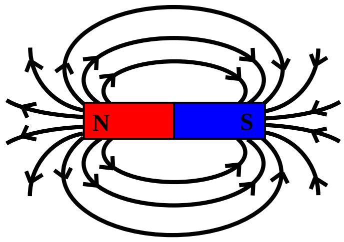
Unit 1 – Electromagnetism

Magnetic fields

A magnetic field is a region where magnetic materials feel a force. Magnetic fields are created by magnets, or current flowing in a wire. Here are some magnetic fields you should know about :

A bar magnet



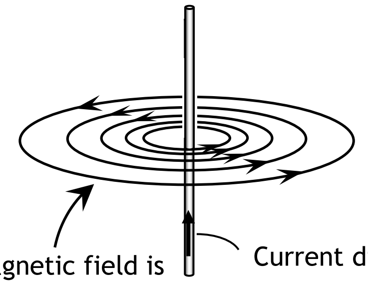
Notice that the magnetic field lines show three things :

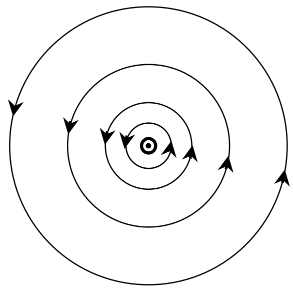
1) **The shape of the field**

2) **The direction** – out of the North pole; into the South.

3) **The strength of the field** – the field is stronger where the lines are closer together.

A long, straight wire with a current flowing through it

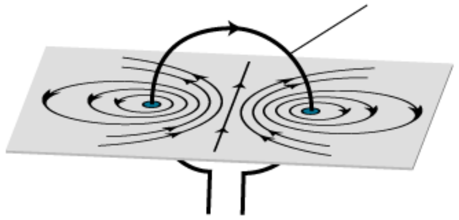




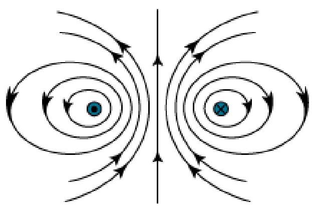
Plan view (bird's-eye)

Notice that the field lines get further apart the further they are from the wire, since the magnetic field is getting weaker.

A flat coil

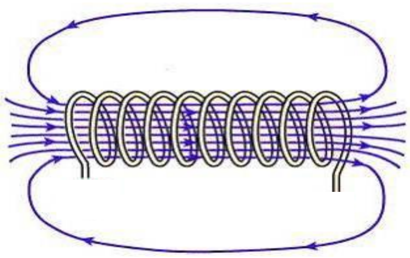


Magnetic field pattern generated by a flat coil



Magnetic field pattern generated by a flat coil (Plan view)

A long coil (solenoid)



Notice that the field lines **inside** the coil are almost straight and parallel – this shows the magnetic field has a constant strength in this region.

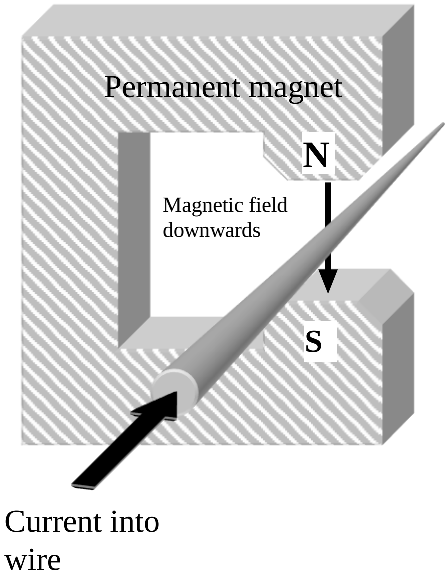
Also, notice that the shape is very similar to that of the magnetic field around a bar magnet.

The Motor Effect

We can use the magnetic effect of electricity to produce movement.

If a current-carrying wire is placed in the magnetic field of a permanent magnet, **two** magnetic fields will exist on top of each other - one due to the permanent magnet, and one from the electricity flowing in the wire.

This produces a **force** on the wire, in exactly the same way a force is produced between two magnets placed close together.



The size of the force on the wire can be increased by doing one of three things :

1. **Increasing the current**
2. **Increasing the magnetic field strength**
3. **Increasing the number of wires in the field**

The force produced on a wire can be used to create movement (rotational), and is known as the 'Motor Effect'.

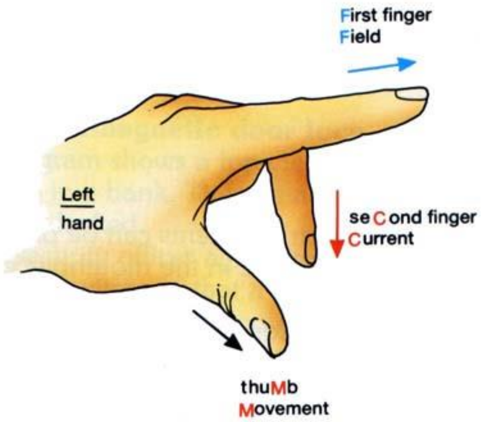
It's possible to predict the direction of the force by using **Fleming's LEFT hand rule**.

If the thumb and first two fingers of the left hand are placed at right angles to each other as shown then . . . .

the **F**irst finger is in the direction of the **F**ield

the se**C**ond finger is in the direction of the **C**urrent

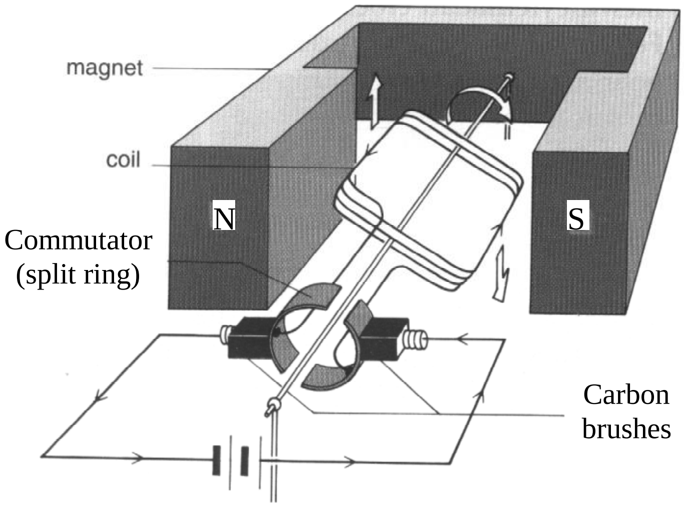
and the thu**M**b is in the direction of **M**otion.



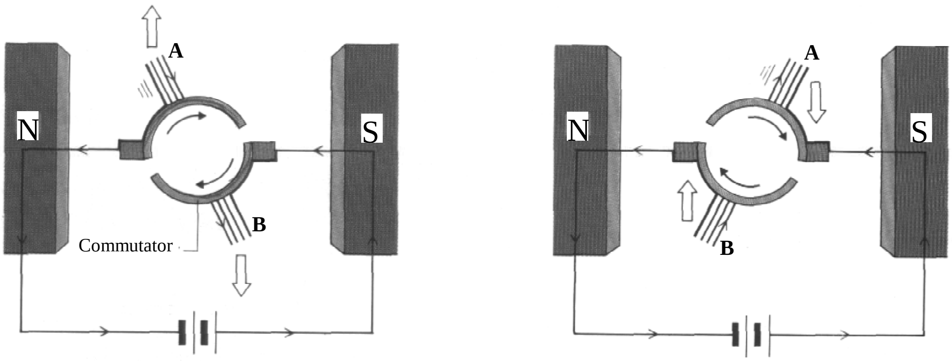
The Motor

When current passes through the coil, a force acts upwards on one side of the coil, and downwards on the other side.

The overall effect of these forces is to make the coil turn on its axis.

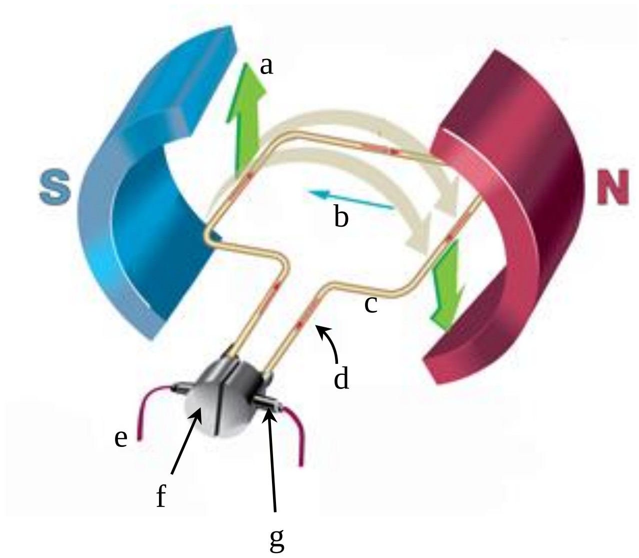


The split ring commutator ensures that the force on any wire on the left hand side of the motor is always directed upwards, and that the force on the right hand side is always downwards. This makes sure that the coil turns continuously in one direction.



<u>Question</u> : Match each label (1➔7) to the correct part (a➔g) for the simple dc electric motor below :

1. Commutator (Split rings)
2. Voltage in
3. Magnetic field
4. Motion / Force
5. Coil
6. Electric current
7. Brushes

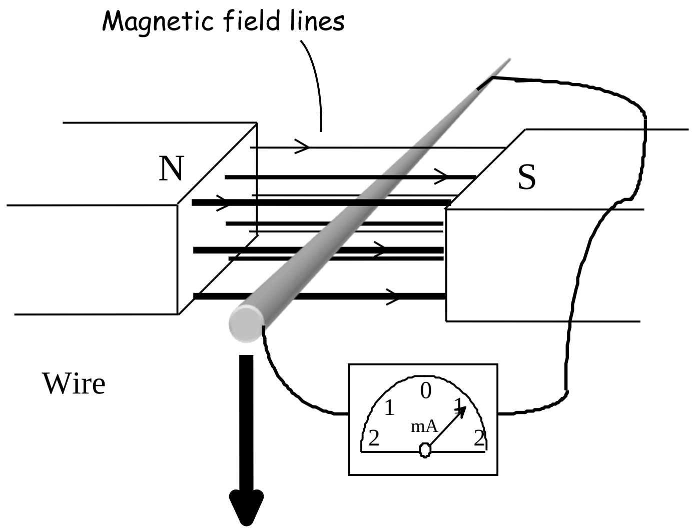


Answer : 1=f, 2=e, 3=b, 4=a, 5=c, 6=d, 7=g

Electromagnetic Induction

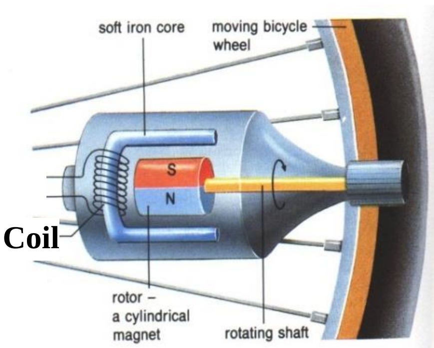
If a metal wire is forced to move through a magnetic field (or a magnetic field is moved through a wire), a **voltage** is produced across the wire.
If this wire is part of a complete circuit, this voltage will push a current around the circuit.

Another way of saying this would be :
“electricity is induced (created) when a wire CUTS through magnetic field lines”.

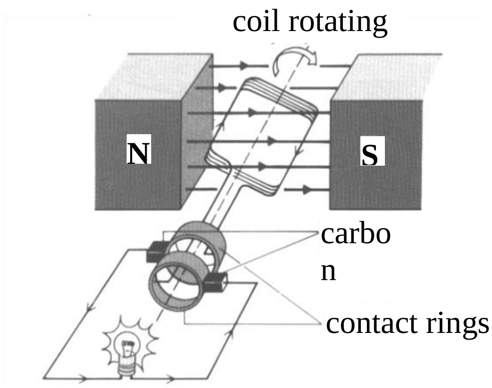


Wire is forced downwards, cutting through the field.

As you can see in the diagrams below, it makes no difference whether it’s a magnet turning inside a coil, or a coil turning inside a magnetic field, the effect is the same – electricity is induced in the coil.

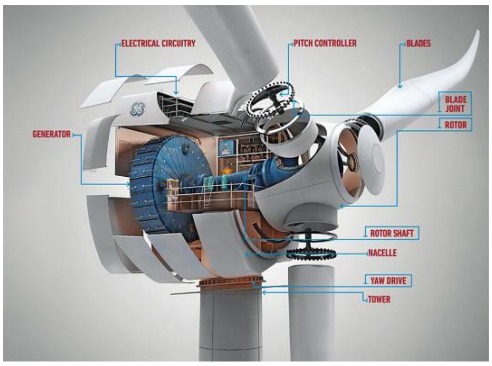


A ‘dynamo’ on a bicycle wheel

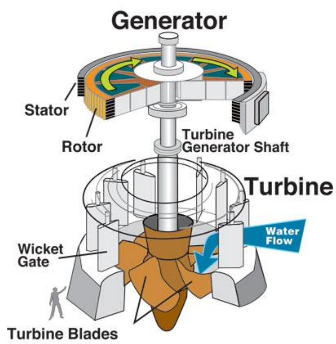


A small generator, e.g. a wind up torch

Generators are a crucial part of all power stations (except for solar PV).
Shown below is a wind turbine – the generator can be seen at the back.



Here’s a generator from a hydroelectric power station ➔



Generators

The output voltage/current is **proportional** (doubling one variable doubles the voltage/current) to :

1. **the speed of rotation**
2. **the number of turns on the coil**

and increases if the **magnetic field strength** increases.

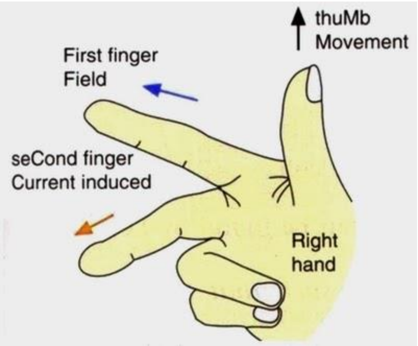
The direction of the induced current can be predicted by using Fleming's **RIGHT** hand rule.

If the thumb and first two fingers of the right hand are placed at right angles to each other as shown then,

the First finger is in the direction of the Field

the thuMb is in the direction of Motion

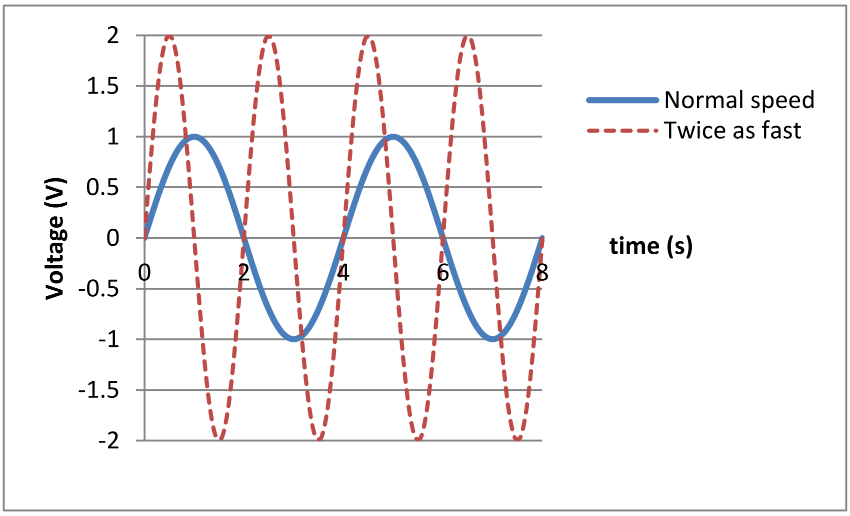
and the seCond finger is in the direction of the Current



What type of output voltage/current is produced by a generator ?

Usually, the circular movement that occurs in generators produces an alternating voltage or current. 'Alternating' means that the current/voltage direction changes regularly. For most generators the circular movement also means that the output current is constantly changing in size - this is explained on the next page.

Here's a graph showing a typical output from a generator :

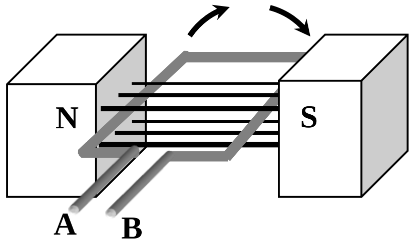


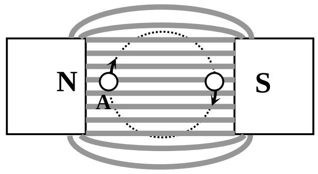
Notice the effect of **doubling** the speed of rotation of the generator.

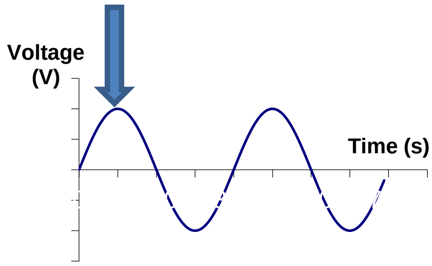
One 'rotation' or cycle takes 2 seconds (rather than 4s).

Also, the peak voltage is now **twice** as large since the coil in the generator is breaking through magnetic field **twice** as quickly - see point 1 at the top of the page !

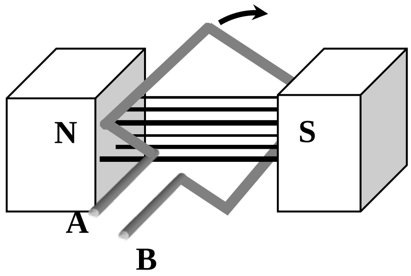
Understanding the shape of the output voltage of a generator

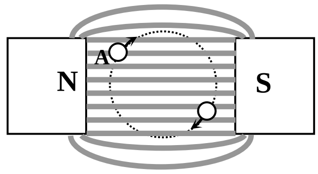


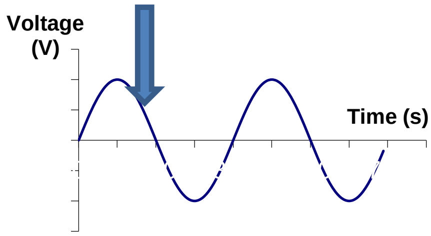




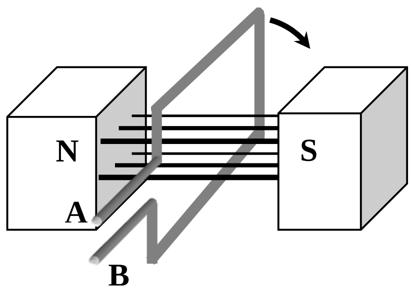
The coil is cutting through magnetic field lines at its greatest rate, and so this is when the maximum voltage/current is produced.

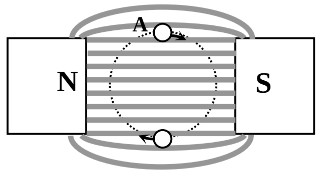


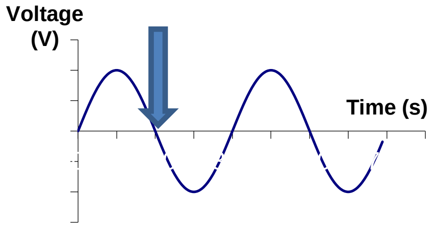




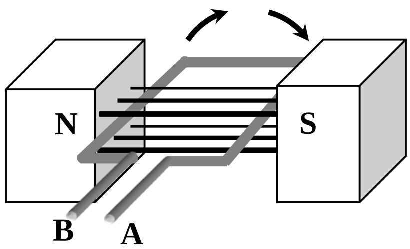
Side “A” of the coil is still cutting **upwards** through magnetic field lines, and so the voltage is still positive. However, because of the angle, the coil isn’t cutting the lines as quickly as before, and so there’s less voltage.

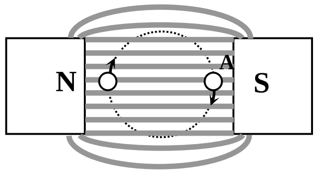


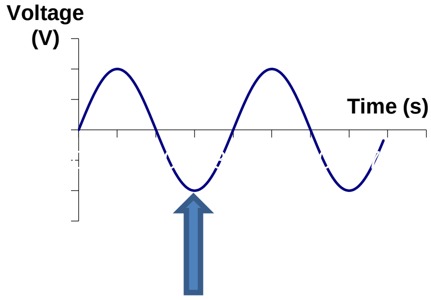




The coil is **not** cutting any field lines - its just moving along with them in the North-South direction.
This means that **NO** voltage is produced.





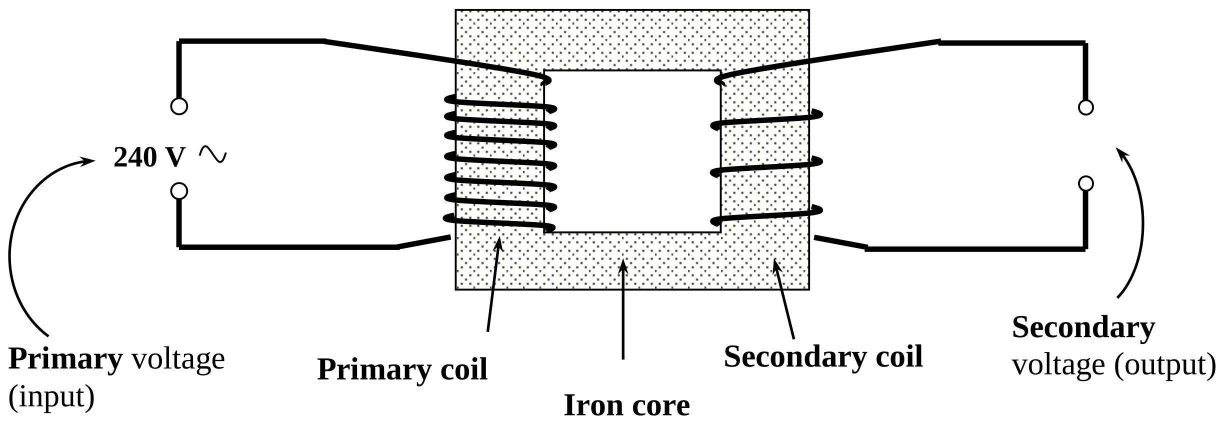


Once again lines are being cut at maximum rate, but side “A” of the coil is now cutting **down** through the magnetic field.
This changes the direction of the voltage.

Using Induction - TRANSFORMERS

A transformer is a device that makes use of the fact that electricity can be created (induced) by a **changing magnetic field**. Transformers are used to increase (step-up) or decrease (step-down) the voltage.

Here's a diagram of a transformer where two separate coils have been wound around two sides of the same piece of solid iron 'core':



← Here's a large transformer in the National grid ……

…… and here's a small transformer – a phone charger →

The explanation for how electricity is created in the secondary coil could be asked for in a "QWC"-style examination question. Here's an example of a well-structured answer :

The alternating current in the primary coil creates a changing magnetic field around it. Iron is a magnetic material, and so easily transmits this magnetic field to the secondary coil. The constantly changing magnetic field around the secondary coil induces a voltage in this coil.

Additionally, whether this output voltage is greater or lesser than the primary voltage depends on the amount of turns in the secondary coil as compared to the primary.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

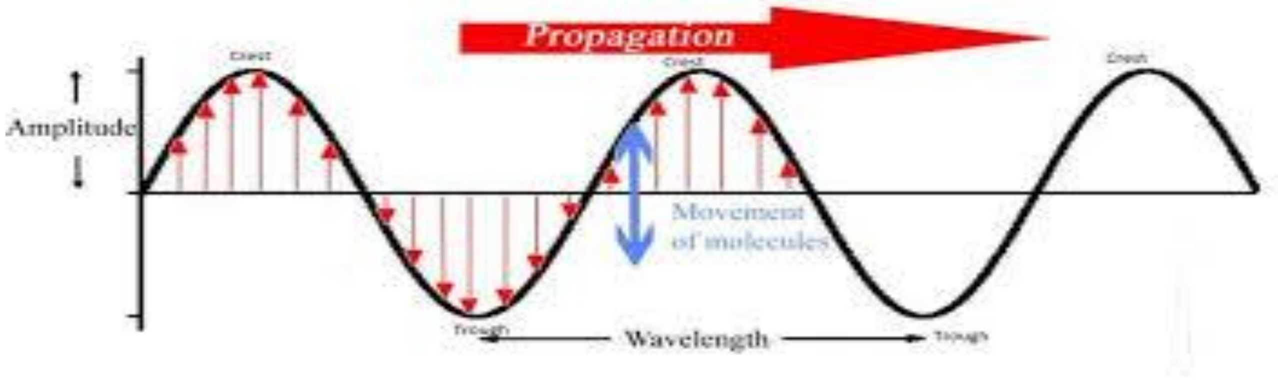
where

V_1 = voltage across the primary coil
V_2 = voltage across the secondary coil
N_1 = number of turns on the primary coil
N_2 = number of turns on the secondary coil

Example : *The input (primary) voltage of a phone charger is 240V (mains). The output needs to be 4.8 V. Calculate "N_2" (the number of turns on the secondary coil) if N_1 = 2000.*

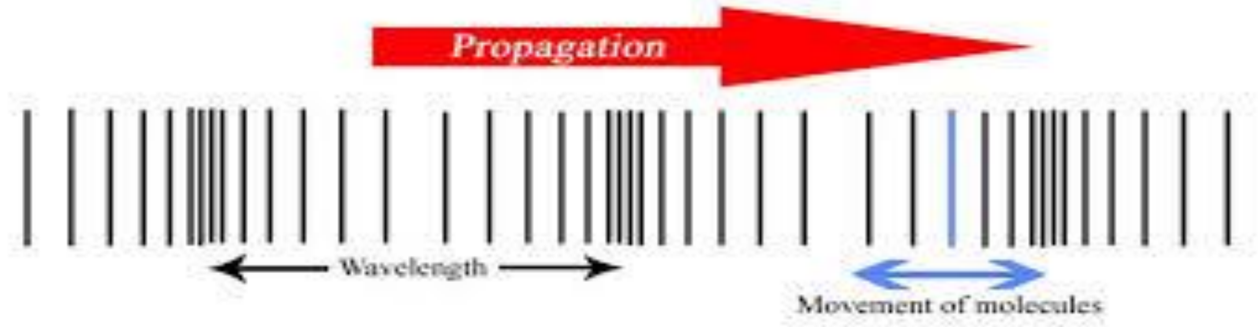
$$N_2 = \frac{N_1 \times V_2}{V_1} = \frac{2000 \times 4.8}{240} = 40 \text{ turns}$$

Transverse: ***The oscillations of the particles are at right angles (90°) to the direction of travel (propagation) of the wave.***



Examples: All electromagnetic waves (Light, microwaves etc), S-waves,

Longitudinal waves: ***The oscillations of the particles are in the same direction as the wave is moving.***



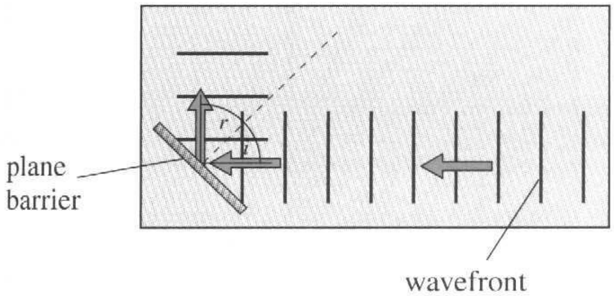
Examples: Sound waves, P-waves

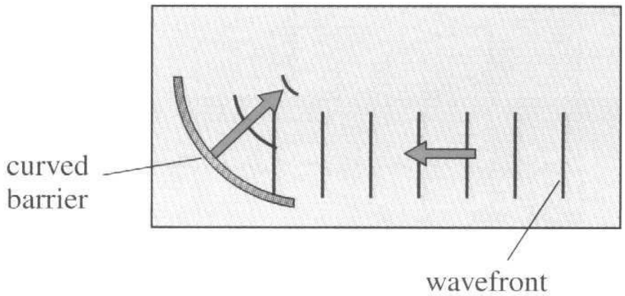
Characteristics	What is it?	Units
1.Wavelength λ	The distance from a crest to the next crest or the distance it takes to repeat itself.If there are 10 waves in 5 metres then the wavelength is 0.5m	Metres, m
2. Frequency **f**	The number waves per second. 1 Hz is 1waves per second. If there are 40 waves in 10 seconds then the frequency is 4 Hz.	Hertz, Hz
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

Properties of waves

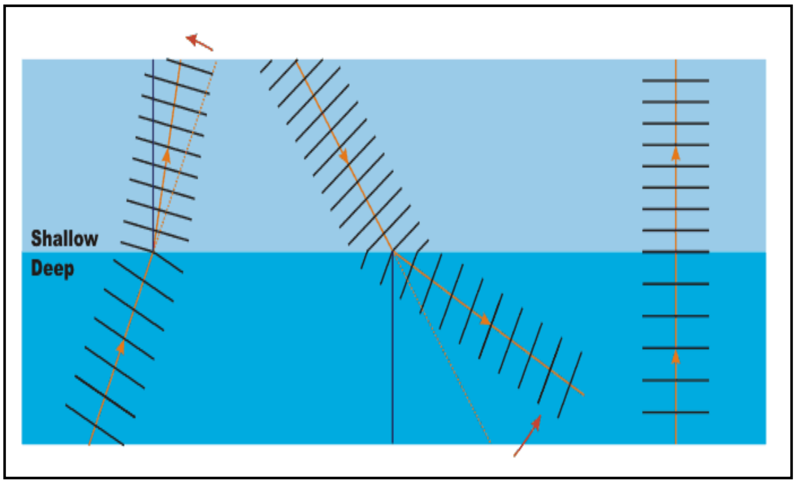
Reflection. As the waves strike a plane (flat) barrier they are reflected. This is very similar for a beam of light reflecting on a plane mirror. If a curved (concave) barrier such as a satellite dish is used, the waves can be made to converge (concentrate) at a point. The angle of incidence and reflection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

Reflection on a satellite dish.



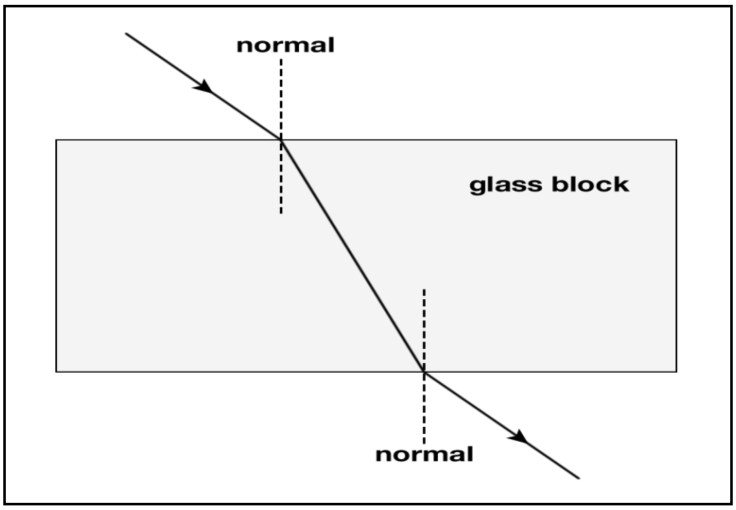


Refraction: Refraction is the change in direction of a wave at the boundary between two materials. This is caused by a change in speed.

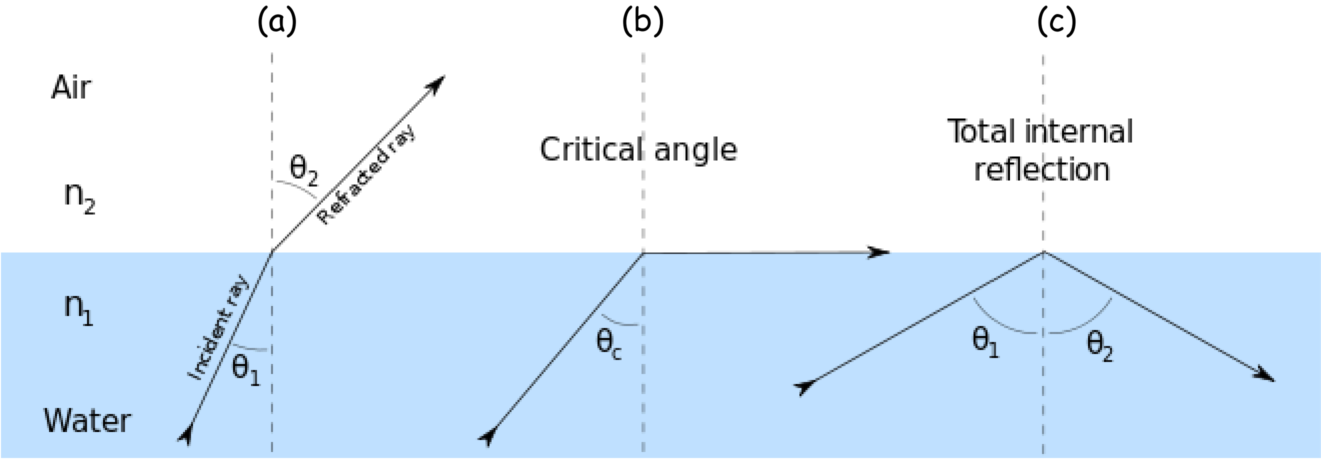


Water. This occurs when water waves pass between deep and shallow water. The waves move more slowly in shallow water. The ***frequency of the waves remain constant*** and so the wavelength decreases. When the waves move from shallow to deeper water, their speed increase and they change direction away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

Light. When light passes in between materials of different optical densities, it causes the light ray to refract. When the light moves from air to glass it slows down, and bends towards the normal. When the light emerges from the glass block it speeds up and bends away from the normal (opposite direction).



Total internal reflection



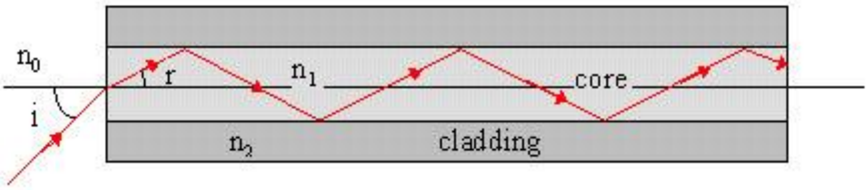
This phenomenon occurs when light moves from a more optically dense material (e.g. water) to a less optically dense material (e.g. air) causing a change in speed.

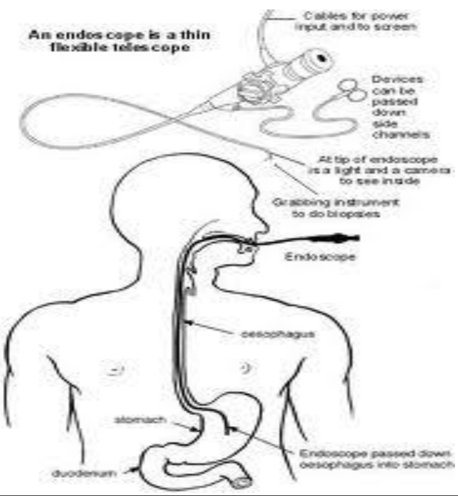
1. The incident angle θ_1 is ***less than*** the critical angle and so the light ray refracts/ bends away from the normal as it emerges from the water. θ_2 is the **angle of refraction.**
2. The incident angle θ_1 ***equal*** to the critical angle and so the light ray passes along the surface of the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

$\theta_1 = \theta_2$

Uses of total internal reflection.

Optical Fibres: these can be used to carry information by using infra-red light. There are many uses from internet, cable TV, phone, some signs



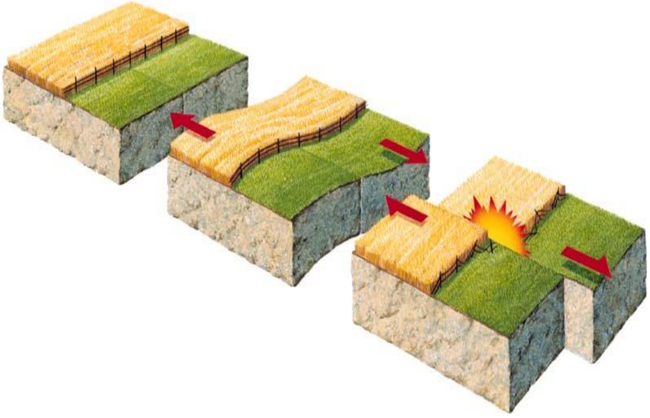


Endoscope: An endoscope is any instrument used to look inside the body. Thousands of optical fibres are bundled together in an endoscope which is inserted into a human body by the doctor. Light can be directed down the fibres even if they are bent, allowing the surgeon to illuminate the area under observation. He/she can then view this from a television camera linked to a monitor.

Seismic waves / Earthquakes

The mechanisms and processes involved when earthquakes occur are extremely complex. However some of the characteristics of earthquakes can be explained:

- Over time stresses in the Earth build up (often caused by the slow movements of tectonic plates)
- At some point the stresses become so great that the Earth breaks … an earthquake rupture occurs and relieves some of the stresses (but generally not all) and a lot of **energy** is released.

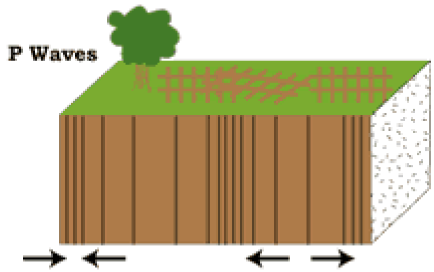


The 3 types of seismic waves.

Earthquakes result from P, S and surface waves generated by the release of energy stored in rocks on either side of a fault.

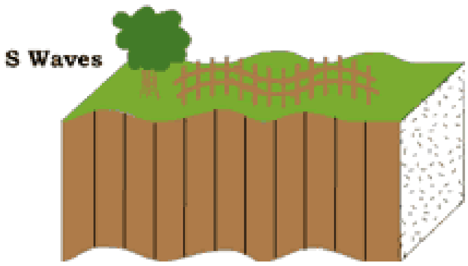
Primary (P) Waves. They are called primary waves because they arrive first. The main characteristics of primary waves are:

- They are longitudinal waves.
- Faster than S waves.
- Can travel through ***liquids*** and ***solids.***



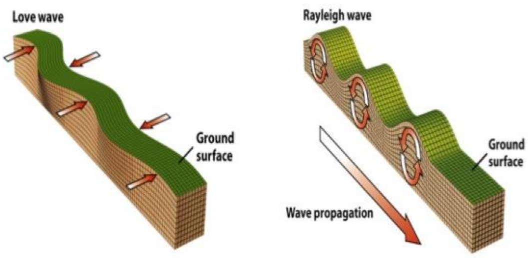
Secondary (S) Waves. They are called secondary waves because they arrive second. The main characteristics of secondary waves are:

- They are transverse waves.
- Travel slower than P waves.
- Can only travel through ***solids.***



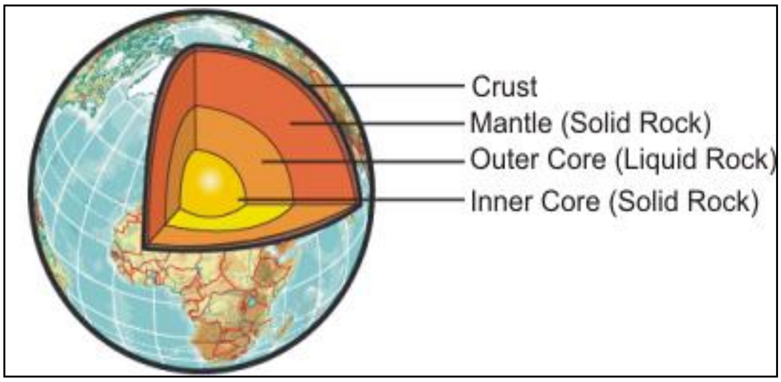
Surface Waves: Travel along the Earth's crust. The main characteristics of surface waves are:

- Have higher amplitudes than P and S waves.
- These usually cause buildings to be knocked down.
- Formed from a combination of P and S waves.
- Generally slowest of the three waves.



The speed of seismic waves.

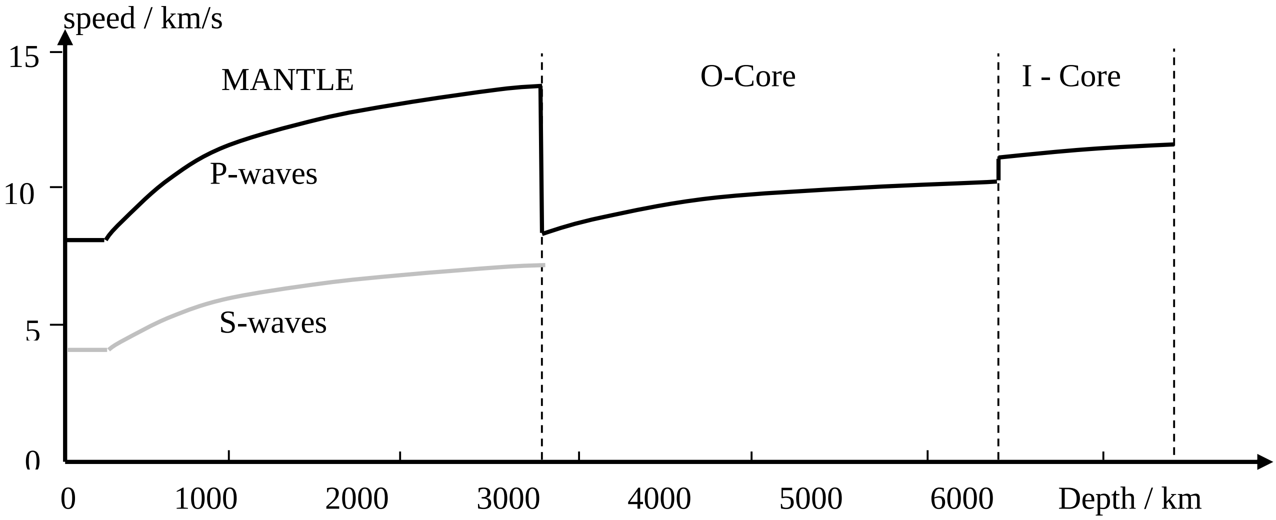
The velocity of a P or S wave depends on the physical properties of the rock. In fact, if the velocity of the wave can be measured, it may be possible to predict the type of rock the wave travelled through - indirect detection of rock type.



The velocity depends upon

1. **The density of the rock/material. The higher the density the more slowly waves travel.**
2. **The rigidity of the material – waves travel more quickly more rigid/stiff materials.**

Speed of P-waves in the core: the density of the iron core is very much greater than that of the mantle, their speed is much less. As in the mantle, the speed increases with depth and the speed increases as it crosses into the more rigid solid inner core.



Rigidity of the material has a greater effect on speed than density.

Look at the graph and notice that there are no S-waves in the outer core. P-waves, S-waves and surface waves can travel in the following.

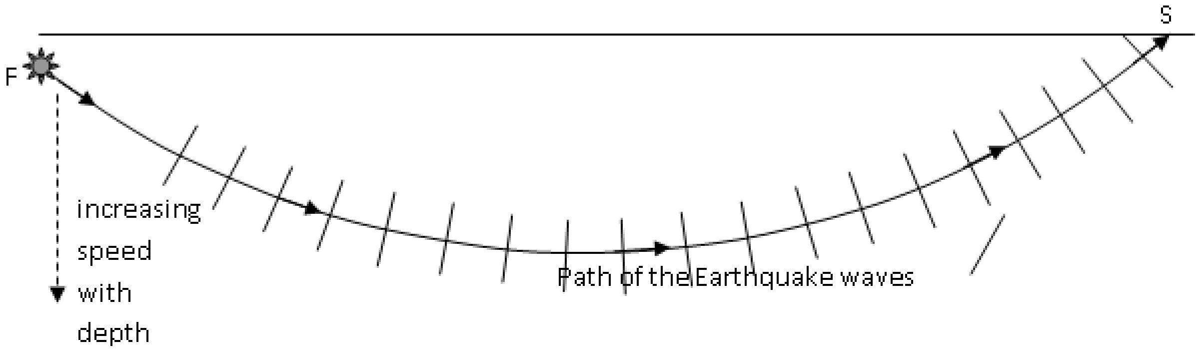
- ***Crust (solid)***: P-waves, S-waves and surface waves.
- **Mantle (solid):** P-waves and S-waves.
- ***Outer core (liquid):*** P-waves only.
- ***Inner core (solid):*** P-waves.

Refraction of seismic waves.

Both the density and stiffness increase with depth in the mantle, but the rigidity wins and so the speed of both S- and P-waves increases with depth. If the speed of the waves changes then the waves will refract and so will change direction.

Refraction in the Mantle Over a few hundred km refraction has the following effect – ignoring the curvature of the Earth:

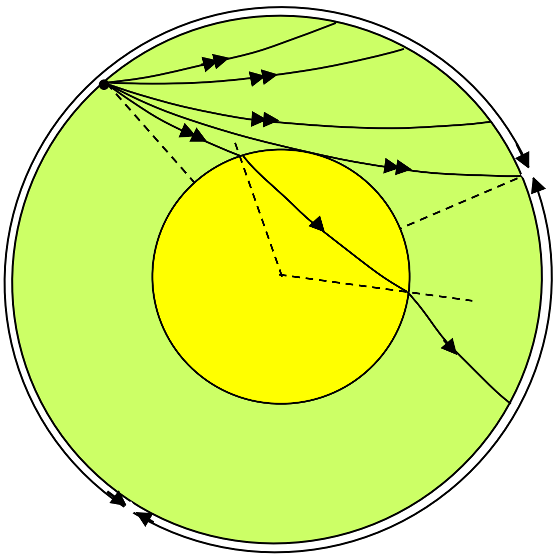
F = earthquake focus S = Seismometer



The waves curve because the bottom edge travels faster than the top edge and so it overtakes the top edge. This makes it bend upwards. Note that both P- and S-waves curve like this. They both travel faster the deeper they go into the mantle.

Inside the core.

The waves refract/bend at the core-mantle boundary because they slow down. Inside the core, the waves curve gradually, just like in the mantle, because the deeper they get, the faster they become - because the core is more rigid at greater depths. They don't refract/bend very much though because the ***speed*** doesn't change very much – see the graph. (The dotted lines represent the normal which is always at 90° to the boundary).



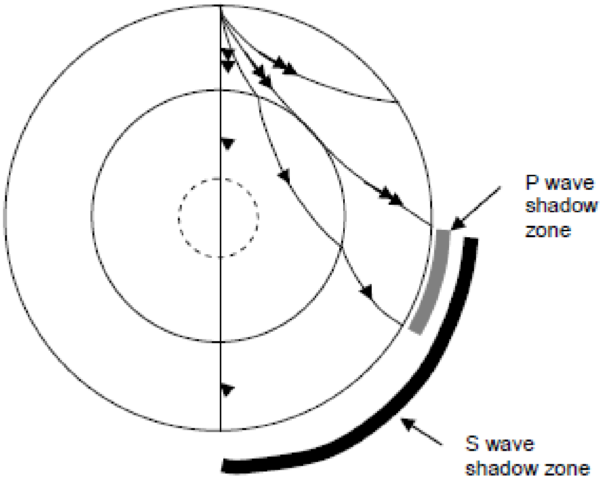
If the waves pass through the inner core, they refract again. They also ***refract*** as they pass back into the mantle.

Shadow zones.

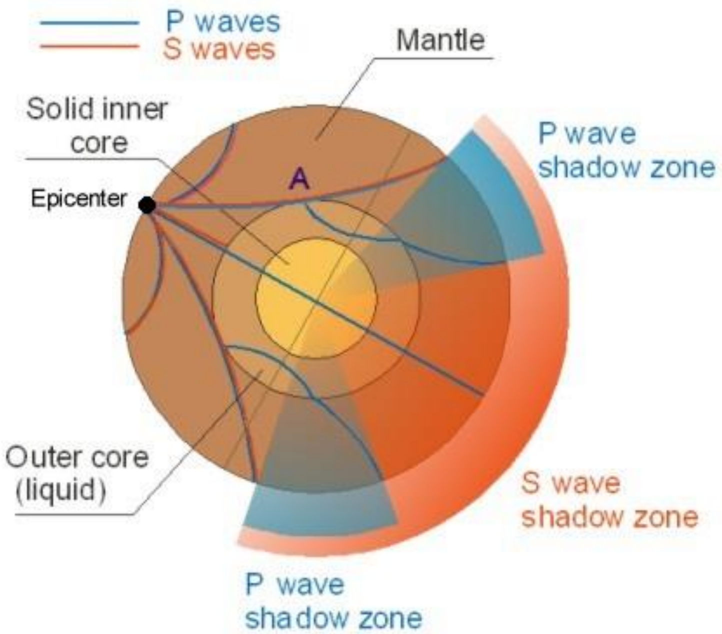
The outer core of the Earth is liquid. The mantle and the inner core are solid. Only 'P' waves can travel through the liquid outer core. By measuring 'P' and 'S' waves after an earthquake at different points across the globe, we can estimate the size of the Earth's liquid outer core.

P and S waves travel **very differently** through the Earth. Initially P and S waves travel in all directions from the epicentre of an earthquake outwards. They are refracted as they travel from the epicentre and follow arcs.
However, S waves **cannot** travel through the liquid outer core of the Earth.

1. the large shadow zone for the S waves on the opposite side of the earth from the epicentre.
2. the two smaller shadow zones for P waves



Note that there is a considerable change in density from the solid mantle to the liquid outer core. By finding the angles at which the P and S waves **both** disappear we can calculate the radius of the liquid core of the earth.



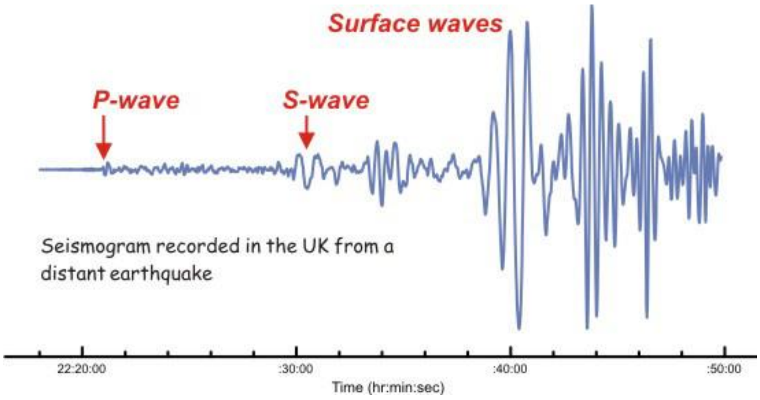
The existence of the ***S shadow zone*** is due to a liquid outer core [at all angles > 104° from the epicentre] shows that there must be a molten layer (liquid) and gives evidence for its size.

The size of the ***P shadow zone*** reveals the amount of **refraction** at the core – hence gives evidence for its density / rigidity.

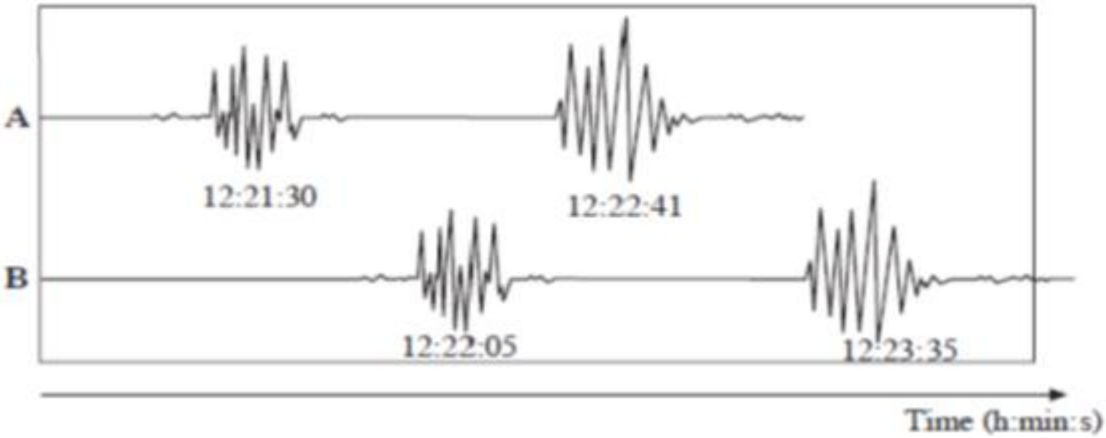
Seismogram.

Seismograms can be used to locate the epicentre of an earthquake.

P-waves arrive first then S-waves followed by the surface wave. The greater the distance from the earthquake to the monitoring station the greater the time lag/gap between the waves. Remember not all monitoring stations will receive the seismic waves due to the shadow zones.



Example question. The diagram shows the first seismic signals received from an earthquake at two monitoring stations A and B.



1. What evidence is shown by the seismic data that suggests A is nearer the epicentre than B?

   Answer: The seismic waves arrive at A before they arrive at B.

2. What evidence suggests P and S waves have travelled with different speeds from the earthquake?

   Answer: P and S waves do not arrive at the same time.

3. The time lag between the arrival of the P and S waves for a seismic station which is 100km from the epicentre of an earthquake is 12s. Calculate the distance of the monitoring station A from the epicentre of this earthquake.

Answer : 1st step is to work out the time gap between P and S waves for station A. Between 12:21 :30 and 12:22:41 there is a 71s gap/delay.

2nd step is to realise that there is a 12s delay for each 100km (as stated). How many times more is 12s than 71s ?

So, $71 \div 12 = 5.92$ and then $5.92 \times 100 =$ 592km

Unit 3 -Motion

The equations

Speed is defined as the distance moved per unit time, and hence, the equation for speed is :

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Distance is measured in **metres** (m)
Time is measured in **seconds (s)**
Speed is measured in **metres per seconds (m/s)**

If the speed is <u>**not**</u> constant this equation can still be used, but it gives a value for the **average speed.**

There are also equations for objects that are **accelerating,** e.g.

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time}}$$

$$a = \frac{v - u}{t}$$

Re-arranging ➔ $v = u + at$

If the acceleration is **constant**, then there are 3 other equations that we can use. These are known as the 'equations of motion' or 'kinematic equations', and are **all given in the examination** :

$$v = u + at$$

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

$$x = ut + \tfrac{1}{2} a t^2$$

$$v^2 = u^2 + 2a x$$

Symbol		Quantity	Unit
x	=	distance/displacement	m
u	=	initial velocity	m/s
v	=	final velocity	m/s
a	=	acceleration	m/s^2
t	=	time	s

All the above quantities, except for 'time', are **vectors**, meaning that they must have a **direction.** For example, displacement is simply the 'straight line' distance between the start and end point of your journey, **in a certain direction.**

The equations

Remember !!
These equations only work if the acceleration is constant.

This means that the equations work well for objects moving under the influence of gravity, but only if the friction and air-resistance are negligible. They work very well on the surface of the moon and Mars etc., since there's little or no air, so the acceleration due to gravity has a constant value near the surface. They also work fairly well on Earth, as long as air-resistance isn't too large !

Mars' curiosity probe, 2012

Example 1

A child, initially sitting on the edge of a diving platform, lets himself drop into the swimming pool 4 m below. Assuming no air-resistance, and given that the acceleration due to gravity is 9.81 m/s^2, calculate,

(i) the child's speed as he hits the water

Start by inserting all known values :

x = 4 m
u = 0 m/s
v = ?
a = 9.81 m/s^2
t = ?

Since 3 of the 5 quantities are known, we can use the equations of motion to calculate the other 2.
The only equation with 'x', 'u', 'v' and 'a' (i.e. not 't') is :

$$v^2 = u^2 + 2ax$$
$$v^2 = 0 + 2 \times 9.81 \times 4$$
$$v^2 = 78.48$$

... and so, the answer is $\mathbf{v = 8.9\ m/s}$

(ii) the time it takes the child to reach the water's surface

We now know 4 values :

x = 4 m
u = 0 m/s
v = **8.9 m/s**
a = 9.81 m/s^2
t = ?

Since 4 of the 5 quantities are known, we can use **any** equation containing 't'. Here's the easiest one :

$$v = u + at$$

Re-arranging ➔ $t = \frac{v - u}{a} = \frac{8.9 - 0}{9.81} = \mathbf{0.91\ s}$

Since these equations only work if the acceleration is constant, we can only calculate the speed of the child just before making contact with the floor, as once contact is made, the acceleration changes. This is very important in cases where something falls to the ground - the final velocity,v, is **NOT ZERO** since we're calculating the velocity just before the object hits the ground.

Remember that displacement, velocity and acceleration are all 'vectors' - you must be aware of their directions.

In the last example this wasn't a problem since the direction of movement was in the same direction as gravity (downwards). However, you must be prepared for examination questions that involve using the correct direction, as shown in the next example :

Example 2

A ball is thrown vertically upwards with a speed of 7.2 m/s.
Taking the acceleration as 9.81 m/s^2 , calculate,

(a) the time it takes to reach its maximum height

We start by deciding on a 'positive' direction. So, let's take **upwards as positive.**
Next, lets insert all given values :

x = ?
u = +7.2 m/s
v = ?
a = - 9.81 m/s^2
t = ?

At first glance it seems we're stuck as we need 3 values but only have 2 ! However, since the question asks for the time it takes to reach the greatest height, we know that, at this instant, the final velocity, v is zero !

Also notice that the acceleration is <u>negative</u> (since it's always downwards)

The only equation containing 'u', 'v', 'a' and 't' (i.e.not 'x') is :

$$v = u + at$$

Re-arranging ➔ $t = \dfrac{v - u}{a} = \dfrac{0 - 7.2}{-9.81} = +0.73$ s

(b) the maximum height reached by the ball

We now know 4 values :

x = ?
u = + 7.2 m/s
v = 0
a = - 9.81
t = 0.73 s

Since 4 of the 5 quantities are known, we can use **any** equation containing 'x':

$$x = ut + \tfrac{1}{2} a t^2$$
$$x = (7.2 \times 0.73) + (0.5 \times -9.81 \times 0.73^2)$$
$$x = 5.256 - 2.614$$
$$\mathbf{x = 2.64\ m}$$

Notice that if we had NOT taken direction into account, the acceleration value would have been positive, and the answer would have been "5.256 + 2.614", which is incorrect !!

Momentum

Momentum is a difficult thing to explain – simply, it is how much 'motion' an object has. However, it is quite easy to calculate the momentum, **p**, of an object if you know the object's mass, **m**, and velocity, **v**, (velocity is the vector version of 'speed'). This is the equation for calculating momentum :

momentum = mass x velocity $\qquad$ **p = m x v**

p = m x v = 3 000 x 10
= 30 000 kgm/s

p = m x v = 70 x 5
= 350 kgm/s

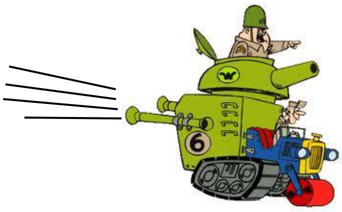
Docked !!

p = m x v = 50 000 000 x 0
= 0 (zero !) kgm/s

Here's the Law of Conservation of Momentum :

The total momentum of a system of interacting bodies is constant provided there are no external forces acting.

This law is perfectly consistent with Newton's 3rd Law ! Take a look at the imminent collision below :



Car A

Car B

As they collide, car A will create a force to the right (➔) on car B. Newton's 3rd Law states that car B will therefore produce an **equal** but opposite force on car A to the left (🡐).
We need Newton's 2nd Law too !

$$F = \frac{\Delta p}{t}$$ where Δp = change in momentum

Re-arranging ➔ $F \times t = \Delta p$

Since the cars are in contact with each other for the same amount of time, **F x t** will have the same value for both cars, and hence, **Δ p** will have the same value for both cars – this is 'conservation of momentum' since any momentum lost by car A will be given to car B.

(Remember that momentum is a vector, and so 'positive momentum' (➔) from car A will seem to 'cancel out' some of car B's negative momentum !)

Momentum

Example

(a)

(i) Two cars of equal mass, 800 kg, collide. Before the collision, car **B** is at rest while car **A** has a constant velocity of 15 m/s. In the questions that follow, ignore the effects of friction.

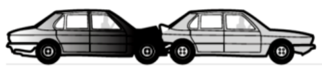
Before collision

Use an equation from page 2 to calculate the momentum of car **A** before the collision. [2]

Momentum = ... kg m/s

(ii) After the collision, the two cars are stuck together.

After collision



Use the equation:

$$\text{velocity} = \frac{\text{momentum}}{\text{mass}}$$

to calculate the velocity v of the cars after the collision. [3]

(iii) During the collision, car **A** exerts a force of 16000 N to the right on car **B**. What force does car **B** exert on car **A** during the collision? [2]

....

(b) Suppose both cars had been travelling towards each other at the same speed.

(i) What would their velocity be after a head-on collision if they stuck together on impact? [1]

....

(ii) Explain your answer. [2]

....

....

Answer

(a) (i) p = mv = 800 x 15 = 12000 kg m/s

(ii) v = p / m = 12000 / 1600 = 7.5 m/s (Notice the mass is the total mass of both cars)

(iii) F = 16 000 N to the **left** (equal but opposite)

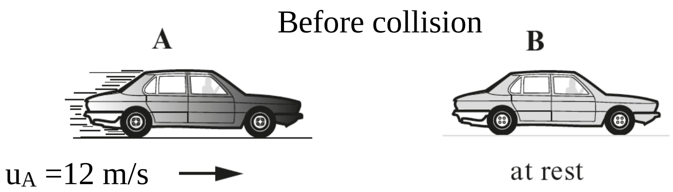
(b) (i) v = zero !!

(ii) Momentum is a vector. The total momentum before collision is therefore zero since they have equal momenta, but in opposite directions. Hence, the total momentum after collision must be zero.

Is kinetic energy conserved in collisions ?

Energy cannot be created or destroyed. However, energy can be transferred from the kinetic energy of a colliding object (e.g. a car) into heat and sound energy which escapes into the surroundings.

This means that it's quite normal (even expected) that KE is 'lost' from the colliding objects during a collision. Look at the situation below :



After colliding, the velocity of car A reduces to 2m/s (➔). If the mass of car A, m_A = 1400 kg, and car B, m_B = 1200 kg, then by conservation of momentum,

$$\begin{aligned}
\text{momentum before} &= \text{momentum after} \\
m_A u_A + m_B u_B &= m_A v_A + m_B v_B \\
16\,800 + 0 &= 2800 + 1200\, v_B \\
16\,800 - 2800 &= 1200\, v_B \\
14\,000 &= 1200\, v_B \\
v_B &= 11.67 \text{ m/s (to the right)}
\end{aligned}$$

Note : Since the answer is a positive number, we therefore know that it is to the right.

We can now check to see what happens to the kinetic energy of the cars :

KE before = $KE_{car\ A}$ = $0.5\ m\ v^2$ = $0.5\ m_A\ u_A^2$ = $0.5 \times 1400 \times 12^2$ = **100 800 J**

KE after = $KE_{car\ A}$ + $KE_{car\ B}$ = 2800 + 81 667 = **84 467 J**

This shows that some KE is lost during the collision. Notice we do not take direction into consideration here since kinetic energy is NOT a vector.

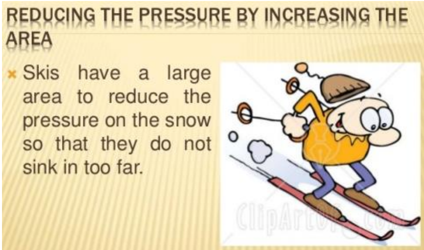
Elastic collision : There is **no** loss in kinetic energy.

Inelastic collision : There **is** loss in kinetic energy.

Unit 4 – Gases & the Kinetic Theory

Pressure

Pressure is a measure of how spread out or concentrated a force is on a surface. For example, when walking on soft snow, a person wearing normal shoes is likely to sink into the snow because the force (the person's weight) is acting on a fairly small area. This leads to a relatively high pressure on the snow. If the same person wears snow-shoes, the pressure is less since the same weight is spread over a larger area.



Here's the equation relating force, area and pressure :

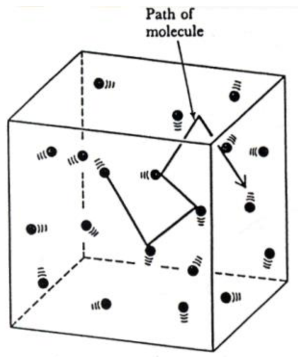
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} \qquad\qquad P = \frac{F}{A}$$

where	force is measured in	newtons, N
	area is measured in	m^2 (or sometimes cm^2)
and so,	pressure is measured in	**N/m^2**.

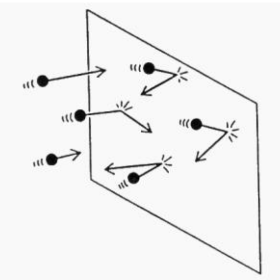
Another common unit for pressure is **Pascal, Pa**, but only if the area is measured in m^2 (rather than cm^2).

The kinetic theory

The kinetic theory is simply the idea that a gas is made from tiny particles that are in constant, random, motion. These particles are assumed to be widely spread and to move in straight lines in between collisions. All collisions are elastic – meaning that <u>no</u> kinetic energy is 'lost' during collisions.



A gas may be pictured as a collection of widely spaced molecules in continuous, chaotic motion.



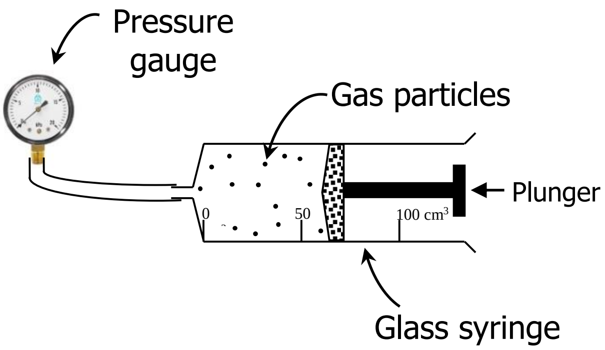
As the molecules of a gas collide with the walls of their container, they exert a force on it. The average force per unit area is the pressure of the gas.

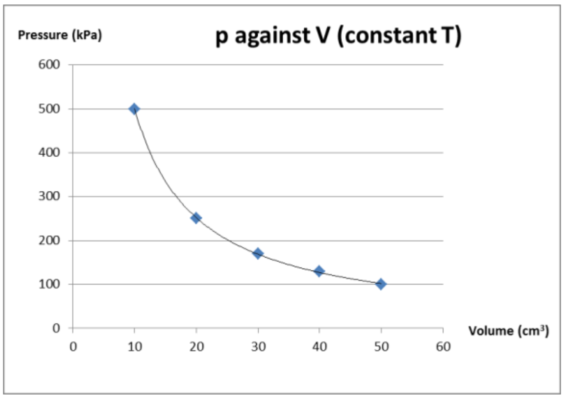
In gases, pressure is created by the gas particles colliding with the inside surface of the container. Every time a particle collides with the inside surface it creates an outward force on the container wall. Millions of such collisions on each square centimetre every second produces outward 'pressure'.

Pressure, Volume & Temperature

A) Relationship between **pressure** and **volume.**

The simple experiment below investigates how changing the volume of a gas affects its pressure. **Temperature is kept constant.**
As the plunger is forced inwards (where the volume decreases), the pressure gauge registers an increase in pressure. The graph on the right shows the results.



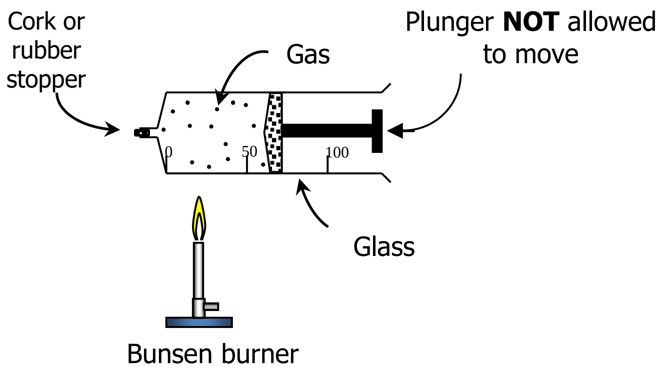


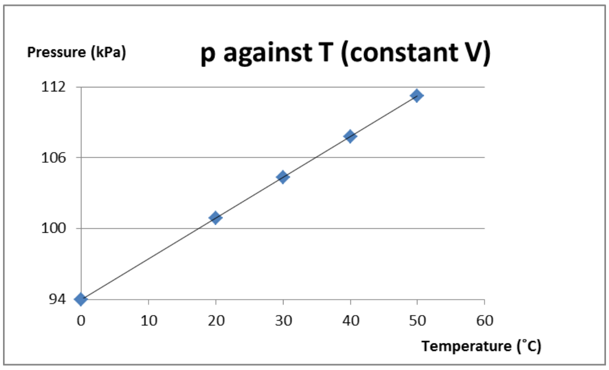
As the volume decreases, the pressure increases. In fact, you can see from the graph that if the volume <u>halves</u>, the pressure <u>doubles</u>. This means that pressure is inversely proportional to the volume, and hence we can write :

$$p \times V = \text{constant}$$

B) Relationship between **pressure** and **temperature.**

This time the **volume is kept constant.**
As the temperature of the gas is increased, the pressure gauge registers an increase in pressure. The graph on the right shows the results.



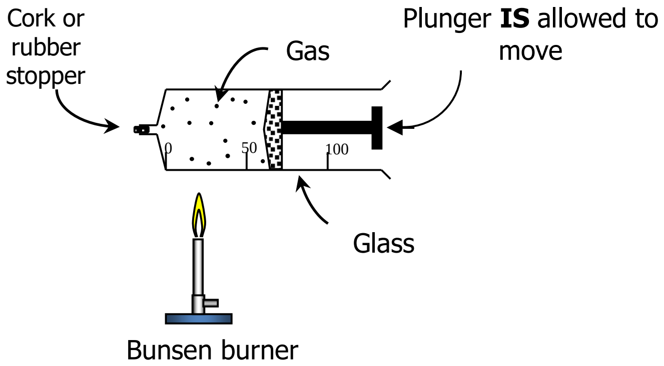


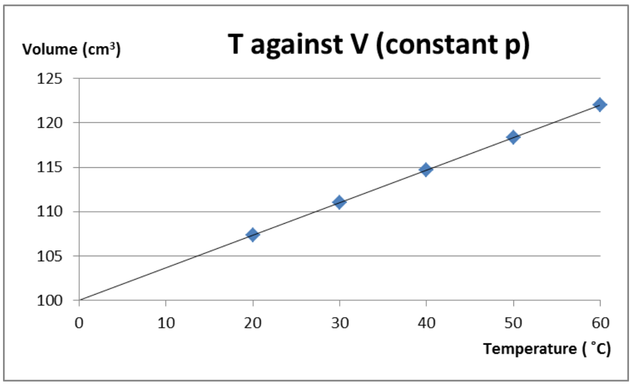
If the temperature is measured in KELVIN rather than degrees Celsius (see later on !), the graph would show that the pressure <u>doubles</u> when the temperature <u>doubles</u>. This means that pressure is directly proportional to the temperature, and hence we can write :

$$\frac{p}{T} = \text{constant}$$

C) Relationship between **temperature** and **volume.**

This time the **pressure is kept constant.**
As the temperature of the gas is increased, the volume increases. The graph below shows the results.





If the temperature is measured in KELVIN rather than degrees Celsius (see later on !), the graph would show that the volume doubles when the temperature doubles. This means that volume is directly proportional to the temperature, and hence we can write :

$$\frac{V}{T} = \text{constant}$$

Combining the three results

If we combine all the results/conclusions from the three 'experiments', we get the following result :

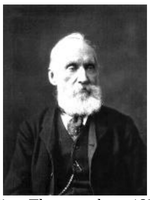
$$\boxed{\frac{pV}{T} = \text{constant}} \quad \text{or} \quad \boxed{\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}}$$

Note
Strictly speaking, this is only true for an "Ideal" gas where the particles don't affect each other **in between** collisions, and their size is extremely small in comparison to their (average) separation. However, this 'ideal gas equation' works very well in most every-day situations.

Temperature

William Thomson, 1846

Once scientists realised that there is a direct link between the temperature of a gas and the average kinetic energy of the particles in that gas, they also realised that there must be a minimum temperature. This minimum temperature is known as **absolute zero**, and occurs when the (average) kinetic energy of the particles is zero, i.e. they stop moving !



William Thomson, born 1824

This led Lord Kelvin (aka William Thomson) to propose a new scale for temperature :

The Kelvin scale is defined so that zero Kelvin, or '0 K' is the temperature of absolute zero, and that a change of 1 ˚C is the same as a change of 1 K.

This then means that the freezing point of water is about 273 K, and the boiling point of water is 373 K.

Any equation used in this section only works if the temperature is measured in kelvin, K.

Example

A can of baked beans is mistakenly left sealed and placed in an oven. The air above the beans is initially at room temperature, 18 ˚C, and atmospheric pressure (100kPa). Calculate the pressure of the air inside the can when its temperature reaches 220 ˚C. (Assume there's no change in volume).

First we must convert the temperatures to kelvin using the following information seen on page 2 of the exam. paper :

$$T\,/\,\mathrm{K} = \theta\,/\,°\mathrm{C} + 273$$

18 ˚C = 18 + 273 = 291 K
220 ˚C = 220 + 273 = 493K

Since volume is constant, $\frac{p_1}{T_1} = \frac{p_2}{T_2}$

Re-arranging : $p_2 = \frac{T_2\, p_1}{T_1} = \frac{493 \times 100\,000}{291} = $ **169 415 Pa**

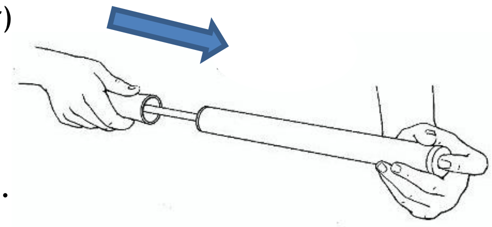
Note : This is likely to cause the can to explode, so do **not** try this at home !!! ;-)

Variation of pressure with volume or temperature

Explaining a change in pressure due to a change in volume

When the volume of a gas is decreased (i.e. the gas is compressed) the pressure increases.

To visualise this, imaging holding a bicycle pump with the air-hole at the top of the pump blocked – the gas (air) inside the pump is now sealed. If you were to push the piston/handle of the pump inwards, you're decreasing the volume of the air inside. This would cause the pressure of the gas inside the pump to increase - you would feel this trying to push the piston/handle back out.



How can we explain this with the kinetic theory of gases ?

As the volume decreases, the same number of gas particles are moving around in a smaller space, and so they are closer together. If this is done at a constant temperature, the average speed of the particles **stays the same**. However, there are now more particles striking each unit area of the inside of the container each second. When particles strike the wall of the container there's a change in momentum of the particles (Newton's 2nd law) which results in a force on the particles and hence an equal but opposite force on the wall (Newton's 3rd law). This means that there is more force acting on the inside surface. Since $P = F / A$, the pressure will increase.

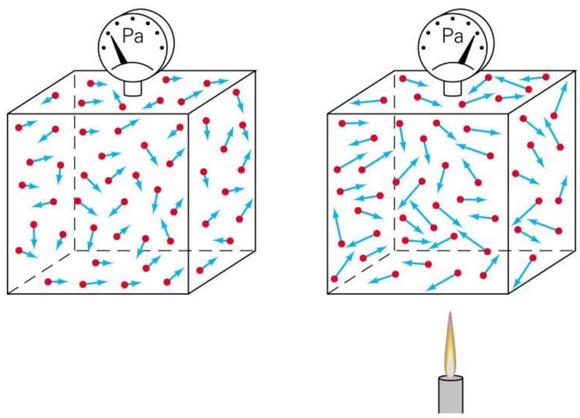
Explaining a change in pressure due to a change in temperature

When the temperature of a gas is increased the pressure increases.

How can we explain this with the kinetic theory of gases ?

As the temperature increases, the average speed of the particles increases.

This means that the particles strike the inside surface of the container **more often** than before. Also, they strike the inside surface **with greater force** than before.
Both these things mean that the particles exert more force on the inside surface. Since $P = F / A$, the pressure therefore increases.

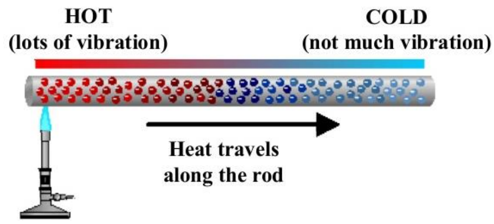


(a) Initial temperature (b) Heat added

A better understanding of Conduction and Convection !

Conduction

The atoms (or molecules) in a solid are close together and so, because they constantly collide with each other, they transfer heat energy quite quickly by conduction.



The atoms in gases are much further apart, and so collide less often. This is why conduction is very slow in gases.

Metals conduct heat very quickly making them better conductors, because they have **free electrons** which can move around within the metal, and therefore can carry the heat energy much more rapidly from one place to another.

Convection

When liquids or gases are heated the atoms or molecules that are heated up move more rapidly. These atoms then collide at higher speed and more often with other atoms around them.

This leads to a short-lived, **localized** increase in pressure, and so this part of the fluid expands. (It's very similar to the section where V/T = constant, i.e. gases expanding at constant pressure).

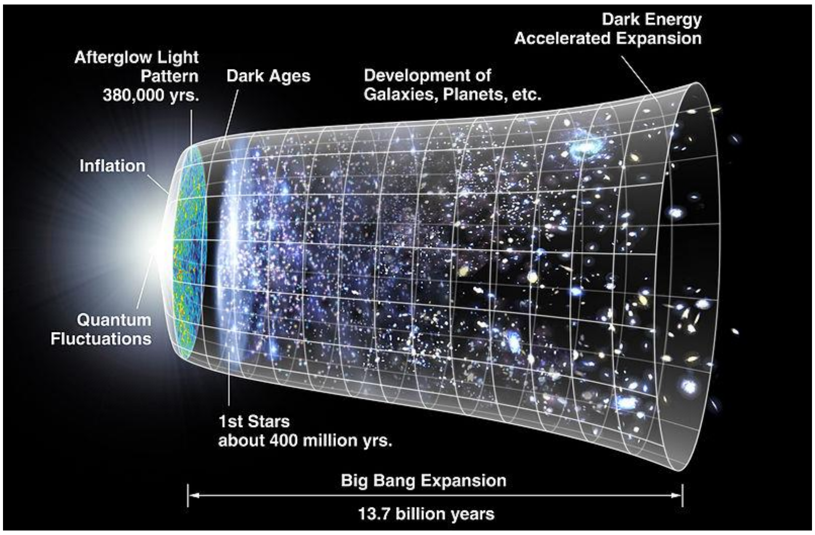
The fluid in this locality is now less dense than surrounding fluid, and so it rises, forming a **convection current.**

UNIT 5 - Origin of the chemical elements.

The Big Bang

It is believed that the universe started with a Big Bang about 13.7 billion years ago. What evidence do we have to support this theory?

1. Red shift of galaxies showing that they are moving away.
2. CMBR (Cosmic microwave background radiation).

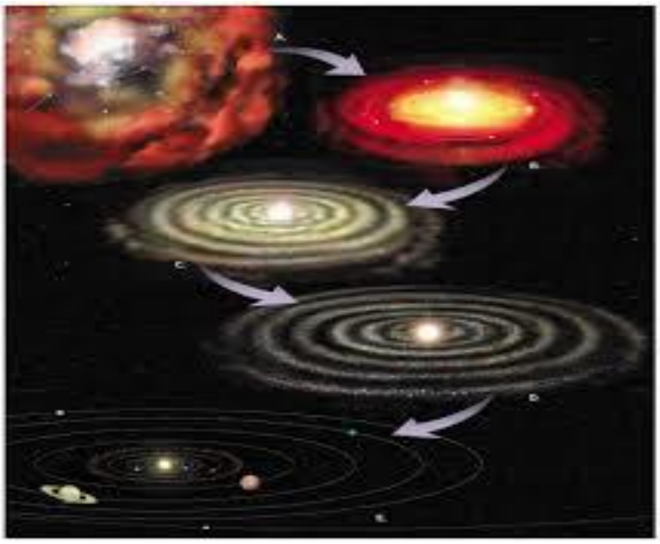


As the universe cooled, the protons and electrons combined to make deuterium (an isotope of hydrogen). The deuterium combined to make helium. Trace amounts of lithium were also produced at this time. This process of light element formation in the early universe is called "Big Bang nucleosynthesis".

Initial Elemental Composition for the Universe. (remember)

- **75% Hydrogen**
- **25% Helium**
- **Very small quantities of other light elements e.g. lithium**

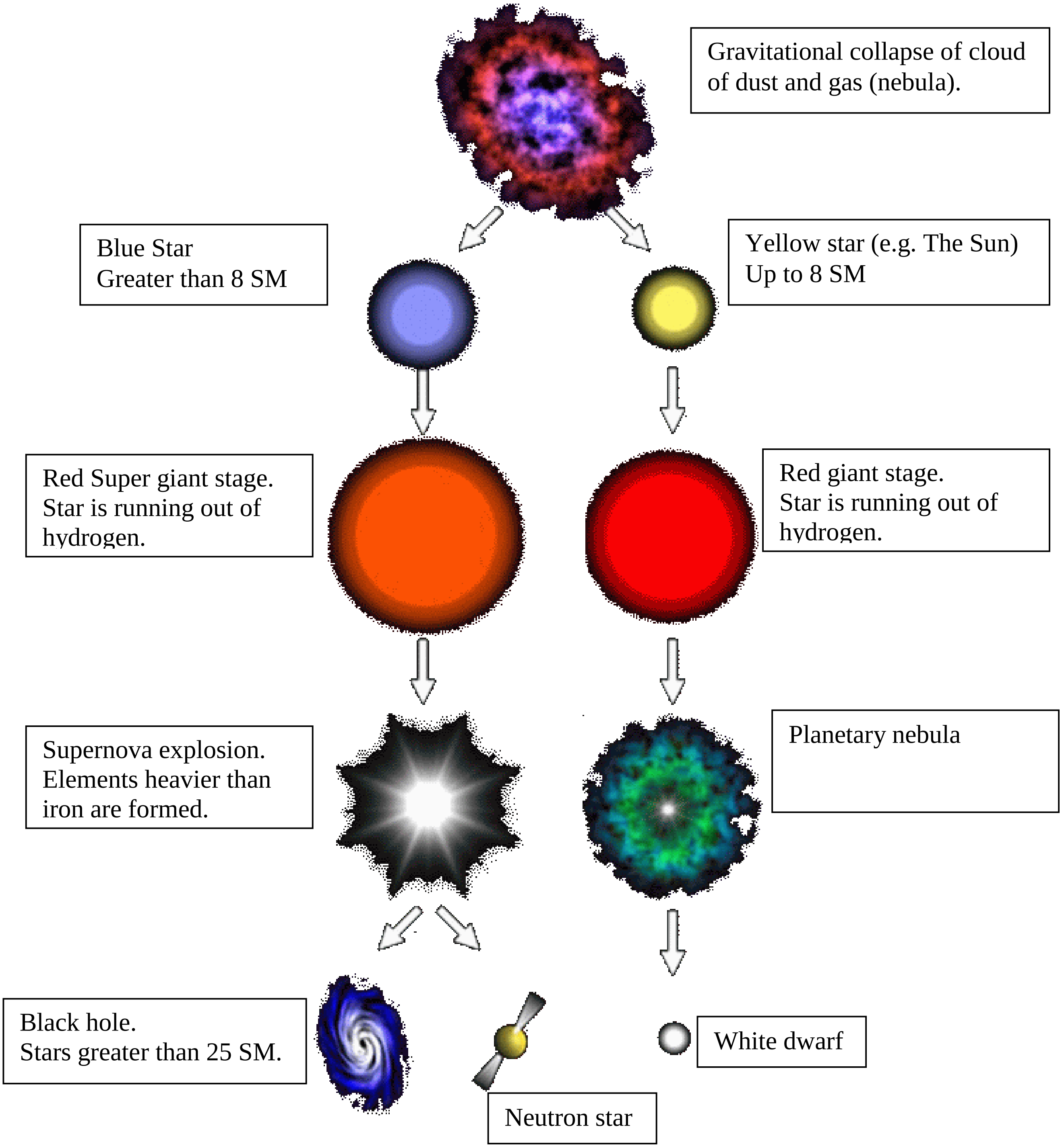
Therefore we can deduce that all the other elements were not created in the Big Bang but in STARS. If only hydrogen and helium existed in the early universe how did stars form and subsequently the heavier elements ?



1st Generation stars. It is believed that these stars were composed **mainly of hydrogen and helium,** since none of the heavier elements had yet been synthesised.

Life cycle of the stars.

The diagram below shows the possible life cycle for stars of different masses. **SM** stands for **Solar Masses**. If a star is 3SM then it is 3 times the mass of the Sun.



Brown dwarfs are failed stars that never have enough mass in order to get hot enough to achieve nuclear fusion.

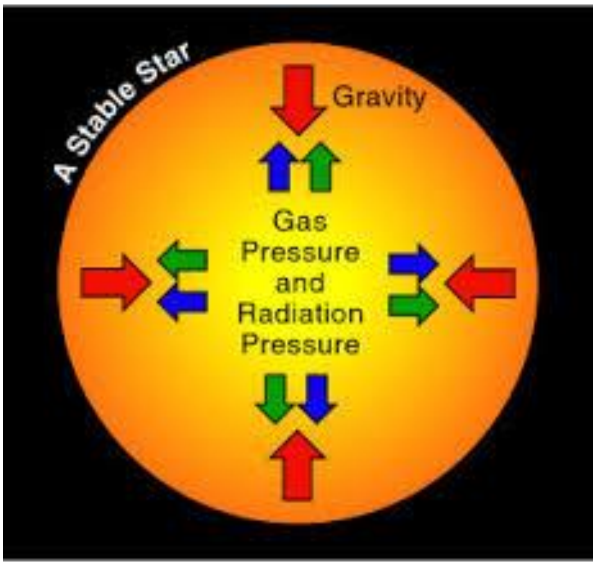
Red dwarf stars: these are low mass stars that **do** achieve nuclear fusion. They are not very bright and have long lifetimes. They are main sequence stars.

Forces within a star.

There are 2 forces at acting inside a star.

1. Inward force of gravity

2.Outward: combination of gas and radiation pressure.



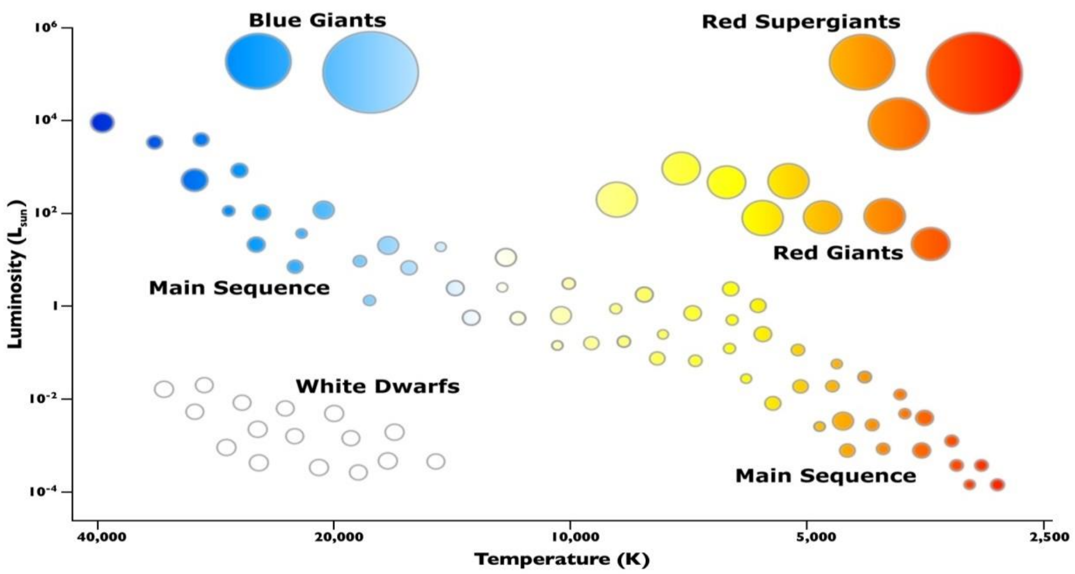
Gas pressure: caused by rapid random motion of particles in the sun.
Radiation pressure: caused by light hitting the particles.

For most of the life of a star it is in a stable state in which the inward force of gravity on any part of the star is balanced (equal) by a force due to the increasing pressure towards the centre.

If the pressure in the middle ***falls***, this will cause a star to ***shrink*** – this will cause the pressure to rise once more until a new equilibrium is established with the star smaller. If the pressure increases, the star will ***expand.***

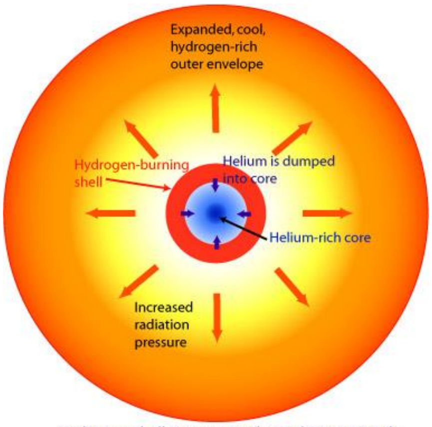
Main sequence stars.

Main sequence stars fuse ***hydrogen*** to ***helium*** in their cores.
The colour of a star depends upon the temperature of the star. Our sun is a yellow star which is one of the most common type. Surface temperature is 5800°C. Stable lifetime is around 10,000 million years. The diagram below is a Hertzsprung-Russell diagram.



End of main sequence stage.

Once a star has exhausted (run out) of its supply of hydrogen it will swell up into a red giant. The temperature of the star will decrease as nuclear fusion ceases. This means that the gravitational force is greater than the gas and radiation pressure causing the core to shrink.
Fusion of helium has begun and the temperature increases once again resulting in an increase in gas and radiation pressure.



Hydrogen Shell Burning on the Red Giant Branch

In at the end of the main sequence stage of our Sun the:

- Light elements (Hydrogen and Helium) fuse in the centre
- Centre is exhausted of light elements – nuclear reactions stop, causing pressure to drop
- Star nucleus shrinks, making density and temperature go up, allowing heavier elements to fuse
- Meanwhile the lighter elements continue fusing in a shell around the nucleus
- Stars like the Sun never reach sufficient temperatures to fuse elements heavier than oxygen
- The outer layers of the star are pushed off by the radiation pressure of the core – enriching the interstellar medium with heavier elements.
- A very dense core remains known as a white dwarf (1 teaspoon has a mass of 5 tons).

Useful website http://aspire.cosmic-ray.org/Labs/StarLife/starlife_main.html

Nuclear fusion

All **main sequence stars** generate their energy by the fusion of hydrogen to helium, according to the equation (remember):

$$4\ {}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\ {}^{0}_{1}e$$

Hydrogen — Helium — Positron

A and Z numbers on left and right hand side are balanced.

Left: total A = 4 x 1 = 4 | Right: total A= 4 + (2 x 0) = 4

total Z = 4 x 1 = 4 | total Z = 2 + (2 x 1) = 4

A positron is the antiparticle of an electron. When a particle and its corresponding particle meet they annihilate one another releasing a large amount of energy. Therefore when a positron is created during fusion it meets an electron and is annihilated.

Other fusion reactions occur in stars.

$$^{3}_{2}He + ^{3}_{2}He \longrightarrow ^{4}_{2}He + 2\ ^{A}_{Z}X$$

Determine the value of A and Z.

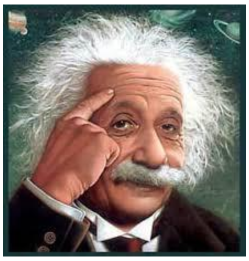
A=1 Z=1

$$^{2}_{1}H + ^{1}_{1}H \longrightarrow ^{A}_{Z}X + \gamma \text{ (gamma ray)}$$

Determine the value of A and Z.

A=3 Z=2

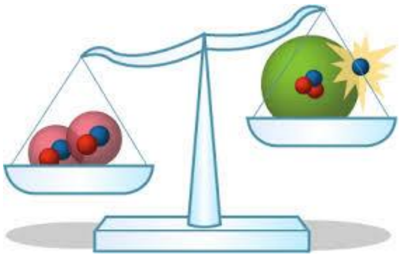
Why is energy released during fusion?



Look at the last equation showing the fusion of hydrogen and deuterium. The total mass of the helium formed is less than the mass of the 2 hydrogen isotopes and **that mass is converted into energy.** A famous scientist (Albert Einstein) predicted this to be true and gave one of the most famous of equations:

$$\mathbf{E = mc^2}$$

Energy (J) = mass (kg) x speed of light squared (m/s) (300,000,000 m/s or 3×10^8)



Question 1. When 1kg of coal is burnt 3×10^7J of energy is released. Calculate the mass lost.

$E = mc^2$ rearrange formula $m = \frac{E}{c^2}$ $m = \frac{3 \times 10^7}{(3\times10^8)^2} = 3.33\times10^{-10}$ kg

As you can see this is a very small mass so it is ***negligible/insignificant.***

Question 2. Calculate the mass loss per second from the Sun given that its energy output is 4×10^{26} W and the speed of light is 3×10^8 m/s.

The first step is to realise that power is energy transferred per second. So the energy transferred from mass into energy per second is 4×10^{26} J. Now we must calculate how much mass this is equivalent to.

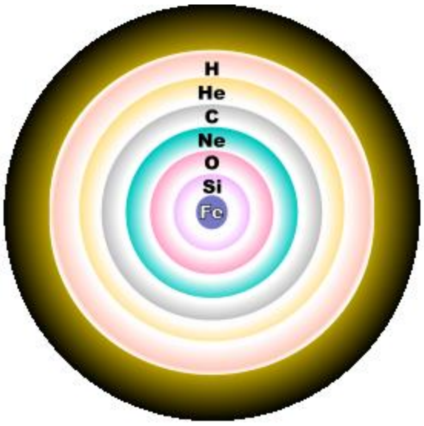
$E = mc^2$ rearrange formula $m = \frac{E}{c^2}$ $m = \frac{4\times10^{26}}{(3\times10^8)^2} = 4.44\times10^9$ kg

This means that the sun is losing ***4.4 million tonnes a second***!!!!!!!!!!!!

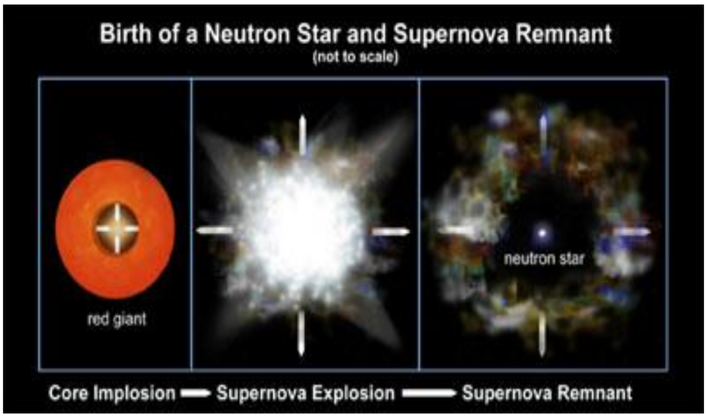
What happens to Stars which are heavier than our Sun?

It is much more difficult to fuse heavier elements because heavier nuclei ***repel each other*** more strongly than light nuclei and so require much higher temperatures and pressures to fuse. So the fusion of heavier nuclei only occurs in stars of greater mass than our Sun.

- The lifetime of these massive stars is much shorter as they use their fuel up much more quickly.
- Core temperature is much higher - **300,000,000°C.**
- The production of increasingly heavier elements, up to iron-56, occurs in shells around the core of a star and the limit of this depends upon the mass/temperature of the star.



Useful video - http://www.bbc.co.uk/science/space/universe/sights/supernovae#p00fk7yv



When the nuclear power (fusion) source at the center or core of a star is exhausted, the core collapses. In less than a second the core collapses giving a supernova explosion and a neutron star (or a black hole if the star is extremely massive) is formed. If the **core** of the star is heavier than about **3.5 × the sun** it becomes a black hole.

The neutron star is very dense indeed. **One teaspoon has a mass of 6 billion tons.**

Fusion stops →	**Gravitational pull → is too much**	**Core Collapse →**	**Supernova explosion**

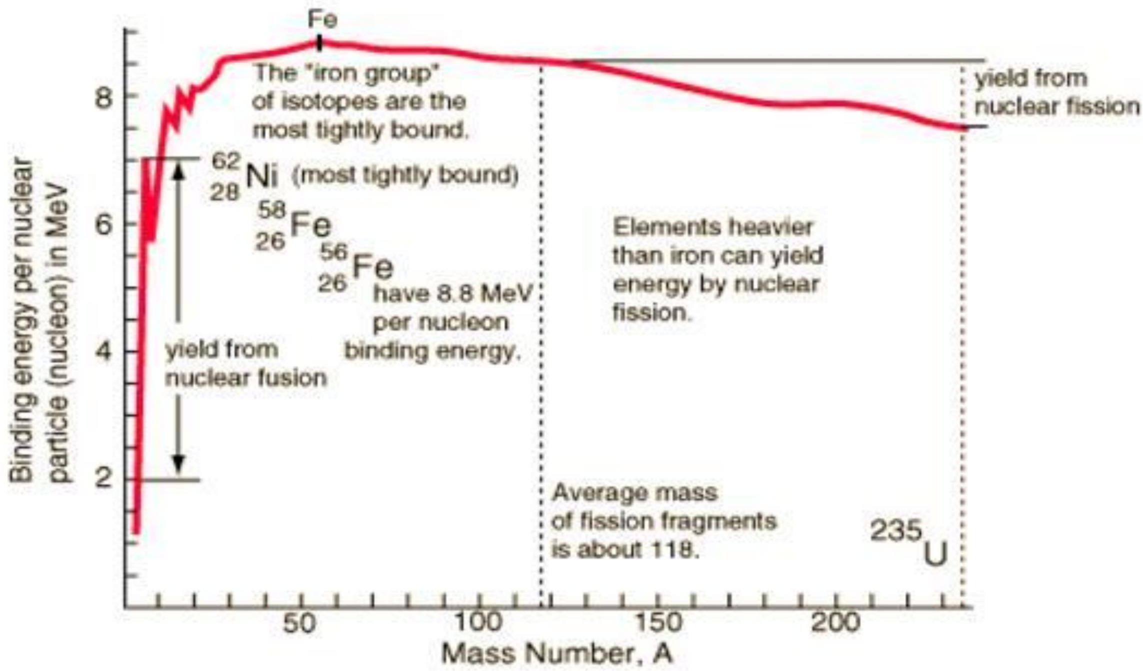
During the supernova explosion **two** very important things happen.

1. Much of the material (elements) from within the star is blasted out into space. The material spews off into interstellar space to form new stars.

2. As the shock encounters material in the star's outer layers, the material is heated to billions of degrees, fusing to form the heavier elements. All elements heavier than iron/nickel-56 (all the way up to Uranium) are formed in supernovae explosions.

Nucleosynthesis - Binding energy.

Formation of the elements. The graph below is of the binding energy per nucleon for atoms of differing nucleon number.

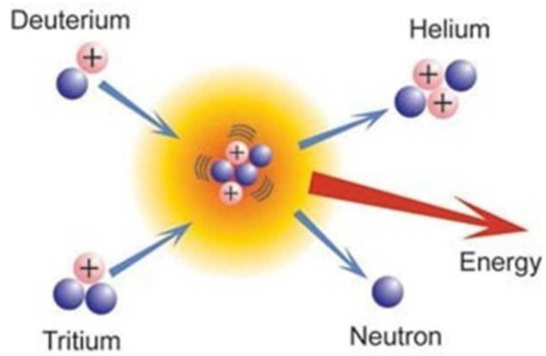


Useful video - http://www.youtube.com/watch?v=jk6Hm1QoDYY

This curve indicates how stable atomic nuclei are. The higher the binding energy per nucleon the more stable the nuclei are. Iron (Fe) is the most stable nucleus.

Fusion.

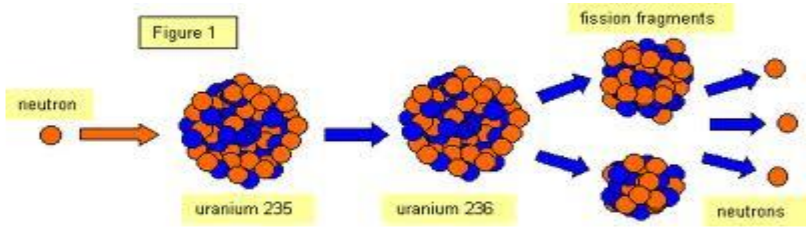
Elements above iron in the periodic table cannot be formed in the normal nuclear fusion processes in stars. Energy is only released up to a nucleon number of 56 (iron or nickel) and thus can proceed. But since the "iron group" is at the peak of the binding energy curve, fusion of elements above iron dramatically absorbs energy. Heavier elements absorb energy when they fuse.



Very heavy stars run out of energy when they produce iron and nickel 56 and die in a supernova. Because of the extra energy released in a supernova, heavier elements are produced – all the way up to uranium. These are blasted into space and form part of the cloud of gas and dust from which new solar systems are born. So the Earth's uranium, in fact all the heavy elements, were produced in supernovae. Most of the atoms in your body were formed in the core of a star or in a supernova explosion!!!!!!

Fission

Nuclear fission. This is a decay process in which an unstable nucleus splits into two fragments of comparable mass or to put it another way it is the splitting of a heavy nucleus into two lighter nuclei.

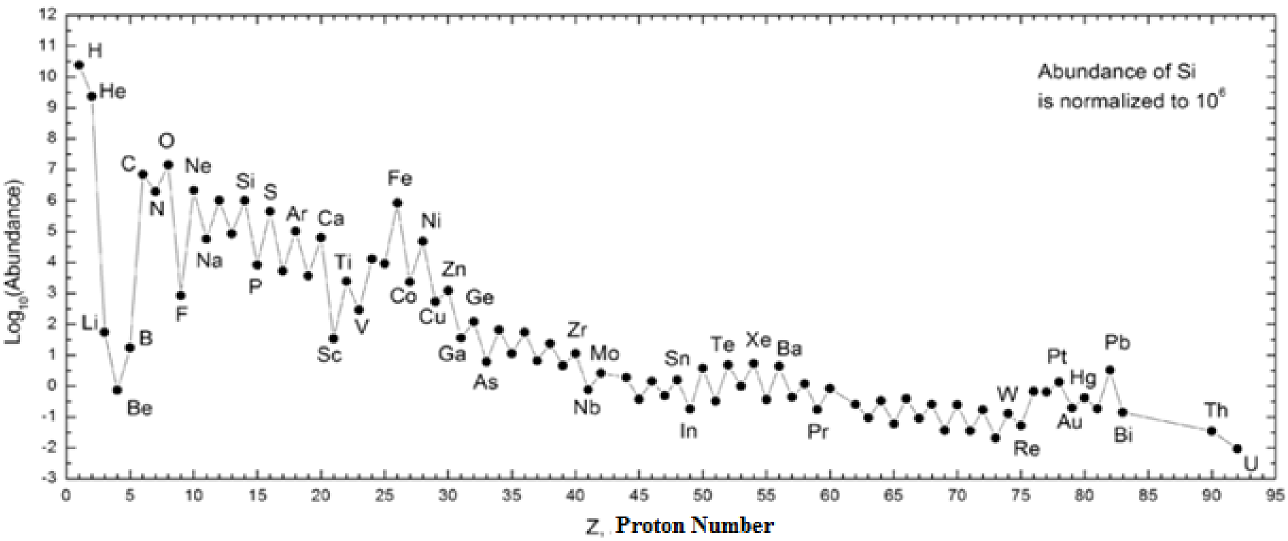


In nuclear fission the elements/nuclei like uranium are split into smaller fragments which have higher binding energy per nucleon than the uranium (parent nucleus). This increase in binding energy per nucleon results in a release of energy.

Elements like uranium, are only produced from the energy released during the ***gravitational collapse*** of massive stars, and so we are only able to use uranium in a fission reactor because of the release of this element in a supernova.

How science works.

The graph below shows the relative abundance of different elements.



Main points.

- Hydrogen and helium are the most common elements, followed by oxygen and iron.
- The general trend is for the abundance of the elements to decrease with an increase in proton number. You would expect a decrease for elements heavier than iron since they are only formed in supernova explosion.
- The fact that some elements like oxygen and carbon are more common has been explained through scientific research.

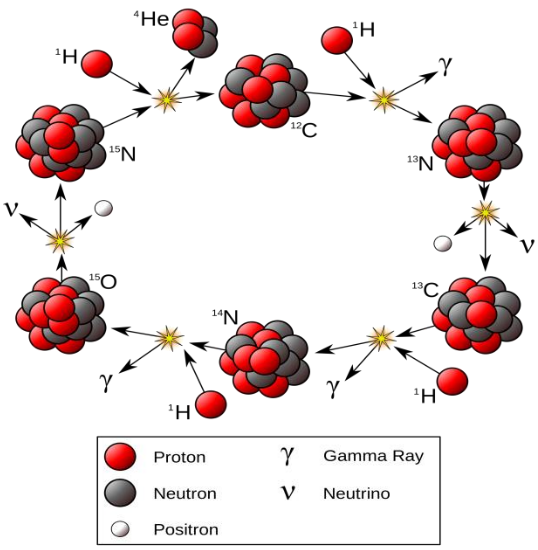
How science works - Fred Hoyle

Overview : Working from experimental results on the results of collision experiments between nuclei, and making assumptions about conditions in stars, including supernovae, Hoyle *and others* were able to show that heavy elements could be produced and they were able to explain why some elements are much more common than others, e.g. Carbon and Oxygen

In summary, ***Sir Fred Hoyle and others used experimental results to:***

(i) Show how the heavy elements could be produced.

(ii) Explain why some elements were more common than others e.g Carbon and oxygen.



They came up with a theory about how carbon, nitrogen and oxygen were produced. They were then able to prove this experimentally. A good example of how science works.

i.e. 1. Make an observation.

2. Come up with a theory.

3. Carry out an experiment to test this theory.