interference is destructive, and there is little or no wave disturbance.



If the path S_1P is equal in length to the path S_2P (in the centre), this means that the two waves arrive at P in phase. So we get constructive interference.

If the path difference $S_2P- S_1P = n\lambda$
Then the waves arrive in Phase at P which means constructive interference.

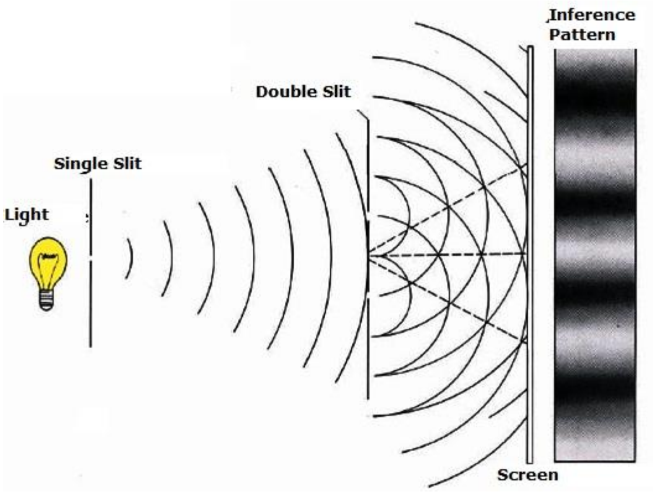
If the path difference $S_2P- S_1P = \lambda/2$ or multiples of this.
Then the waves arrive at P in antiphase which destructive interference.

This two source interference can be demonstrated using sound waves, microwaves or using a laser. The sources must have a ***zero or constant phase difference*** and have ***oscillations in the same direction***.

Young’s double slit experiment.

Two light sources at the double slits are produced. Because these two light sources originate from the same primary source, they are coherent and create a sustained and observable interference pattern as seen in the photograph of the dark and bright interference fringes. With a laser a single slit is not required.

Bright fringes = constructive interference.
Dark fringes = destructive interference.



Young’s double slit experiment.

The double slit experiment can be used to determine the wavelength of light.

λ – Wavelength (m)
Δy- fringe separation (m)
a -distance between the centre of the slits (m)
D- distance from double slit to screen

$$\lambda = \frac{a\Delta y}{D}$$

Although Young’s original double-slit experiment was carried out with light, the conditions for constructive and destructive interference apply for any two-source situation. The same formula applies for all types of wave e.g. microwaves, provided that the fringes are detected at a distance of many wavelengths from the two sources.

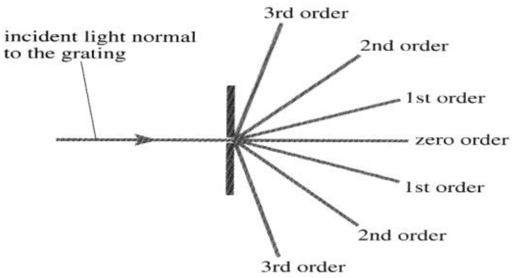
Worked example.
Calculate the wavelength of light that produces fringes of width 0.50 mm on a screen 60 cm from two slits 0.75 mm apart.

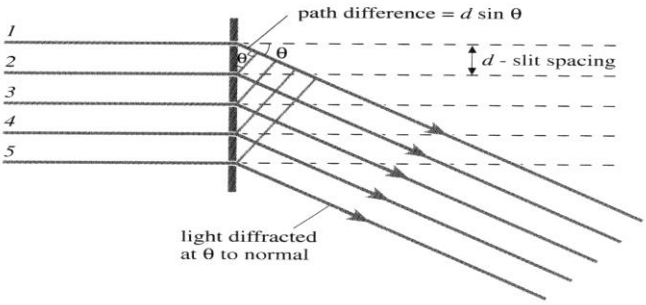
$$\lambda = \frac{0.75\text{x}10^{-3}\ \text{x}\ 0.50\text{x}10^{-3}}{0.60} = 6.25\text{x}10^{-7}\ \text{m}$$

Historical importance of Young’s double slit experiment (1801).
Newton believed that light was particle like in nature but this experiment demonstrated that light had wave like properties.

The diffraction grating

A diffraction grating is a plate on which there is a very large number of parallel, identical, very closely spaced slits. If monochromatic light is incident on this plate, a pattern of narrow bright fringes is produced, as shown in the diagram below. It works on the same principle as the double slit experiment.





Because there are so many slits, the bright fringes (or bands) are extremely narrow, and usually much further apart (large ‘y’ since slit separation, ‘d’ is very small).

$$d\sin\theta = n\lambda$$

d - slit width (m) **n - order number** **λ - wavelength (m)** **θ- angle (˚)**

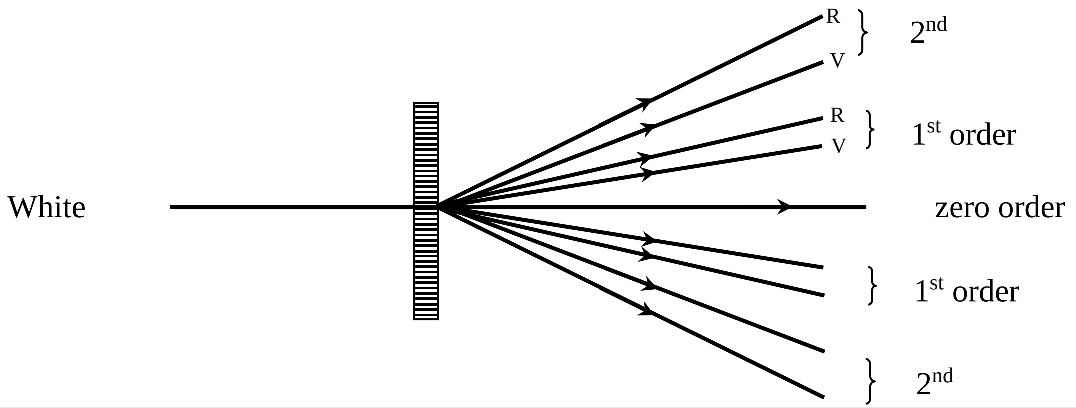
Maximum value of θ < 90˚

For a diffraction grating a very small *d* makes beams (“orders”) much further apart than in Young’s experiment, and that the large number of slits makes the bright beams much sharper.

The diffraction grating with white light

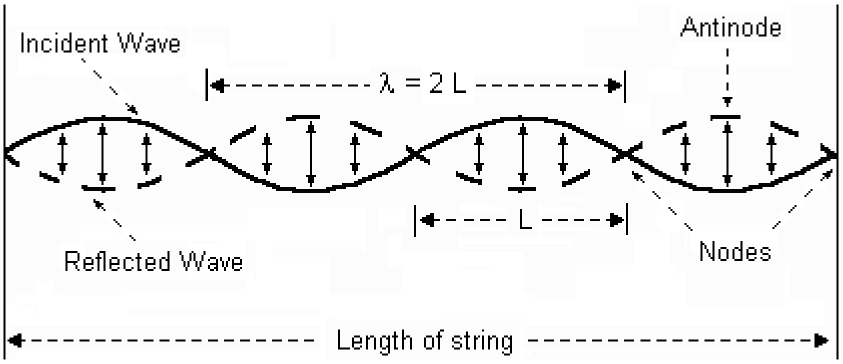
If white light is incident on a diffraction grating, each wavelength λ, making up the white light is diffracted by a different amount. Red light, because it has the longest wavelength in the spectrum, is diffracted through the largest angle. Violet light has the lowest wavelength, and is diffracted the least.

Depending on the grating spacing, there may be some overlapping of different orders. For example, the red component of the first-order image may overlap with the blue end of the second-order spectrum.



Stationary waves

A stationary wave is a pattern of disturbances in a medium, in which energy is not propagated. The amplitude of particle oscillations is zero at equally-spaced *nodes*, rising to maxima at *antinodes*, midway between the nodes.



Internodal distance (distance between nodes) = λ/2

Stationary waves are produced from the superposition of two progressive waves of equal amplitude and frequency, travelling in opposite directions.

The amplitude of a progressive wave remains constant. The amplitude of a stationary wave varies from zero at the nodes to a maximum at the antinodes. Between adjacent nodes, all points of the standing wave vibrate in phase. That is, all particles of the string are at their maximum displacement at the same instant, in a progressive wave, phase varies continuously along the wave.

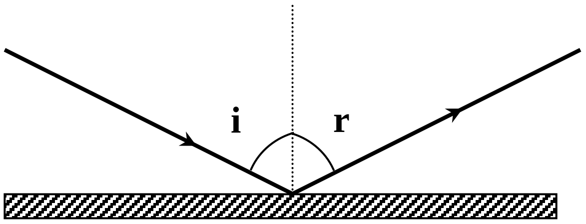
Refraction of light - Snell's law.

Reflection

When any type of wave encounters a barrier that it reflects from it always follows this simple rule :

incident angle, i = reflected angle, r

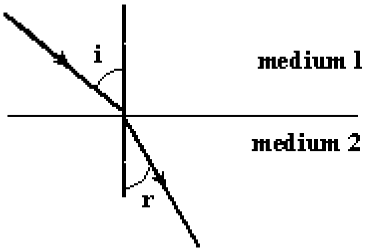
Reflecting off a plane mirror :



Snell's law.

Experiments have shown us that there is a direct link between the incident and refracted angles for any one particular material or medium. This relationship is known as:

$$\frac{\sin i}{\sin r} = \text{a constant value}$$



Snell's Law: At the boundary between any two given materials, the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant.

All media through which light travels have what is called REFRACTIVE INDEX denoted by n. Defined

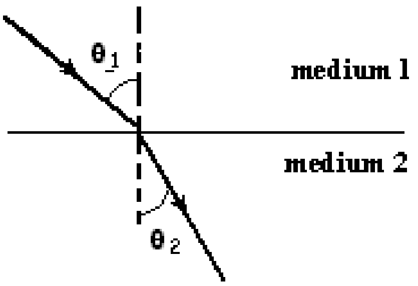
$$\boxed{n = \frac{\text{speed of light in a vacuum (free space)}}{\text{speed of light in the medium}} = \frac{c}{v}}$$

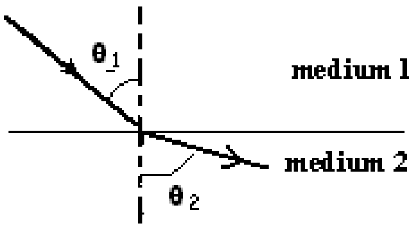
n - refractive index of medium

c – speed of light 3×10^8 ms^{-1}

e.g. for glass $n_g = \frac{\text{speed of light in vacuum}}{\text{speed of light in glass}} = \frac{c}{v_g} \quad \frac{3\times10^8}{2\times10^8} = 1.5$

When light passes between 2 mediums as shown below then we can use two equations.





$$\boxed{n_1 v_1 = n_2 v_2 \quad \text{or} \quad n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

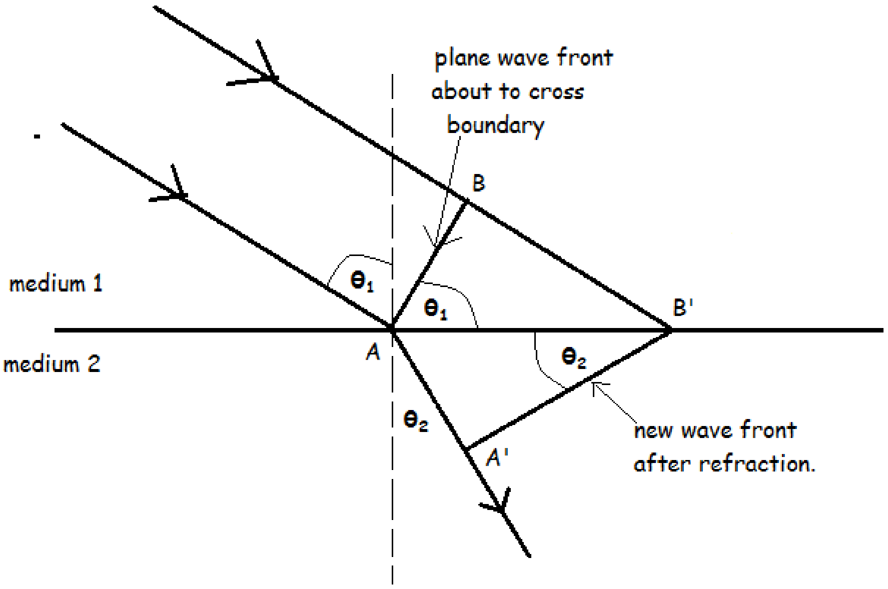
Refraction of light - Snell's law.

Here are the refractive index of different mediums.

Medium	*Refractive Index*
Vacuum	1.000
Air	1.003
Water	1.33
Glass	1.50
Diamond	2.42

Diamond has a high refractive index which explains why it sparkles.

How Snell's law related to the wave model of light propagation.



$n_1 < n_2$ $v_1 > v_2$

Waves travel a distance BB' in time -

So, distance BB' = $v_1 \times t$

During this time the light travels a distance AA' in medium 2

So distance AA' = $v_2 \times t$

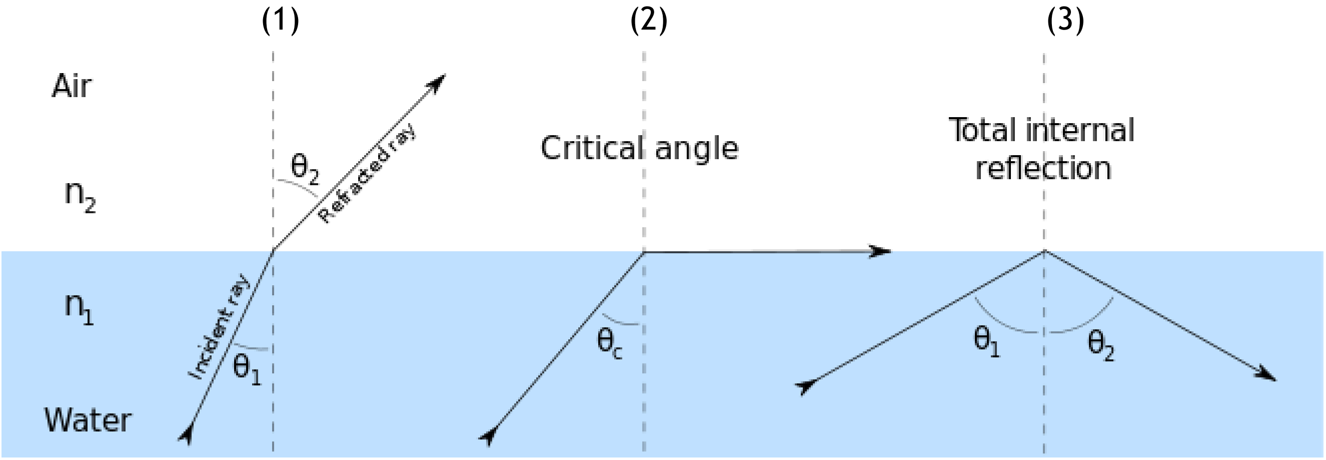
In triangle ABB' $\sin\theta_1 = BB'/AB'$ In traingle AA'B' $\sin\theta_2 = AA'/AB'$

So, $\frac{\sin\theta_1}{\sin\theta_2} = \frac{BB'/AB'}{AA'/AB'} = \frac{BB'}{AA'} = \frac{v_1 \times \cancel{t}}{v_2 \times \cancel{t}}$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

we know that $v_1 n_1 = v_2 n_2 \rightarrow \frac{v_1}{v_2} = \frac{n_2}{n_1}$ → substitute $\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$ → $\mathbf{n_1 \sin\theta_1 = n_2 \sin\theta_2}$

Total internal reflection



This phenomenon occurs when light moves from a more optically dense material (e.g. water) to a less optically dense material (e.g. air) causing a change in speed.

1. The incident angle θ_1 is ***less than*** the critical angle and so the light ray refracts/ bends away from the normal as it emerges from the water. θ_2 is the **angle of refraction.**

2. The incident angle θ_1 ***equal*** to the critical angle and so the light ray passes along the surface of the boundary.

3. The incident angle is ***greater than*** the critical angle and so the light ray is reflected back into the water. This phenomenon is known as ***total internal reflection***.

$\boldsymbol{\theta_1 = \theta_2}$

Using Snell's law to determine the critical angle.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

since $\theta_2 = 90^\circ$ **and sin 90°** = 1

then we can write: $\boxed{n_1 \sin \theta_c = n_2}$

Consider a glass-air boundary

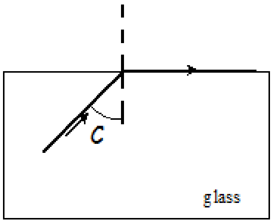
$n_1 \sin \theta_c = n_2$

$\sin \theta_c = n_2 / n_1$

$\theta_c = \sin^{-1} (n_2 / n_1)$

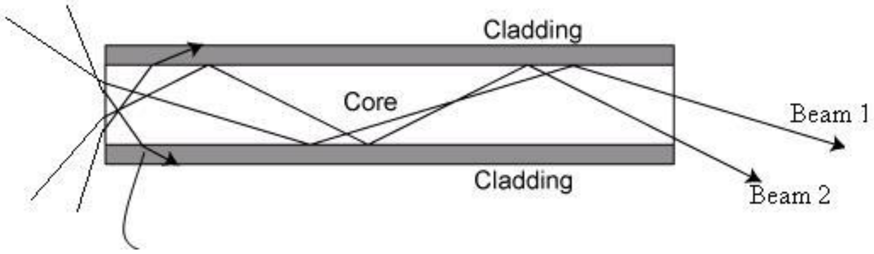
$\theta_c = \sin^{-1} (1/ 1.5)$

$\theta_c = 41.8\ ^\circ$



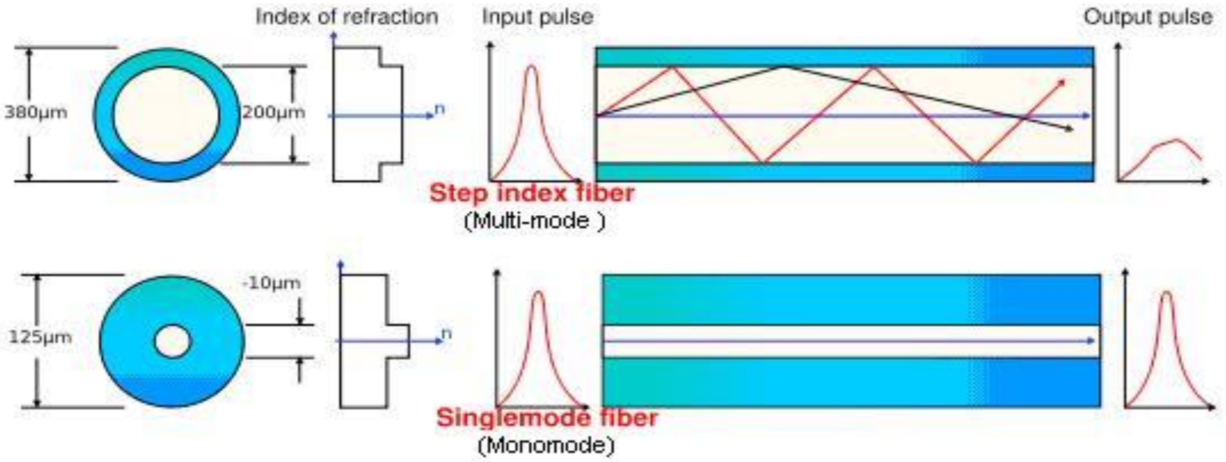
Optical fibres

Optical fibres use total internal reflection to work. The refractive index of the cladding is less than the core and so the rays of infra-red light are reflected back into the core as long as the angle is greater than the critical angle.



Monomode (Single mode) Fibres. Fibres where the core diameter is so small that the only path possible through the fibre, is along its axis i.e. **parallel to axis.**

Multimode fibres. These fibres results in the transmitted signal being subjected to very little distortion, even after several hundred km of propagation. This preservation of the shape of the signal means that very rapidly changing and 'complicated' waves that carry lots of data can be sent along and accurately received. Monomode fibres are thus better suited to long distance communication than multimode fibres (approx 50 times further). The infra-red light in multimode fibres travels in **zig-zag paths** and some paths involve reflections.



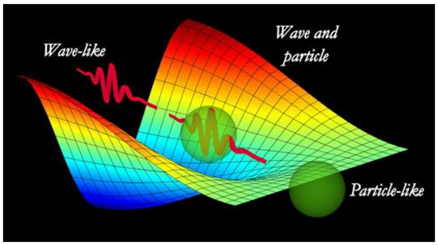
The advantages of monomode optical fibres over multimode optical fibres.

- Paths at different angles to the axis are of different lengths so data doesn't travels on different paths which would arrive at different times so data is not muddled / smeared out or overlapping.

Using angles close to critical angle minimises multimode dispersion by:

- cuts down range of path lengths
- less pulse broadening **or** less likelihood of overlapping **or** more rapid data sequence possible

Photons



We have discussed and observed properties about the wave nature of light. Light can also behave as a stream of particles. This can be seen using a weak light source for studying the interference pattern. The observed pattern is built up or emerges over a period of time as a series of spots is gradually increased.

This behaviour suggests that the energy in a light wave is not a continuous stream but rather is quantised into a little bundles of energy known as **QUANTA** or **PHOTONS.**

Max Planck: Introduced the concept of quantisation energy in 1900. This means that energy of a photon is a fixed amount/quantity.

Einstein: In 1905 Einstein recognised that this quantisation of energy was a fundamental property of light. Einstein concluded from experimental work that the energy of a photon is proportional to the frequency of the radiation.

Energy of a photon, $E = hf$ or $E = \frac{hc}{\lambda}$

REMEMBER NOT GIVEN on DATA SHEET

E- photon energy (J), h – Planck constant 6.63×10^{-34} Js, f- frequency (Hz),
c – speed of light in a vacuum (3.0×10^{8} ms^{-1})

A photon is a discrete packets of energy

Worked example.
An LED emits red light of wavelength 620nm. (a) calculate the energy in J of each photon of the emitted light. (b) The LED radiates a power of 0.5mW. How many photons are emitted each second?

(a) $E = hc/\lambda = \frac{6.63\times10^{-34} \times 3.0\times10^{8}}{620\times10^{-9}} = 3.21\times10^{-19}$ J

(b) 0.5mW is 0.5×10^{-3} W, which is equivalent to 0.5×10^{-3} Joules per second
By dividing the total energy per second by the energy of 1 photon (a) then we will get the total number of photons = $0.5\times10^{-3} / 3.21\times10^{-19} = 1.56\times10^{15}$ photons

The electronvolt.

The joule is a very large quantity of energy when used to describe the energy of a single photon. We therefore require a much smaller quantity of energy.

Definition: ***One electronvolt (eV) is the energy of an electron accelerated by a potential difference of 1 volt.***

Converting between eV and J.

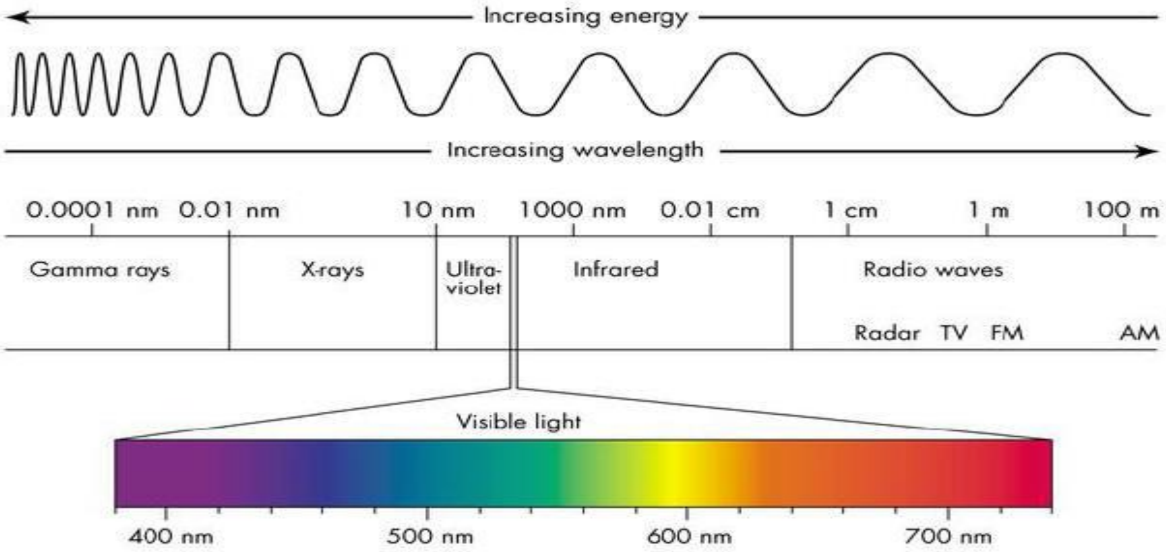
1 eV = 1.6×10^{-19} J

$50\text{eV} \times 1.6\times10^{-19} \rightarrow 8.0\times10^{-18}$ J

$900{,}000 \text{ eV} \leftarrow \frac{1.44\times10^{-13}\text{ J}}{1.6\times10^{-19}}$

The electromagnetic spectrum.

A family of waves that travel at the same speed in a vacuum and have similar properties.

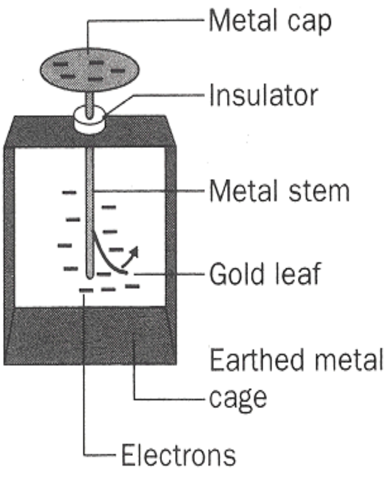


You need to remember the typical wavelength of different regions of the spectrum and then be able to calculate the typical photon energy using $E=hc/\lambda$.

Region/Part of spectrum	Typical Wavelength (m)	Typical Photon energy (eV)
Gamma	10^{-12}	10^{6}
X-ray	10^{-10}	10^{4}
UV	10^{-7} or 10^{-8}	10^{1}
Visible	$4x10^{-7}$ → $7x10^{-7}$	3.1 → 1.8
Infra red	10^{-5}	10^{-1}
Microwave	10^{-2}	10^{-4}
Radio	10^{2}	10^{-8}

The photoelectric effect

Using a zinc plate with a gold leaf electroscope

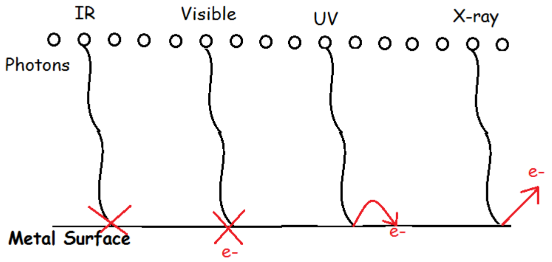


- Clean a zinc plate with fine emery paper or steel wool.
- Attach the plate to the top disc on a gold leaf electroscope, so there is good electrical contact.
- Charge the zinc plate and inner assembly of the electroscope negatively, e.g. by rubbing the zinc plate with a polythene rod which has been rubbed with a duster. The gold leaf should now be raised, because the leaf and the back plate are both charged negatively and repel each other.
- Place an ultraviolet lamp near the zinc plate. Switch it on. The leaf should be seen to fall. Clearly the plate is losing charge.
- Repeat the procedure, but charging the zinc plate and inner assembly of the electroscope positively, e.g. by rubbing the plate with a charged perspex rod.

This time the ultraviolet does not affect the leaf. Charge is not lost.

Explanation: The ultraviolet causes electrons to be emitted from the zinc plate. If the plate is charged positively, the electrons are attracted back again. If the plate is charged negatively the emitted electrons are repelled and lost from the plate for ever.

The photoelectric effect - Vaccum photocell



Photoelectric effect: when light or ultraviolet radiation of short enough wavelength falls on a surface, electrons are emitted from the surface.

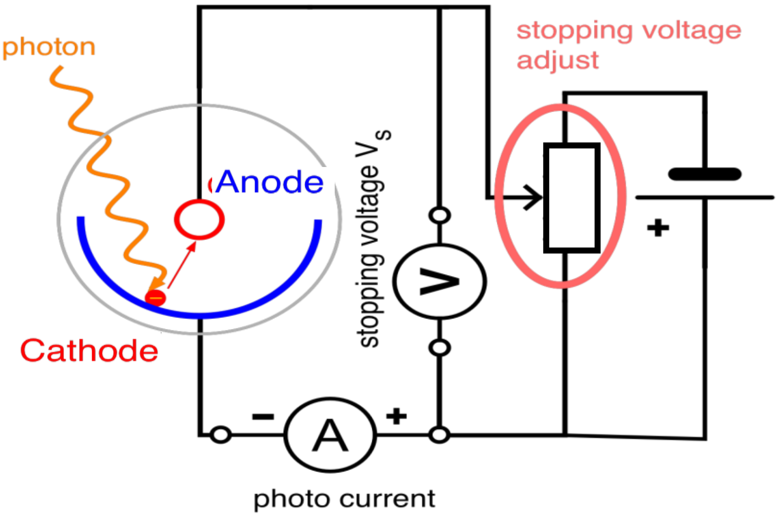
The electrons in each different metal needs a certain amount of energy to leave the surface, this is known as the work function.
The work function - (Φ) of a surface is the minimum energy needed to remove an electron from the surface. Unit: J or eV.
Any energy left over/remaining will be seen as the kinetic energy of the ejected photoelectron. **This is known as $E_{k\ max}$.**

The photons of light need to give enough energy for it to leave the metal surface.
Threshold frequency- (f_0) this is the minimum frequency of a photon that will cause the emission of an electron from a particular metal surface.

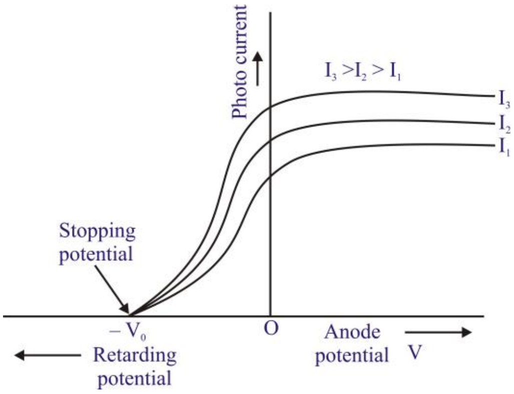
The experiment. http://phet.colorado.edu/simulations/sims.php?sim=Photoelectric_Effect
When e-m radiation of enough energy (high enough frequency) strikes the cathode surface electrons are ejected. The photoelectrons (ejected electrons) travel across to the anode and a current flows in the circuit. A current is recorded on the ammeter. The p.d. is increased until the photoelectrons are being repelled from the anode. At a certain p.d. the electrons will not have enough energy to reach the anode. The cathode and anode must be in a vacuum otherwise the ejected electrons could collide with molecules in the air.

Steps:

1. Shine light on cathode.
2. Increase / adjust pd until micro-ammeter shows zero current.
3. Read voltmeter.
4. Plot a graph of current (I) on the y-axis and p.d. (V) on the x-axis.



The graph is shown below.



If the intensity of light is increased then it's the number of photons of light that increases. This increases the amount of ejected electrons and so a larger current flows since. The stopping voltage remains the same since this depends upon the $E_{k\ max}$ of the ejected photoelectron.

$$E_{k\ max} = eV_s$$

where V_s is the stopping voltage.

Einstein’s photoelectric equation.

This equation is based on the conservation of energy.

$$E_{k\ max} = hf - \Phi$$

$E_{k\ max}$ - the maximum energy that a photoelectron can have once it has used some of the photon energy to leave the metal surface.

hf – is the energy (J)of the photon.

minimum energy (J) an electron needs to leave the surface.

If the energy of the photon (threshold frequency – f_0) is just enough to cause an electron to be ejected then the photoelectron will have no E_k so we can write:

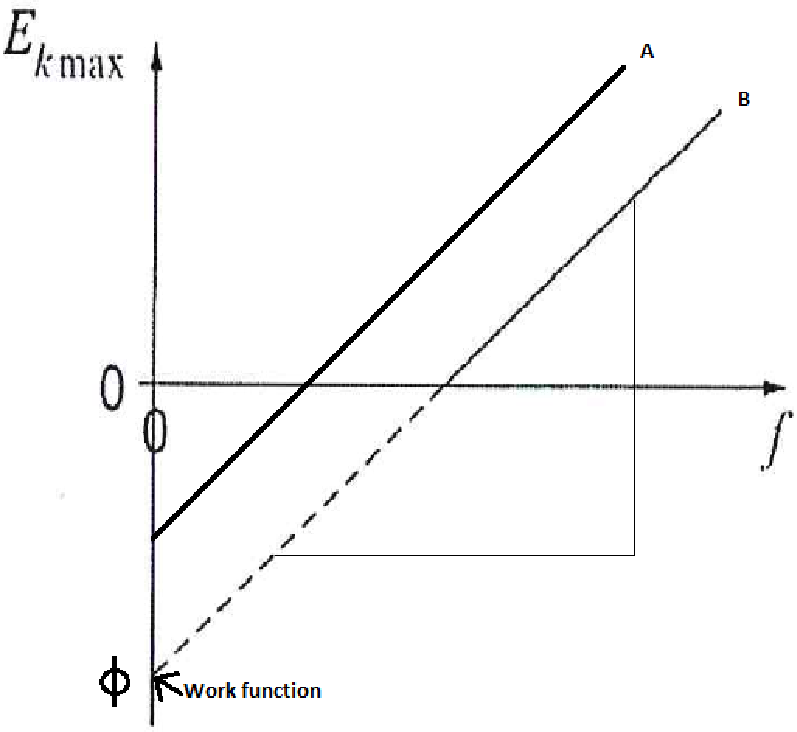
$$hf_0 = \Phi$$

If the light is not of high enough frequency then it doesn’t matter how long the light is shone on the surface i.e. photons cannot combine/join together to give the electron sufficient energy. This is evidence for the **particle nature of light.**

The same as experiment as on the previous page except that a graph is plotted of $E_{k\ max}$ and frequency for a certain metal (B). $E_{k\ max}$ is calculated from the stopping voltage (V_s).
$E_{k\ max} = eV_s$.

Comparing with the equation for a straight line graph.

$$\boxed{\begin{array}{l} E_{k\ max} = h\ f - \Phi \\ y\ =\ \ m\ x + c \end{array}}$$



The intercept gives the work function of the metal e.g. Magnesium 5.9×10^{-19} J.

The gradient of the graph gives you Planck’s constant. (6.63×10^{-34} Js).

If a graph is plotted for a different metal (A) with a lower work function (e.g. 3×10^{-19} J) then the line has the same gradient since it is a constant.

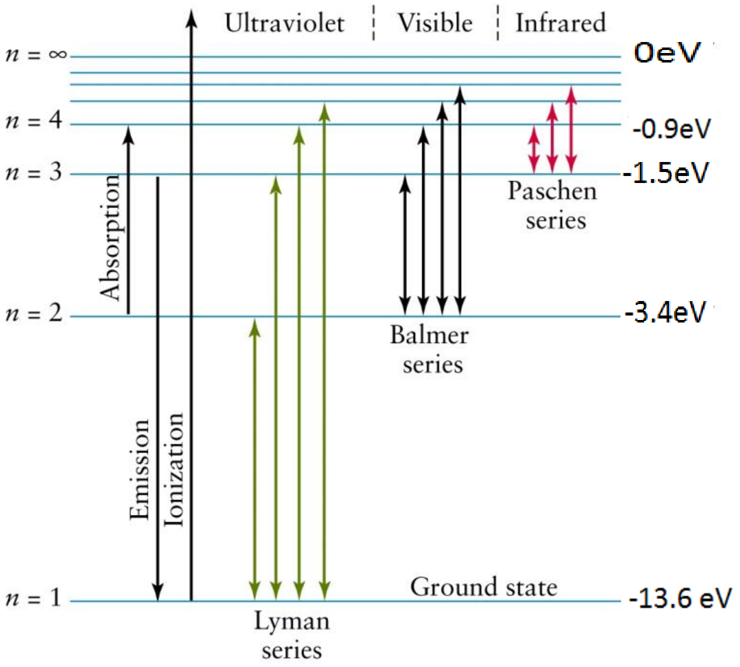
Photocells are used in light sensors for cameras and burglar alarms.

Atomic energy levels

Niels Bohr in 1913 (Danish) developed the idea that energy in an atoms was quantised and that the electrons existed in specific energy levels. The electrons can move between the energy levels as long as they are given the correct/precise quantity of energy usually in the form of a photon.

The energy levels of the atom can be given in eV or in Joules.
The electron in a hydrogen atom will in the ground state (n=1).
If the atom is excited then the electron can be promoted to a higher energy level e.g. n=2.

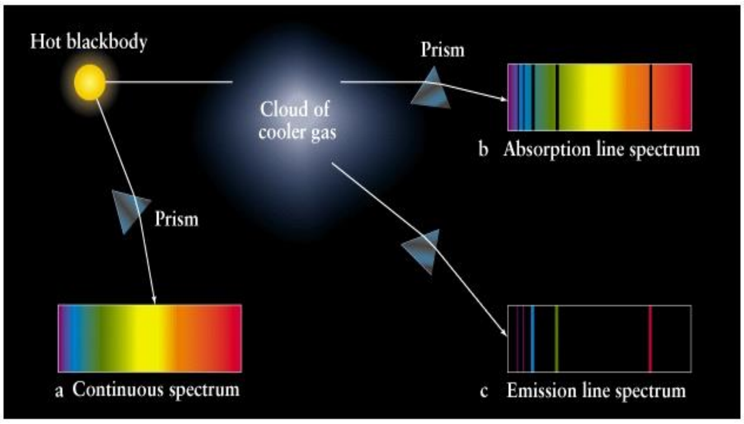
If an electron wants to move up an energy level then it must absorb a photon. If the electrons want to move down an energy level then it must emit a photon of energy. The photon energy must be equal to the energy gap.



Ionisation energy.

The ionisation energy of an atom is the minimum energy needed to remove an electron from the atom in its ground state. To ionise the atom the electron must escape from the ground state (n=1) and leave the atom (n=∞).
The energy gap = 0 – (-13.6eV) = 13.6eV.
This energy must be changed to J and then the wavelength of light can be calculated.

$13.6 \times 1.6\times10^{-19} = 2.176\times10^{-18}\text{J} \quad \rightarrow \quad \lambda = hc/E = \dfrac{6.63\times10^{-34} \times 3\times10^{8}}{2.176\times10^{-18}} = 9.14\times10^{-8}\text{m (UV)}$



Absorption spectra.

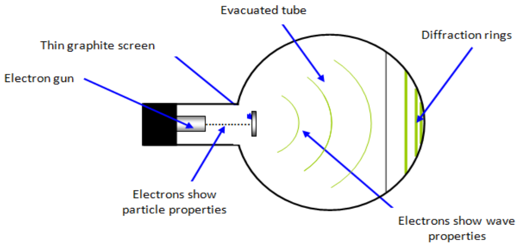
The light emitted from a source like a star or an incandescent bulb gives a continuous spectrum. When this light passes a cloud of gas (e.g. in space) then certain wavelengths of light are absorbed as electrons are promoted to higher energy levels. These wavelengths will be missing and so we get an absorption line spectrum. The light is later re-emitted but in all directions. We observe a continuous spectrum crossed with dark lines (Fraunhofer lines).

Emission spectrum. We observe this with a gas at low pressure which has been excited. Electrons collide with the atoms in the gas and cause electrons to be promoted to higher energy levels. This time we get bright lines but at specific wavelengths (colours) which is characteristic of the elements.

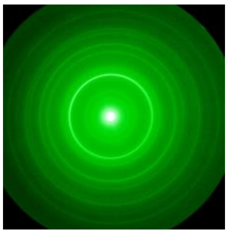
Wave-particle duality

Electron diffraction: in 1927 when Davisson and Germer performed an experiment. They accelerated a beam of electrons through a thin polycrystallite graphite film in an evacuated chamber and used a fluorescent screen to see where the electrons came out on the other side. https://www.youtube.com/watch?v=DfPeprQ7oGc

Experiment to demonstrate wave-particle duality.



Diffraction pattern for electrons.



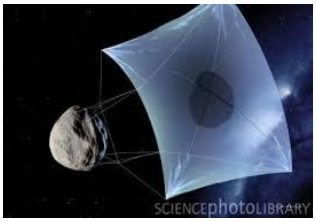
Electromagnetic waves can behave both as waves (diffraction, reflection, refraction) and particles (photoelectric effect, emission and absorption spectrum). Particles (electrons, protons etc.) can also exhibit wave like properties as shown in the experiment above. The double slit experiment can be performed using electrons which gives a pattern of bright and dark fringes. Even if the electrons are passed through one at a time then an interference pattern is observed!!!

Momentum of light. Since light waves have no mass, and since $p = m.v$, it seems logical to assume that $p_{light} = 0 \times v = 0$!! However, deBroglie derived the equation, which suggests that all particles have wave-like properties, but also that all waves have particle-like properties.

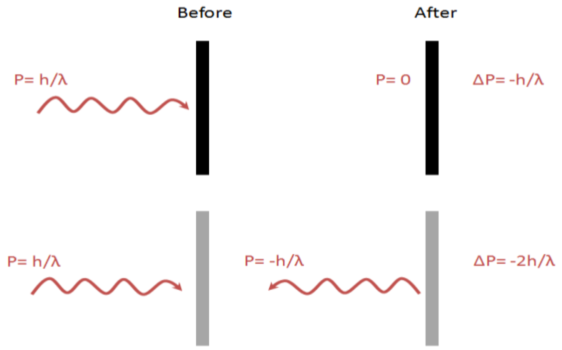
$$\boxed{\lambda = \frac{h}{p} \quad \text{or} \quad p = \frac{hf}{c}}$$

p - momentum ($kgms^{-1}$) h - Planck's constant λ - wavelength (m)

If light has momentum then it can exert a Force on surface and hence a pressure. If the light is reflected or absorbed then there will be a change in the momentum (Newton's 2nd law) of light. The change in momentum is double if the photons are reflected and hence a greater force (momentum is a vector quantity). There will be an equal but opposite force on the surface (Newton's 3rd law).



Calculating the radiation pressure when light falls on a surface.



Momentum of a photon $p = \frac{h}{\lambda}$

Force on surface → $F = \frac{\Delta p}{t}$

Number of photons = $\frac{\text{Power of light}}{\text{photon Energy}}$

Pressure of 1 photon $P = F/A$ **(A is surface area)**

Total pressure = number of photons x pressure of 1 photon

Wave-particle duality

Wavelength of particles - the same equation can be used to determine the wavelength of particles e.g. electrons, protons etc.

de Broglie equation $\boxed{\lambda = \frac{h}{p}}$

where p = m x v , momentum = mass x velocity

This was quite radical and even today it may seem like science fiction. However, de Broglie was proven correct by the experiment shown on the previous page.

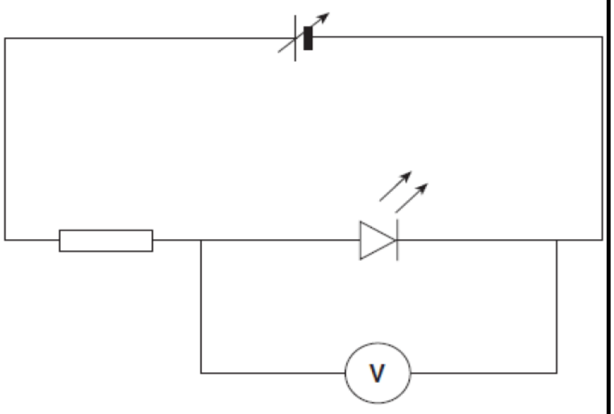
Worked example.
Neutrons can be used for analysing the atomic/crystal structure of various materials. Their mass is $1.67\text{x}10^{27}$ kg. If their velocity 3000ms^{-1}, determine their wavelength.

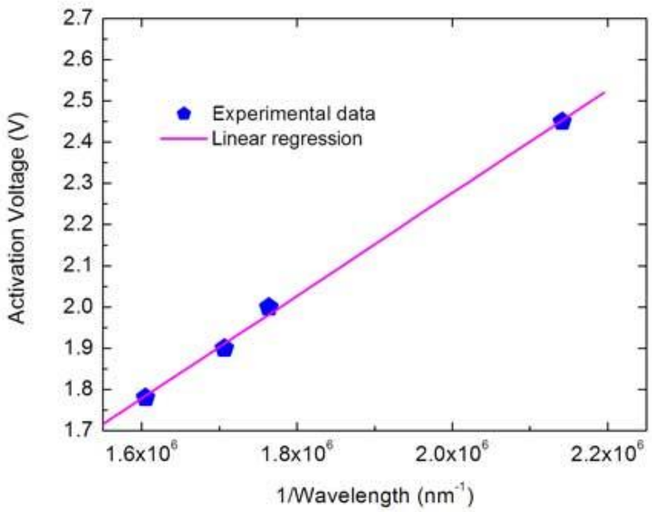
1st step, $p = mv = 1.67\text{x}10^{-27} \text{ x } 3000 = 5.01\text{x}10^{-24}$ kgms^{-1}

2nd step $\lambda = h/p = 6.63\text{x}10^{-34} \text{ x } 5.01\text{x}10^{-24} = 1.32\text{x}10^{-10}$ m (wavelength similar to distance between atoms)

Determination of h using LED's

The Planck constant, *h*, can be determined by using a light emitting diode (LED) and measuring the minimum voltage, V_{min}, at which light is just emitted by the diode. The Planck constant can then be determined from the equation $V=hc/e\lambda$ where *c* is the speed of light 3.00×10^{8} ms^{-1} and *e* is the electronic charge, 1.60×10^{-19} C.
A graph of V_{min} against $1/\lambda$ should be a straight line with the gradient equal to hc/e.





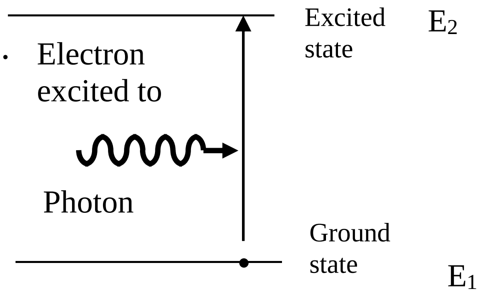
The voltage should be varied until light is just emitted by the LED. Record the voltage it corresponds to $V_{min.}$ The LED should be replaced and the procedure repeated for LEDs with different wavelengths of light. Plot a graph of V_{min} (*x*-axis) against $1/\lambda$ (*y*-axis) and use it to determine a value for *h*.

Lasers

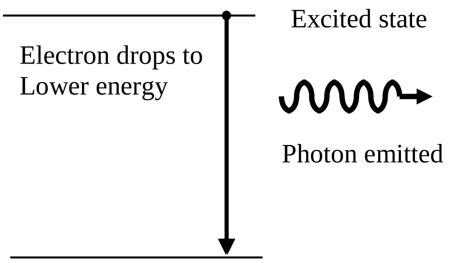
LASER - Light Amplification by Stimulated Emission of Radiation

http://www.materials.ac.uk/elearning/matter/Electrons_in_Crystals/Lasers/index.html

Photon Absorption: an electron is excited to a higher energy level by absorbing the energy of an incoming photon. The energy of the incoming photon must be equal to the difference between the two energy levels in order for it to be absorbed. $hf = E_{photon} = E_2 - E_1$

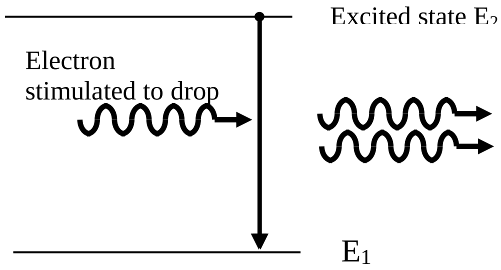


Photon Emission: The decay of an electron from one energy state to lower energy state results in the creation of a photon.



Spontaneous Emission: A photon is created spontaneously. Consider the diagram showing an excited electron at energy level E_2 it can lose some of its energy by emitting a photon. The emitted photon will have energy $E_{photon} = E_2 - E_1$ The frequency of the emitted light is also determined by the difference in energy levels because $hf = E_{photon} = E_2 - E_1$.

Stimulated Emission: This is the emission of a photon from an excited atom, triggered by a passing photon of energy equal to the energy gap between the excited state and a state of lower energy in the atom. The emitted photon has the same frequency, phase, direction of travel/propagation and polarisation direction as the passing photon i.e. coherent.

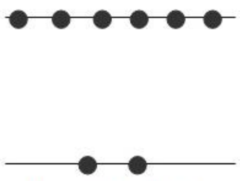


Incoming photon and emitted photon have same wavelength and exit in phase and in the same direction i.e. **coherent**

Population Inversion: $N_2 > N_1$

A *population inversion* is a situation in which a higher energy state in an atomic system is more heavily populated than a lower energy state (i.e. a less excited state or the ground state) of the same system.

In order to get as much light out of a system as is possible we need ***more electrons in an excited state*** so more will drop and emit photons. However, there is one serious problem that arises when we produce a lot of light - the very photons that we produce are the actual photons that can be absorbed (they have the correct energy to produce both effects). If we have photons being absorbed all the time then our laser beam isn't getting any stronger.

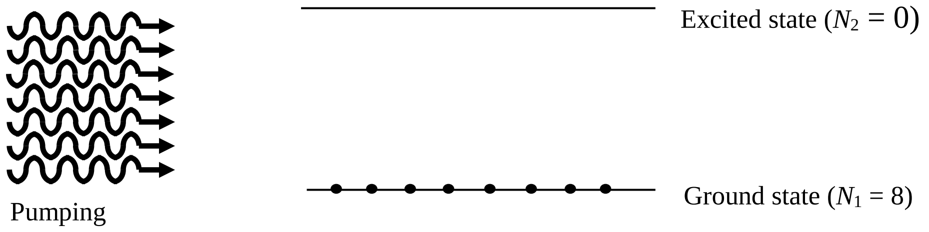


Inverted Population

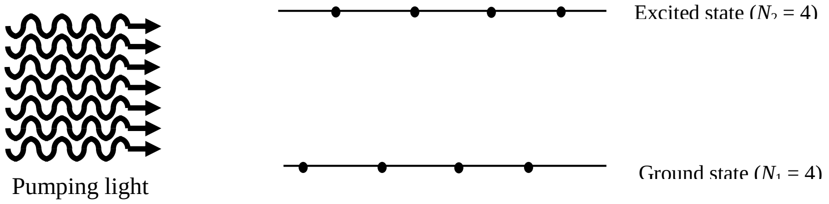
We need to arrive at a situation where **stimulated emission** is more likely than **absorption** so that the laser beam increases in intensity. This is done by pumping. ***Pumping* is feeding energy into the amplifying medium of a laser to produce a population inversion.** Since stimulated emission occurs if the electrons are in the upper level and absorption occurs when electrons are in the lower level we need to get more electrons into the upper, excited level.

Lasers

Population inversion is not usually possible if we only have two energy levels (if pumping is carried out by light). As we start to pump our system we have the following situation:



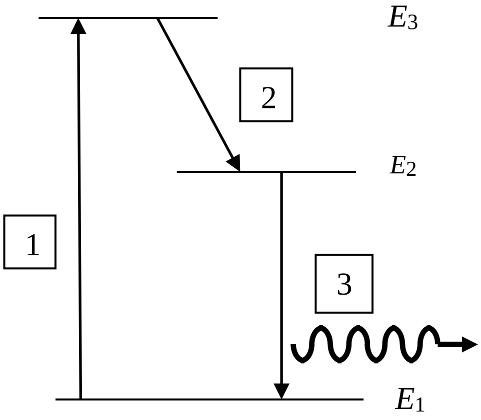
Many electrons will be promoted to the higher energy and all seems fine. Unfortunately, if we succeed in exciting half the electrons we are now in the following situation:



In this situation the incoming flood of photons is just as likely to cause an electron to drop (stimulated emission) as it is to cause an electron to rise (absorption). The best we can achieve here is $N_2 = N_1$ which is not quite good enough.

The 3 Energy Level Laser System

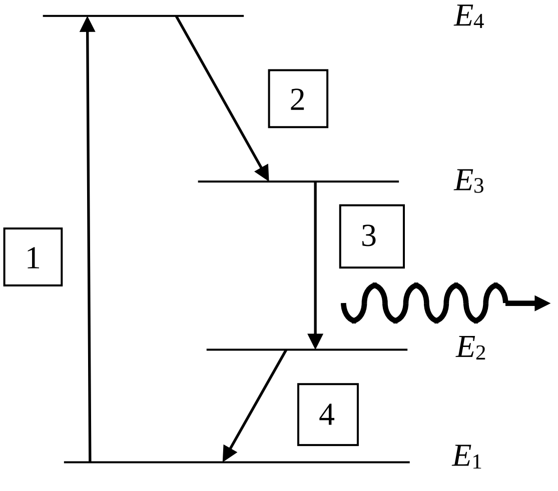
1. Pumping. Electrons are promoted from the ground state ($E1$) to $E3$ usually by using an external light source *or by electron collisions.*
2. Electrons drop quickly (because E_3 is chosen to have a short lifetime *of the order of nanoseconds*) to the **metastable** (E_2). Calling E_2 metastable means that it has a long lifetime and electrons stay there for a long time (*not that long really around a millisecond but that's a very long time for an electron*).
3. This is the transition that produces the laser photons so we must have $N_2 > N_1$. Note that, although stimulated emission still reduces our population inversion, the pumping is at a different wavelength. We have to make sure that the pumping [1] exceeds the stimulated emission [3] to maintain a population inversion.



The 4 Energy Level Laser System

1. Pumping again.
2. Fast drop to the metastable state E_3.
3. This is the laser light producing transition so this time $N_3 > N_2$. However, because E_1 is the ground state, E_2 is practically **empty initially** so obtaining population inversion is far, far easier.
4. Another fast transition so E_2 has a short lifetime. This is because we want E_2 to be empty so that we have a population inversion (if N_2 is small it's easier for N_3 to be larger than N_2).

So this is where a 4-level laser is better, in that E_2 is as depopulated as possible, which means less pumping is required and the laser is more efficient.

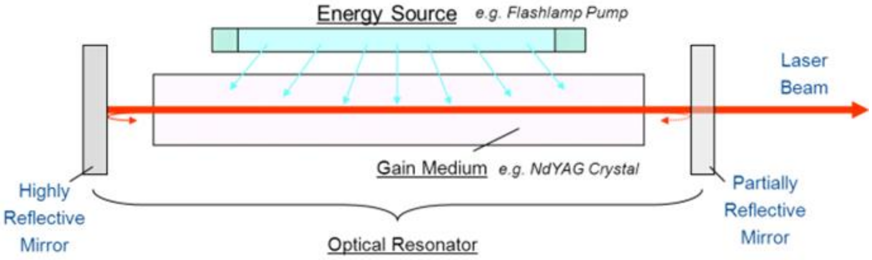


Laser Construction

Light from a laser differs from normal light in that it has these properties:

- Polarised
- Coherent
- Monochromatic (one wavelength)
- Parallel beam

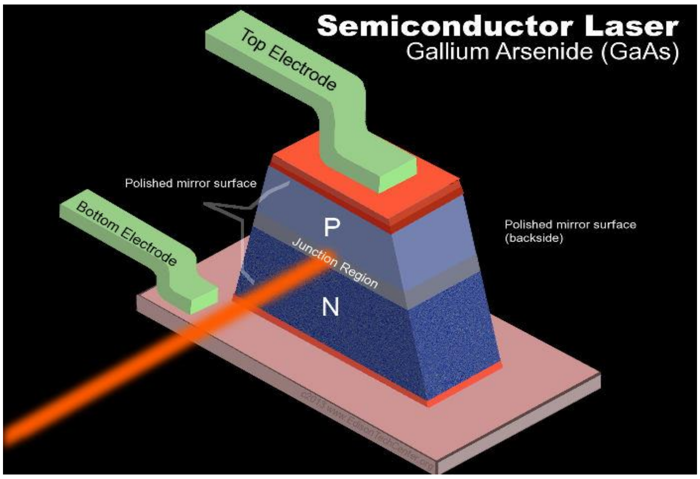
The photons are reflected backwards and forwards stimulating more photons and eventually the photons can escape through the partially reflective mirror. As more photons escape, more photons are produced by stimulated emission so and equilibrium is achieved. The amplifying medium is the region where the population inversion exists.



Under these conditions one photon has the potential to produce two photons and these can produce 4 photons, then 8 photons etc. Like a chain reaction, this process will lead to an exponential increase in output energy. Because only 1% of the light exits each time it reflects back and forth between the mirrors, on average, the beam will pass through the amplifying medium a hundred times before it exits.

High intensity pumping combined with the high intensity of the laser beam means that the amplifying medium will get very hot. So, there will be large heat losses. To make this matter worse, we need to cool the amplifying medium usually so that it, or its container, doesn't melt.

Semiconductor Lasers.



Small, cheap, efficient. Approximately 70% efficient. Pumping voltage = 3V. The basic structure of a standard 'edge emitting' semiconductor laser is shown.

The population inversion inside the semiconductor sandwich area is millions of times higher than in gas lasers.

The exponential increase in light intensity (i.e. 1 photon becoming two, becoming four etc.) occurs far more quickly because of the higher population inversion.

Advantages:	Some Uses:
Cheaper Smaller More efficient Easy to mass produce	Inside DVD and CD players Barcode readers Telecommunications (via optical fibres) Image scanning Laser surgery