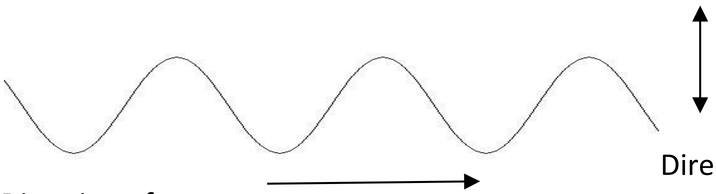
Waves & Radiations Summary Notes

A wave transfers energy from one place to another. Waves are made from particles vibrating. In this unit we will consider two types of waves, transverse waves and longitudinal waves.

A **transverse** wave is one in which the vibrations making up the waves are at right angles to the direction of the wave travel.

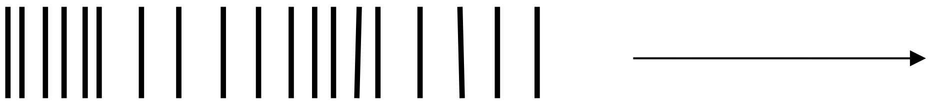


Direction of vibration of particles.

Direction of wave

Waves on a rope, water waves, light waves and all members of the electromagnetic spectrum are transverse waves.

A **longitudinal** wave is one in which the vibrations are in the same direction as the wave travels.

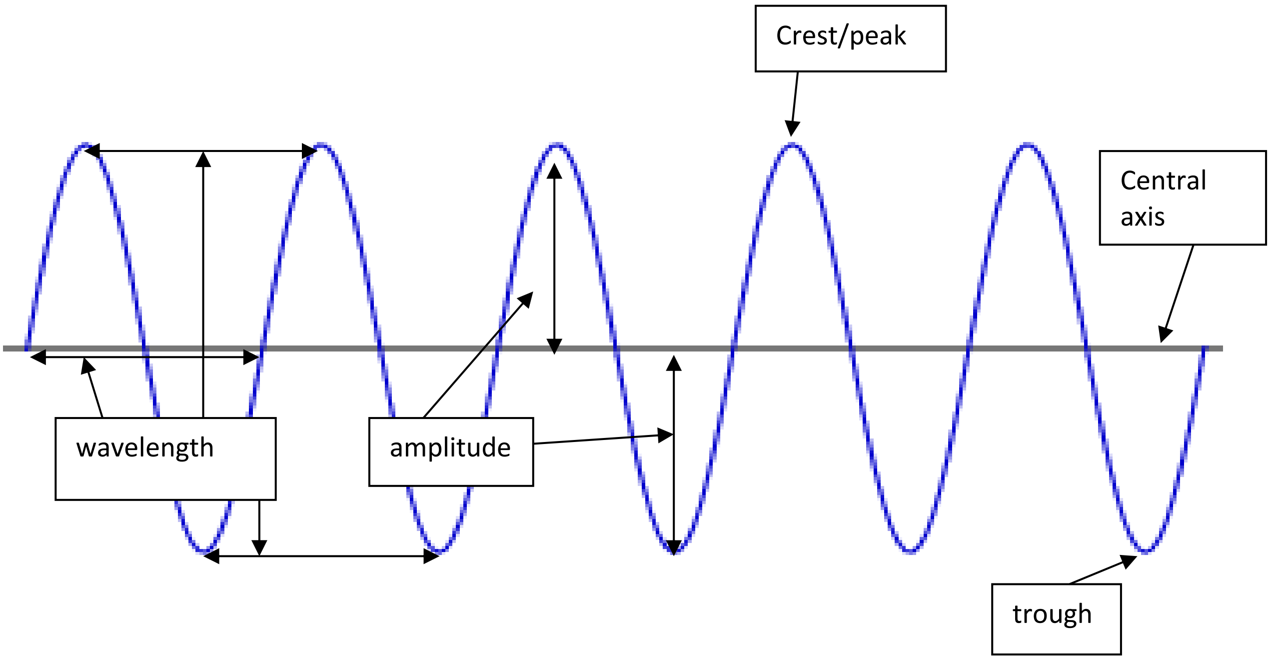


Direction of vibration of particles

Direction of wave

Sound is a longitudinal wave.

Wave Properties



Frequency, f – the number of waves produced (passing a point) each second, unit: Hertz (Hz)

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

Wavespeed, v – distance travelled by a wave in one second, unit: metres per second (m/s)

$$v = \frac{d}{t}$$

amplitude – size of the maximum disturbance from the central axis (distance from central axis to crest/trough), unit: metres (m)

Wavelength, λ – distance from one point on a wave to the same point on the next wave, unit: metres (m)

$\lambda = d / N$ where d is distance and N is number of waves (not on formula sheet!)

Period , T – time taken to produce a wave, unit: seconds (s)

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

Loud notes have more energy than quiet notes and therefore have a larger amplitude. High pitch notes produce more waves per second and therefore have a higher frequency.

Wave Relationships

Speed, distance and time:

Relationship:	distance	=	speed	x	time
Symbol:	d		v		t
Unit:	metres		meters per second		seconds
Abbreviation:	m		m/s [ms^{-1}]		s

The Wave Equation:

$$v=f\lambda$$

Relationship:	speed	=	frequency	x	wavelength
Symbol:	v		f		λ
Unit:	metres per second		hertz		metres
Abbreviation:	m/s [ms^{-1}]		Hz		m

Examples: A wave travels 90 metres in 30 seconds. Calculate the speed of the wave.

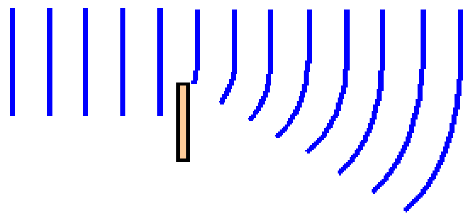
$$d = vt$$
$$90 = v \times 30$$
$$v = 90 / 30$$
$$v = 3\ ms^{-1}$$

A wave has a wavelength of 0.5 metres and a frequency of 4 hertz. What is its speed?

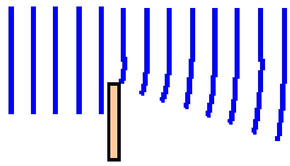
$$v = f\lambda$$
$$= 4 \times 0.5$$
$$= 2\ ms^{-1}$$

Diffraction

Waves are able to bend around obstacles. This bending of waves around corners is called **diffraction**. Long wavelength waves diffract more than short wavelength waves.



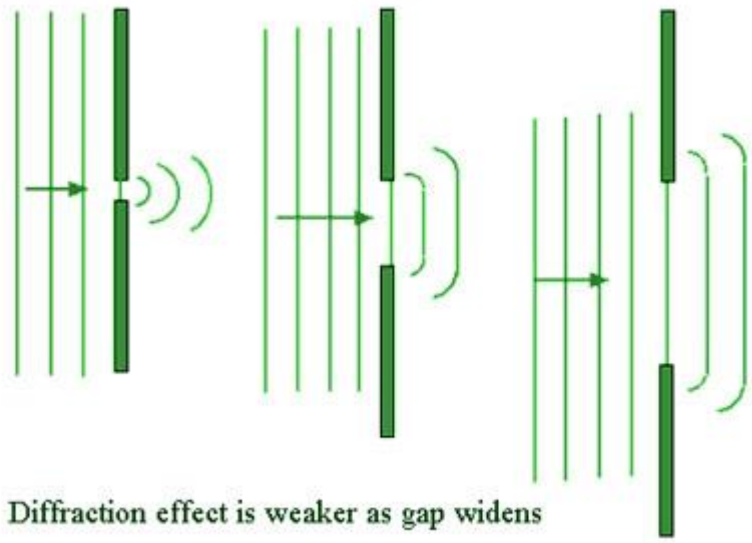
Long wavelength



Short wavelength

As longer wavelengths diffract more than short wavelengths, radio transmissions from ground stations are more likely to be received than shorter wavelength TV waves.

When waves pass through a gap between two barriers the effect is different. When the gap between the barriers is smaller the diffraction of the waves is greater. This is shown in the diagrams below.



When the gap is smaller than the wavelength of the waves the diffracted waves form a circular wavefront.
When the wavelength of the waves is increased there is more diffraction of the waves.

Sound

N4 Only

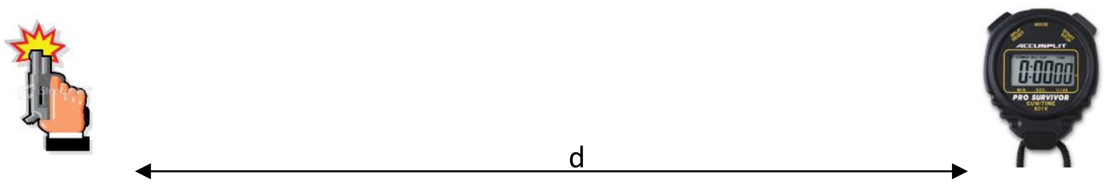
Sound waves can only be transmitted through solids, liquids and gases. Sound cannot travel through a vacuum as a vacuum does not contain particles. The speed of sound in air varies but is approximately 340 metres per second which is much slower than the speed of light in air at 300 000 000 metres per second..

Speed of sound in air

We will consider two methods to measure the speed of sound in air.

Method 1

An observer with a stopwatch stands a long distance away from a starter at an athletics meeting. When the starter fires their starting pistol, the observer sees the flash from the gun instantly and hears the sound after a short delay. The observer starts their stopwatch as soon as they see the flash and stop it when they hear the sound. Using the distance, d, travelled by the sound (which must be measured) and the time, t, for the sound to travel to them (from the stopwatch) the speed of sound can be calculated from: d = vt.



This is not a particularly accurate method as it relies on human reaction time.

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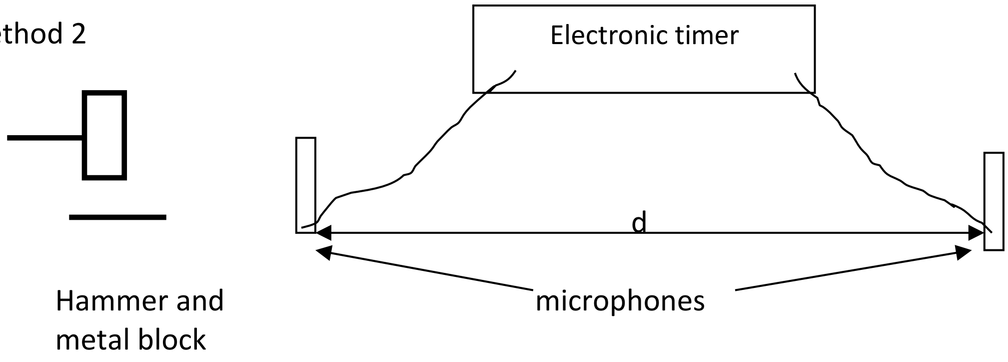
Speed of sound in air

Method 2

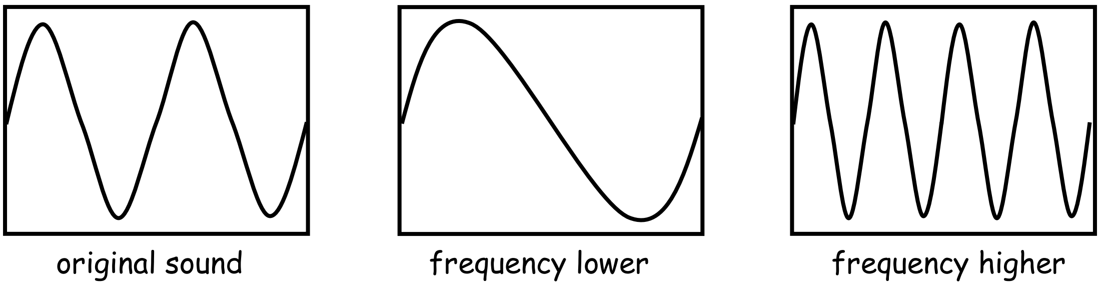


The distance, d, is measured with a metre stick. The hammer is struck against the block. As the sound reaches the first microphone the timer is started, when it reaches the second microphone the timer is stopped. The equation $d = vt$ is used to calculate the speed again. This is a much more accurate method.
The exact value for the speed of sound in air can vary, however it is around **340 m/s**.

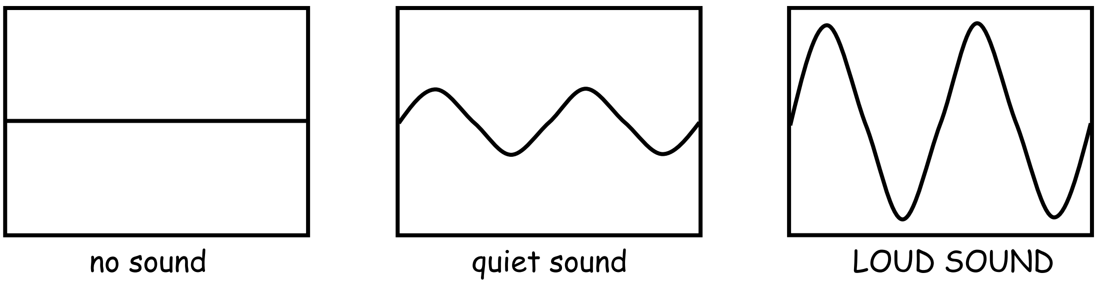
N4 Only

Amplitude and frequency

An oscilloscope can be used to analyse wave patterns and what effect changing certain properties has on the shape of a wave.



Waves with a low frequency would be low pitched and waves with a high frequency would be high pitched.



Waves with a small amplitude would be quiet and those with a large amplitude would be loud.

N4 Only

Decibel scale and noise pollution

Noise pollution is any unwanted sound. Noise levels are measured in **decibels** (dB). These can be measured using a sound level meter. Regular exposure to sounds above 85-90dB can cause damage to hearing. Some typical noise levels are given below

Situation	Decibels
Threshold of human hearing	0
Whisper, rustling paper	30
Inside average home	50
Normal conversation at 1m distance	60
Alarm clock at 0.5 m distance	80
Threshold of hearing damage	85
Truck heard from pavement, busy factory	90
Rock concert 1m from loudspeaker	120
Jet engine at a distance of 50m	130
Threshold of pain	120 - 140

We can protect against damage to hearing by loud noises by wearing ear plugs or ear protectors. Ear protectors, sometimes called ear defenders, work by absorbing sound energy. This reduces the amplitude of the sound wave.

High frequency deafness is a condition where a human has difficulty in hearing frequencies in the upper limits of the range of human hearing. The normal range of human hearing is between 20 hertz and 20 000 hertz, although there is considerable variation between individuals, especially at the high frequency end, where a gradual decline with age is considered normal.

Sonar and ultrasound

Humans can hear sounds with frequencies between 20Hz and 20000Hz. Sounds with a frequency above 20000Hz are called **ultrasound**.

Ultrasound can be used to examine a foetus in the womb. A picture is built up by timing how long it takes to receive an echo from an ultrasound pulse. Ultrasound can also be used to break up kidney stones without the need for invasive surgery. Ultrasound can also be used by physiotherapists in the treatment of sports injuries.

Boats and submarines use **sonar** to detect shoals of fish, the sea bed or other submarines. Pulses of sound are sent out and then the echo is detected. This is similar to how bats and dolphins use echolocation.

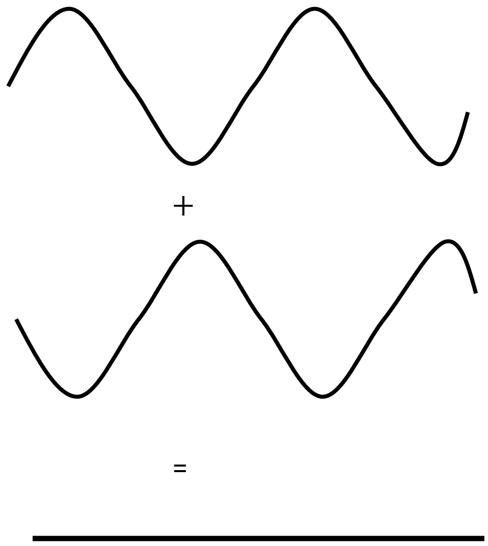
N4 Only

Sound reproduction and noise cancellation

Sound is an **analogue** signal. This means that it varies continuously over a range of values. Most recording technology nowadays uses **digital** technology. Digital signals can be one of two values with nothing in between. Analogue to digital converters are used to process the sound signal so that it can be transmitted easier, then a digital to analogue device allows the sound to be reproduced faithfully at the other end.

If two waves travelling in opposite directions were to meet, the result would be that they cancel each other out. The same would happen any time a crest of one wave meets a trough of another.

This effect is called interference of waves. We can make use of this effect in noise cancelling technology.



Noise cancelling headphones use a technique called "active noise control", to block out background sound to allow you to hear the sound fed through the headphones more clearly. For example:

- blocking out aircraft engines when you are trying to listen to music on your MP3 player.
- Blocking out rotor noise on a helicopter to allow you to speak to someone else inside the helicopter.

This cancellation is done in an electronic circuit. The active noise cancellation works in the circuit by detecting the unwanted outside noise signal and generating the exact same noise signal but the inverse of it. Since the two signals are equal but opposite they cancel each other out. Since the circuit requires energy to work, the noise cancelling headsets must have their own power source such as a battery to work.

Do some research of your own to find out about noise cancellation in Humvees.

Electromagnetic spectrum

Electromagnetic spectrum

There are a number of waves which travel at the speed of light. They are all part of the **electromagnetic spectrum**. These waves are all **transverse waves** and travel at 300 000 000 m/s (3×10^8 ms^{-1}) in a vacuum.

The different parts of the electromagnetic spectrum differ in wavelength and frequency

Increasing wavelength ↓ | ↑ increasing frequency and energy

- Gamma rays
- X-rays
- Ultraviolet
- Visible light
- Infrared
- Microwaves
- TV and Radio

The different parts of the electromagnetic spectrum can also be distinguished by their energy. Higher frequency electromagnetic radiation has a greater amount of energy than lower frequency electromagnetic radiation.

Electromagnetic spectrum continued

Some information on each part of the spectrum is given below:

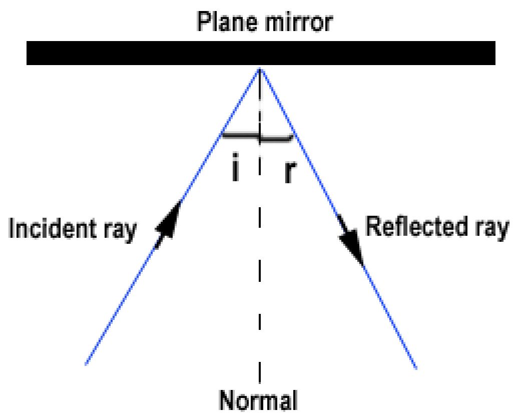
Type of e-m radiation	Typical source	Application	Detector	Possible hazard
Radio & TV	Electrical antennae	Telecommunications (bluetooth and wireless devices)	Aerial	Potential increased cancer risk
Microwaves	Cosmic sources, magnetron	Cooking, Radar, Telecommunications	Diode probe	Heating of body tissues
Infra-red	Heat-emitting objects	Thermograms, TV remotes, telecommunications	Photodiode.	Over heating of body tissues causing dehydration
Visible light	Stars	Vision	Eye, photographic film	Intense light can damage the retina
Ultraviolet	Sunlight	Treating skin conditions, check bank notes for forgeries	Fluorescent paint	Can cause skin cancer
X-rays	X-ray tube, cosmic sources	Medical imaging (detecting broken bones), scanning luggage at airport	Photographic film	Destroys cells which can lead to cancer,
Gamma rays	Nuclear decay	Treating tumours, used as a tracer.	Geiger–Müller tube and counter	Destroys cells which can lead to cancer

Light

Reflection

N4 Only

The law of reflection states that the angle of incidence, i, is equal to the angle of reflection, r.
Remember that all angles in a ray diagram are measured from the normal to the line representing the ray (wave).

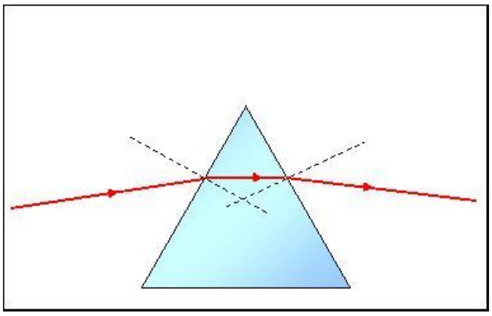


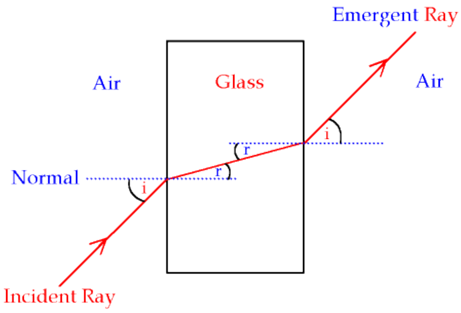
Refraction

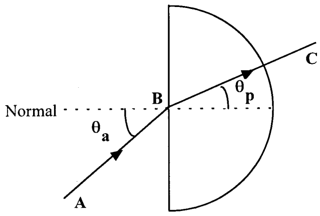
At the boundary between different types of materials, the **speed of the light wave changes**. This results in a **change in wavelength**, and can often cause the direction of a wave to change.

The change in light speed when going from one medium into another is known as **refraction**.

This effect is used in lenses or prisms as shown below.







Ray bends towards normal in prism.

i > r moving from air to glass

Θ_a in air > θ_p in Perspex

Notice that in all the diagrams above as light moves from air into glass/perspex it bends **towards** the normal. Glass/perspex is more dense than air.

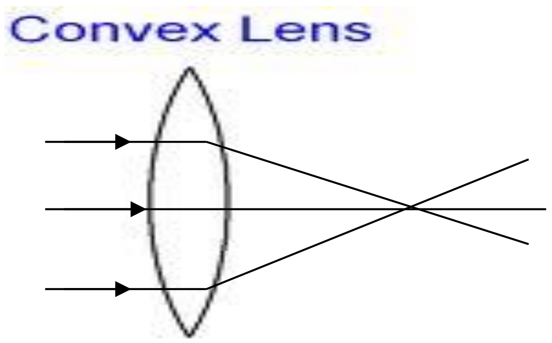
During refraction the frequency stay the same, but wavelength & speed change. As light moves from air into glass, the speed and wavelength decrease.

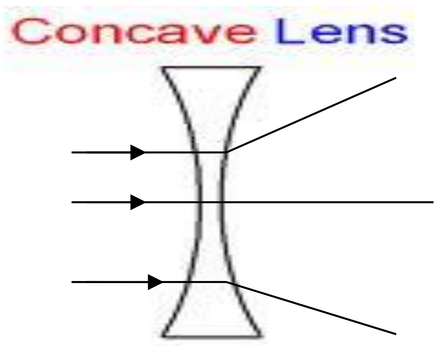
Refraction is greater for violet light than red light.

Lenses

N4 Only

Lenses make use of the effect of refraction that causes light to change direction.

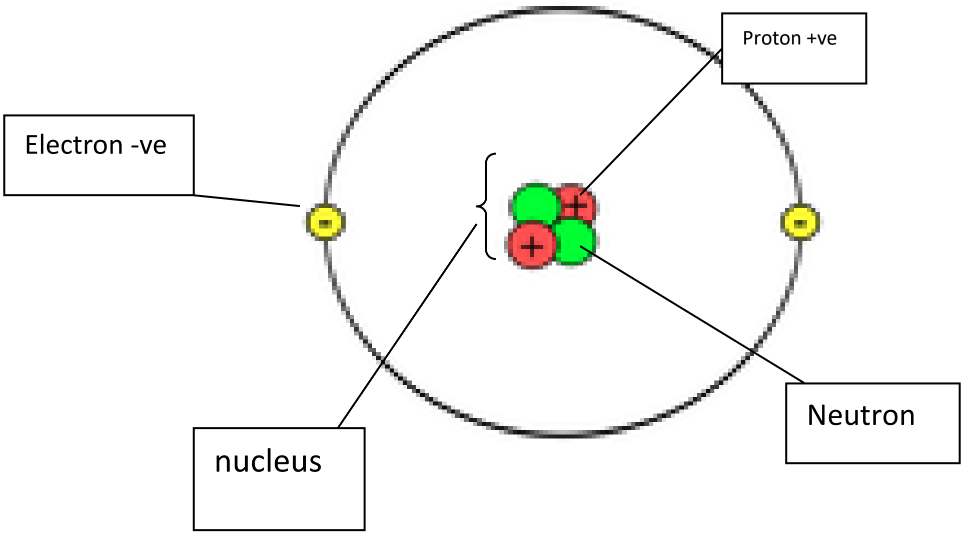




When light rays pass through a convex lens they **come together (converge)**. When light rays pass through a concave lens they **move apart (diverge)**. The more curved a lens is the **greater** the effect on the light rays.

Nuclear radiation

The atom



The above diagram shows a simple model of the atom (it is not to scale).

Nuclear radiation

Nuclear radiation is so called because it originates in the nucleus of an atom. Nuclear radiation can come from natural sources such as cosmic rays and naturally occurring radioactive materials such as uranium. It can also come from artificial sources such as man-made radioisotopes such as plutonium.

Nuclear radiation can be used in medicine to sterilise instruments by killing germs and bacteria. It can also be used to kill the cells which make up a cancerous tumour, however care must be taken in this procedure as nuclear radiation can also kill or damage healthy cells . Nuclear radiation can also be used to examine the body through using radioactive materials in something called a **tracer**. This is a substance that is injected into the body and detected to analyse its progress through the body.

Background radiation

Nuclear radiation is always present in our environment. This is known as **background radiation**. This can come from natural sources e.g. radon gas from rocks and soil, the human body, or cosmic rays from space. Artificial sources include nuclear fallout from weapons, medical uses of radiation, industrial use, and accidents at nuclear power stations.

Nuclear radiation continued

We will look at three different types of nuclear radiation:

type of radiation	symbol	nature	Minimum absorber
alpha	α	two protons and two neutrons (helium nucleus)	sheet of paper, few centimetres of air
beta	β	fast-moving electron	few mm of aluminium
gamma	γ	electromagnetic wave	Several cm of lead

Ionisation

The process by which nuclear radiation damages cells is known as ionisation. This is where electrons are removed from or added to an atom to leave a charged particle called an ion. If the atom gains an electron it has an overall negative charge and if it loses an electron it has an overall positive charge. **Alpha radiation causes more ionisation** than beta or gamma radiation.

Activity

The **activity** or a radioactive source is a measure of **how many radioactive particles are released every second.** It is calculated by

$$A = \frac{N}{t}$$

where A is the activity in becquerels (Bq)

N is the number of nuclei that decay

and t is the time in seconds (s)

The activity of a source decreases over time.

Absorbed dose and equivalent dose

The amount of energy received by a substance per unit mass is known as the **absorbed dose**. This can be calculated by using the equation

$$D = \frac{E}{m}$$

where D is the absorbed dose in grays (Gy)

E is the energy in joules (J)

and m is the mass in kilograms (kg)

Note that 1 gray (Gy) is equivalent to 1 joule per kilogram (Jkg^{-1})

This does not tell the whole story of how a person would be affected by nuclear radiation. It does not take into account the type of radiation encountered.

The **equivalent dose** allows us to take the type of radiation into account. It is calculated by using the equation $$H = Dw_R$$

where H is the equivalent dose in sieverts (Sv)

D is the absorbed dose in grays (Gy)

and w_R is the radiation weighting factor.

The equivalent dose is a measure of the risk of biological harm from a radioactive source.

The equivalent dose depends on:

- The absorbed dose
- The type of radiation
- The body tissue or organ exposed.

The time of exposure (t) to ionising radiation is also important. An equivalent dose of 100 mSv received in one day is more dangerous than the same equivalent dose received over the course of one year.

To compare the exposure to radiation over a period of time we use the **equivalent dose rate**:

$$\dot{H} = \frac{H}{t}$$

where H is the equivalent dose
t is the time and
$\dot{H}$ is the equivalent dose rate.

The unit of $\dot{H}$ is determined by the unit of H and t, e.g if H is in Sv and t is in h then the unit of $\dot{H}$ is Svh^{-1}.

Safety with Radiation

Safety precautions when handling radioactive material include:

- Increase distance from source
    - Always use tongs to handle sources
    - Increase your distance from source
- Shielding
    - Store the source in a lead lined box
    - Wear a lead lined apron
    - Make sure the source is never pointed at anyone
- Limit your time of exposure

Radiation Limits

Limits for equivalent dose have been put in place to reduce the risk of harm to humans.

The limits are set as follows

- Average annual background radiation in UK: **2.2mSv**
- Annual effective dose limit for members of the public: **1mSv**
- Annual effective dose limit for radiation worker: **20mSv**

The limit is higher for radiation workers as their radiation levels and health are monitored closely by medical professionals.

Half-life

Whilst the decay of an individual atom is completely random and unpredictable, the time taken for half the atoms in a sample of a particular material to decay can be predicted as it will always be the same. This is known as the **half-life**. The half-life is the time taken for the activity of a radioactive source to fall to half of its original value.

Different materials have different half lives:

hydrogen-7	1×10^{-22} s	californium-254	60.5 days
carbon-15	2.5 s	plutonium-238	87.7 years
nobelium-259	58 minutes	uranium-238	4.5 billion years

Half-life calculations

Example 1

If a source of activity 8 000 Bq has a half-life of 6 days, what activity will it have after 18 days?

1 half-life = 6 days

18 days = 18 ÷ 6 = 3 half-lives.

8 000 → (1) 4 000 → (2) 2 000 → (3) 1 000

The final activity is 1 000 Bq.

Example 2

Calculate the half-life of a source that decreases in activity from 32 kBq to 8 kBq in 24 days.

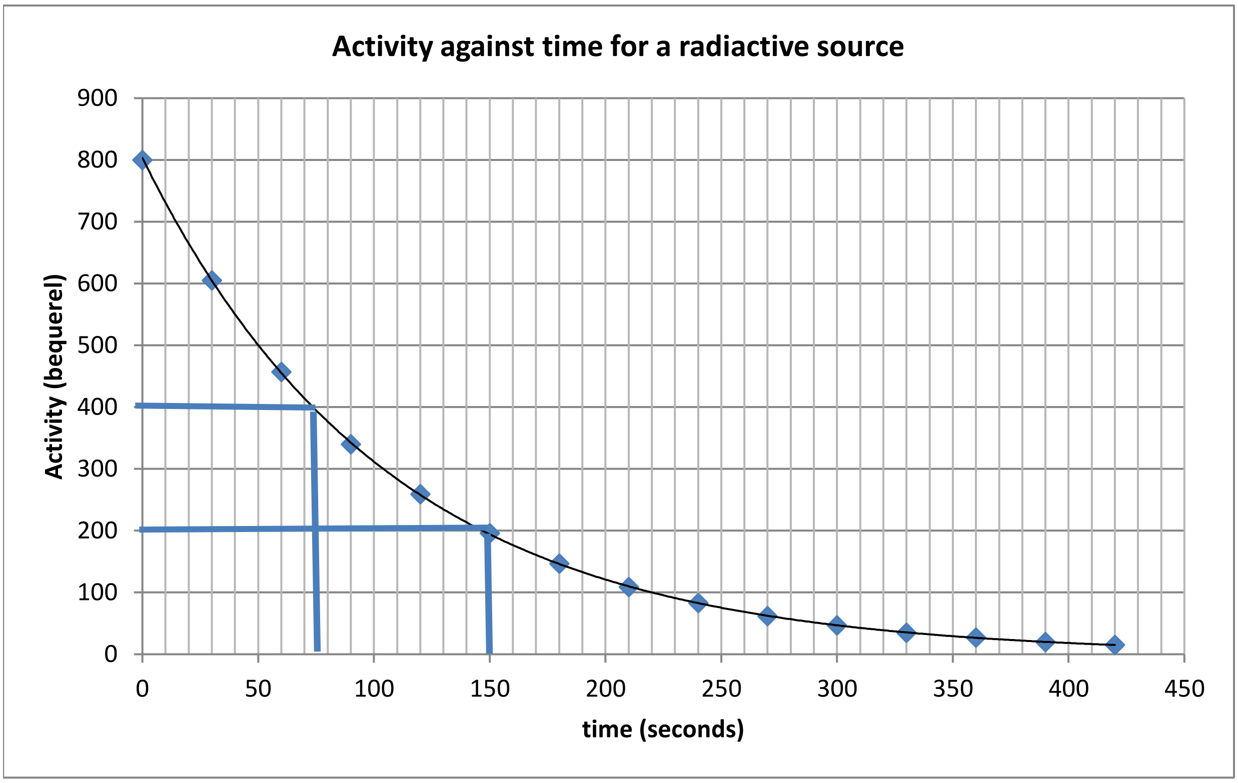
32 → (1) 16 → (2) 8

2 half-lives = 24 days

1 half-life = 12 days

Half-life calculations continued

Half-life can be calculated by graphical methods. A graph of activity against time can be plotted and half-life worked out from it.



- Choose any value of activity on the y-axis (say 400 Bq) and draw a line in to meet the curve.
- From this point on the curve draw a line to meet the time on the x-axis.
- Do this again for a value of activity that is half of the first (200 Bq in this case).
- The **difference** between the values on the time axis is the half-life of the source.

For the above example this is 150 – 75 = 75 seconds.

Selecting a radioactive source with the correct half-life is important when choosing it for an application, for example:

- It would not be wise to choose a radioactive tracer with a long half-life as this would remain active within the body for too long a time.
- It may be be necessary to choose a source with a long half-life to examine an oil pipeline for cracks.

Do some research of your own to find out about the importance of half-life in the application of radioactive substances.

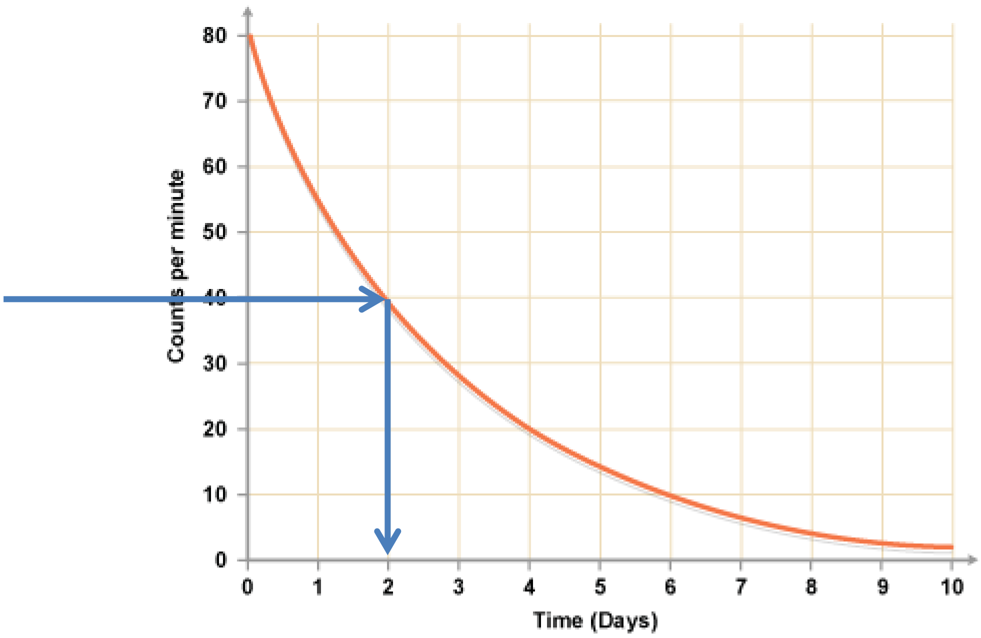
Experiment to measure Half-life

Equipment

- A detector of radiation (Geiger-Muller Tube and counter)
- A stopwatch

Method

- First record the background count rate several times. Calculate an average and subtract this value from all readings.
- Place the source a fixed distance in front of the Geiger counter and record the count rate at regular time intervals.
- Plot the count rate (correct for background count) against time taken on a graph
- Read off the time for the count rate to drop by half.



In the example above the initial count rate was 80 counts per minute. To find the half-life we half this value (40 counts per minute) and read off the time it took for this drop to take place, 2 days. The half-life is 2 days.

Nuclear Reactors

Large amounts of heat are produced in the core of a reactor to heat water which produces steam to turn the turbines of a generator and produce electricity. The fuel in a nuclear reactor is uranium. The nucleus of the uranium atom is split into smaller parts when it is bombarded by neutrons. This process is called nuclear fission and is how the large amounts of heat needed is produced.

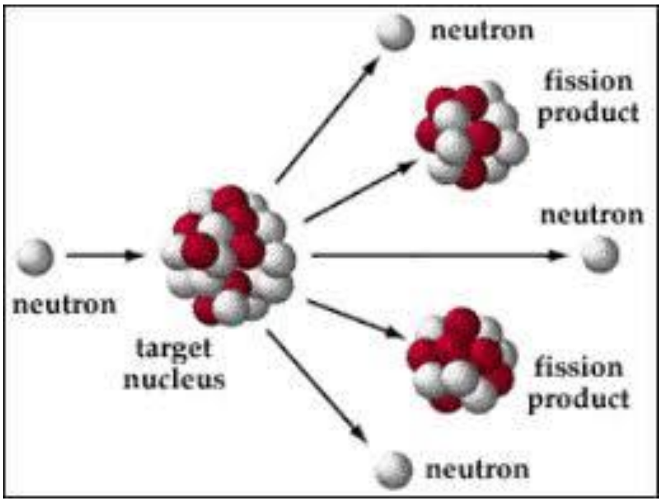
Generating electricity using nuclear power does not come without risks. When deciding whether or not to build a nuclear power station you must compare the risks and the advantages. Here are some of advantages and disadvantages of nuclear power. You decide!

Advantages of nuclear power	Disadvantages of nuclear power
Does not produce waste carbon dioxide	Nuclear power produces radioactive waste that has to be stored for many years
Does not use fossil fuels which are in short supply	Any accidents can be very serious for the surrounding area/environment
A small mass of nuclear fuel produces a lot of energy	At the end of the reactor's life it has to be very carefully dismantled. This is very expensive
The waste produced gets kept in one place and does not get put into the atmosphere	

Energy and nuclear radiation

There are two ways in which nuclear radiation can be used to generate energy.

1. Fission

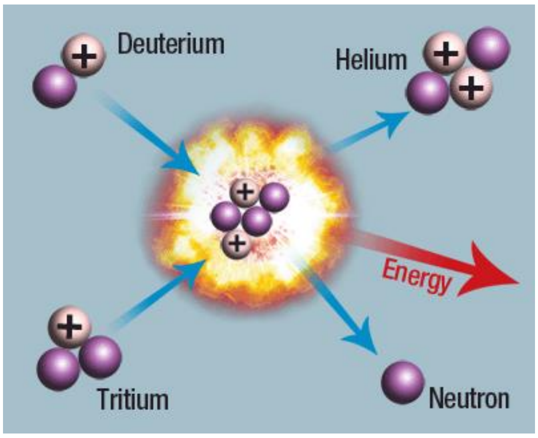


If a neutron is fired at a uranium 235 nucleus, it becomes unstable and separates into two smaller nuclei and releases some more neutrons. The mass of these nuclei and neutrons is slightly less than the mass of the original nucleus and neutron. Using the equation $E = mc^2$, where *m* is the mass lost and *c* is the speed of light, we can calculate the energy released in each fission reaction. If the neutrons that are released are captured by other uranium 235 nuclei, the process can be repeated. This is known as a **chain reaction**.

In nuclear power stations, the energy released is used to heat water to produce steam to turn a turbine. This drives a generator which produces electricity.

Energy and nuclear radiation (continued)

2. Fusion



Fusion is a process where two smaller nuclei are combined to create a larger nucleus. Again, the total mass of the products of this reaction is less than the total mass before the reaction, allowing us to calculate the energy released by using the equation $E = mc^2$.

Fusion reactions take place in the **sun**. Currently, Scientist are working to try and recreate these reactions in the lab as it is believed they could generate far more energy than fission at a much lower risk.

The big issue is that the sun is a source of **plasma** and the reactions take place at exceptionally high temperatures - 150 million degrees! To recreate this in the lab, Scientists use **microwave ovens** to heat the plasma. However the plasma cools when it hits the walls of the oven. To prevent this, a plasma container is used. **Magnetic fields** hold the plasma away from the walls of the oven so the temperature can increase.

Hopefully, in the near future, we can economically be using fusion reactions to generate energy!

Note: It is important that you do not misspell fusion or fission!

Using nuclear radiation to produce electricity reduces the amount of carbon dioxide released into the atmosphere. Carbon dioxide is a greenhouse gas which helps contribute to global warming. However, nuclear reactors produce radioactive waste which needs to be stored for thousands of years before it is safe.