St Ninian's HS



National 5 Physics

Waves and Radiation

Pupil Notes

Unit 1: Waves and Radiation

Topics:

- [ ] 1.1 Wave Parameters and Behaviours
- [ ] 1.2 Electromagnetic Spectrum
- [ ] 1.3 Refraction of Light
- [ ] 1.4 Nuclear Radiation

SQA Course Specifications N5

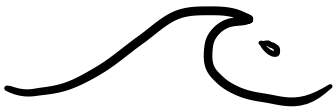
Wave Parameters and behaviours

- Knowledge that waves transfer energy.
- Definition of transverse and longitudinal waves.
- Knowledge that sound is an example of a longitudinal wave and electromagnetic radiation and water waves are examples of transverse waves.
- Determination of the frequency, period, wavelength, amplitude and wave speed for longitudinal and transverse waves.
- Use of appropriate relationships to solve problems involving wave speed, frequency, period, wavelength, distance, number of waves and time.
- Knowledge that diffraction occurs when waves pass through a gap or around an object.
- Comparison of long wave and short-wave diffraction.
- Draw diagrams using wave fronts to show diffraction when waves pass through a gap or around an object.

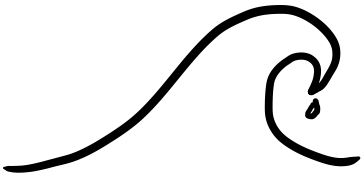
1.1 Wave Parameters and Behaviours

Waves: transfer energy from one place to another.

For example: water waves transfer **kinetic energy.**



smaller waves transfer less kinetic energy



larger waves transfer more kinetic energy

Speed

You can calculate the speed of a wave if you know how long it takes to travel a particular distance using:

distance (m) → $d = vt$ ← time (s)

↑

speed (ms^{-1})

Worked Example:

Water waves travel a distance of 50 m in 10 s. **Calculate** the speed are the waves travelling.

Shopping list:

$v = ?$

$d = 50\ m$

$t = 10\ s$

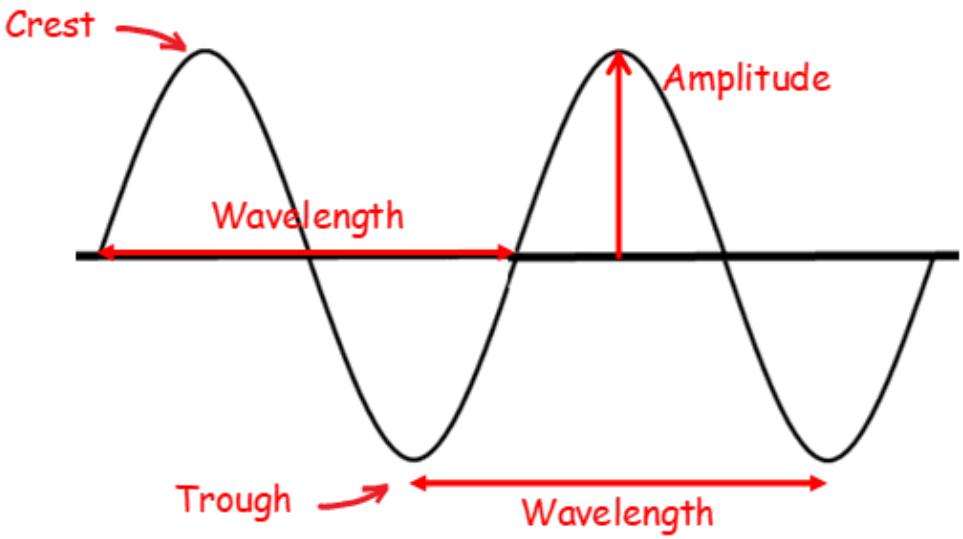
$d = v\,t$ ← Formula ✓

$50 = v \times 10$ ← Sub-in ✓

$v = \frac{50}{10}$

$v = 5\ ms^{-1}$ ← Answer with units ✓

Wave Characteristics



Wavelength: The distance between any point on one wave and the corresponding point on the next wave.

The symbol for wavelength is λ (the Greek letter lambda). Wavelength is measured in metres (m).

Amplitude: The height of the wave measured from the centre line to the top of the crest, or bottom of the trough.

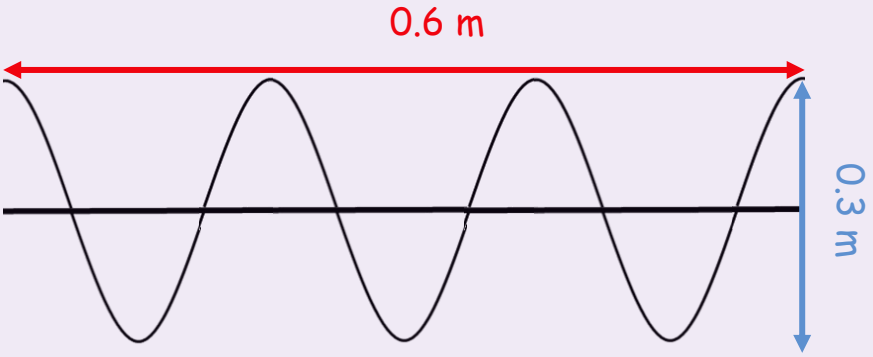
The amplitude is a measure of the energy the wave possesses. The bigger the amplitude, the more energy the wave carries.

The symbol for amplitude is A. Amplitude is measured in metres (m).

Worked Example:

Using the diagram **determine**:

a) The wavelength of the wave.
b) The amplitude of the wave.



Answer:

a) 3 waves = 0·6 m

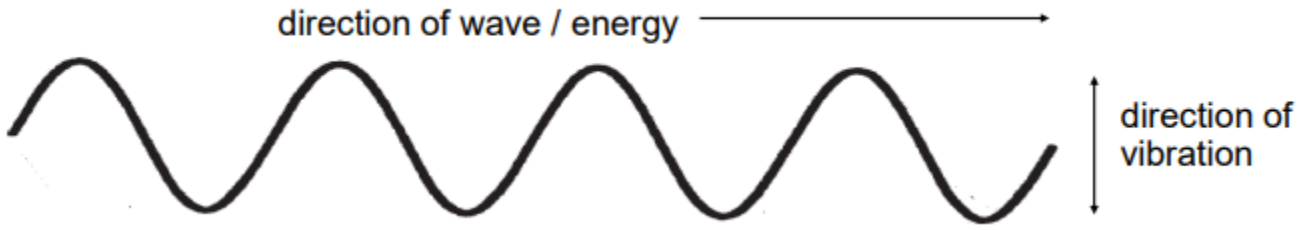
1 wave = 0·6 ÷ 3 = 0·2m

b) Amplitude = 0·3 ÷ 2 = 0·15m

Types of Wave:

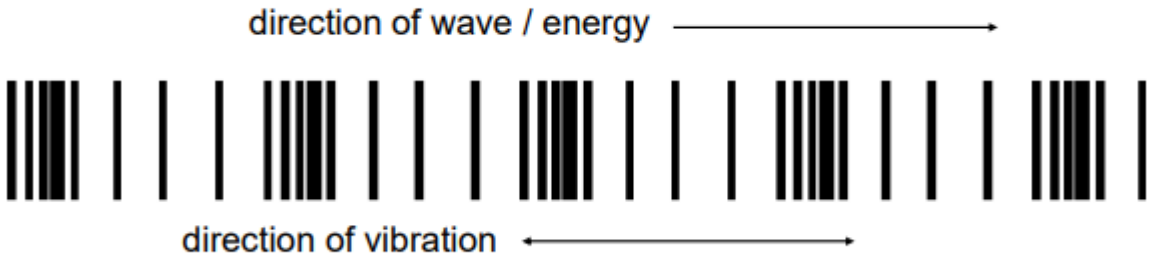
Waves can be categorised as one of the two types below:

Transverse wave: a wave where vibrations are perpendicular to energy transfer.



Examples of transverse waves are water waves, light, gamma rays, X rays, and all members of the electromagnetic spectrum.

Longitudinal wave: a wave where vibrations are parallel to energy transfer.



Sound is an example of a longitudinal wave.

Frequency

Frequency: the number of waves that pass a point per second.

Frequency can be calculated using:

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

frequency (Hz) → f

N ← Number of waves

t ← time (s)

Lower Frequency: Larger Wavelength



Higher Frequency: Smaller Wavelength



Worked Example:

The waves shown in the diagram pass a point in 2s.

Calculate the frequency of the waves.



Shopping list:

$f = ?$

$N = 4$ *Waves (taken from the diagram)*

$t = 2\ s$

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

$$f = \frac{4}{2}$$

$$f = 2\ Hz$$

Period

The period of a wave is the time taken for **one** complete wave to pass a particular point.

It can be calculated using:

period (s) → $T = \frac{1}{f}$ ← frequency (Hz)

Wave Equation

The wave equation relates the following quantities:

speed (ms^{-1}) → $v = f\lambda$ ← wavelength (m)

frequency (Hz) ↑

Worked Example:

Microwaves have a frequency of 300 MHz. If they travel at the speed of light (3×10^8 ms^{-1}). **Calculate** the wavelength of the radio waves.

Solution:

$f = 300\,MHz = 300 \times 10^6\,Hz$

$v = 3 \times 10^8\ ms^{-1}$

$\lambda = ?$

$v = f \times \lambda$

$3 \times 10^8 = 300 \times 10^6 \times \lambda \quad | \div 300 \times 10^6$

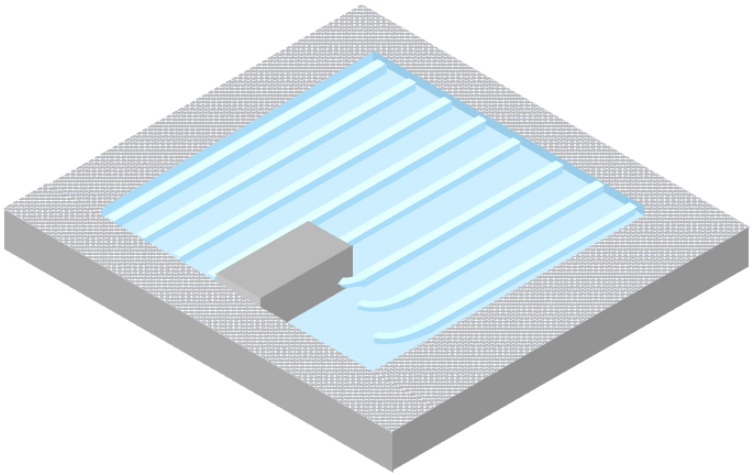
$\lambda = \frac{3 \times 10^8}{300 \times 10^6}$

$\lambda = 1\,m$

In the above solution the prefix M (for Mega) has been replaced with $\times 10^6$

Diffraction

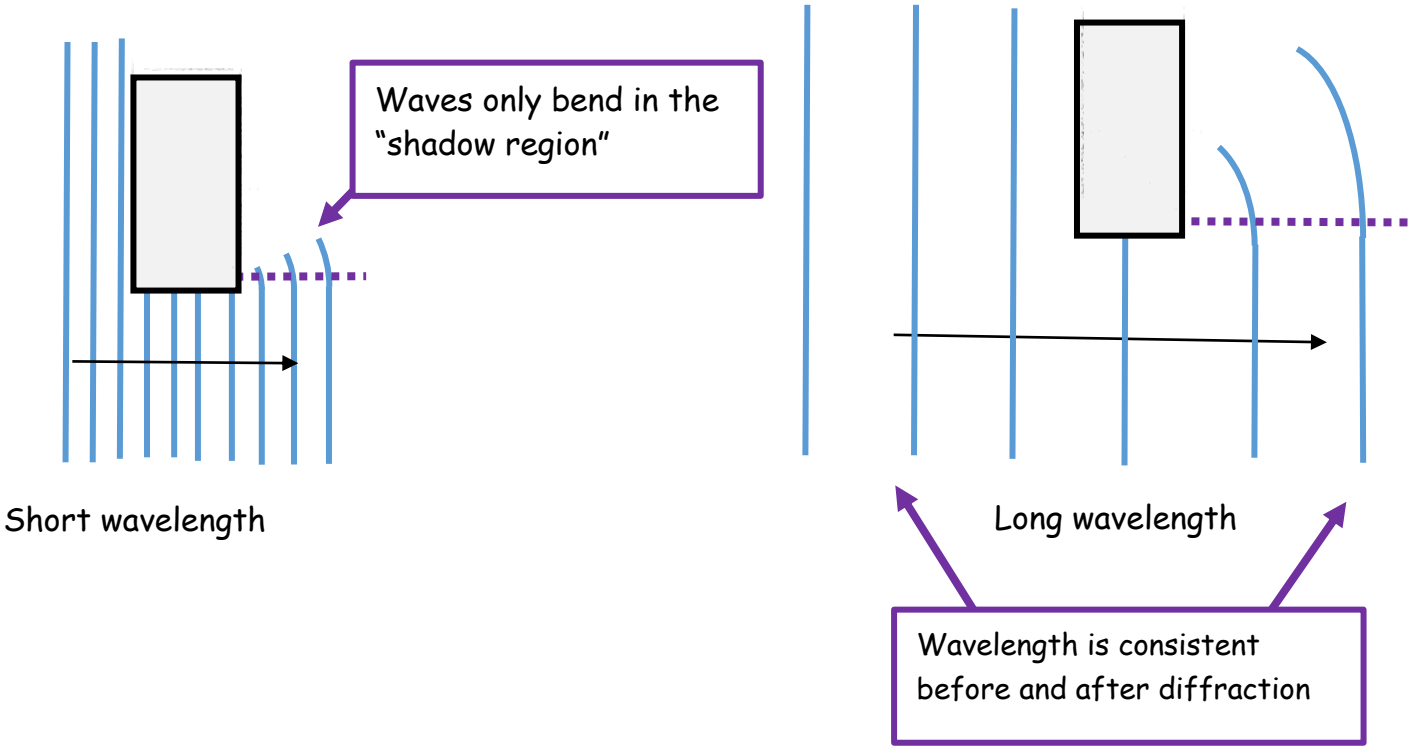
When waves meet a gap or a barrier, they carry on through the gap and spread out into the area beyond the barrier (into the shadow region). How much they spread out depends on how the width of the gap compares to the wavelength of the waves. Significant diffraction only happens when the wavelength is of the same order of magnitude as the gap.



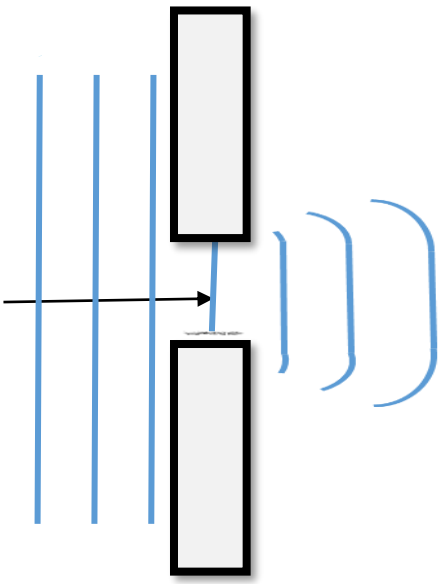
Diffraction: When waves meet the edge of a barrier they bend around it.

The amount of diffraction can be increased or decreased in the following ways:

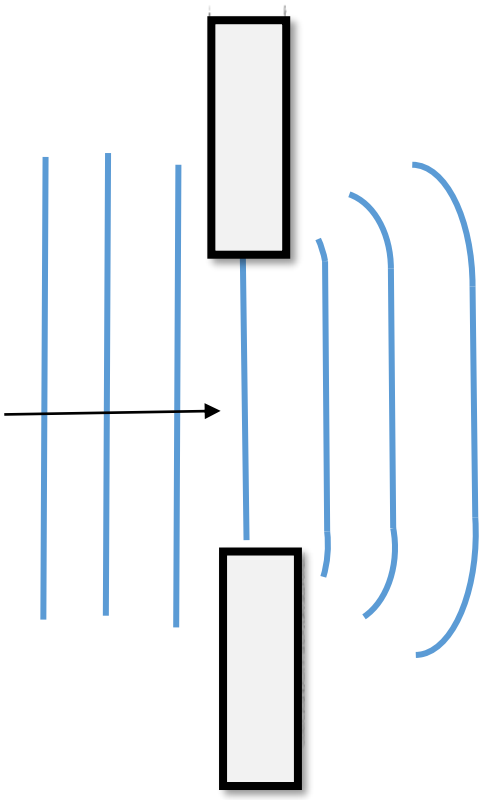
Waves with a longer wavelength diffract more than waves with a short wavelength



The larger the gap the less diffraction takes place



Small Gap

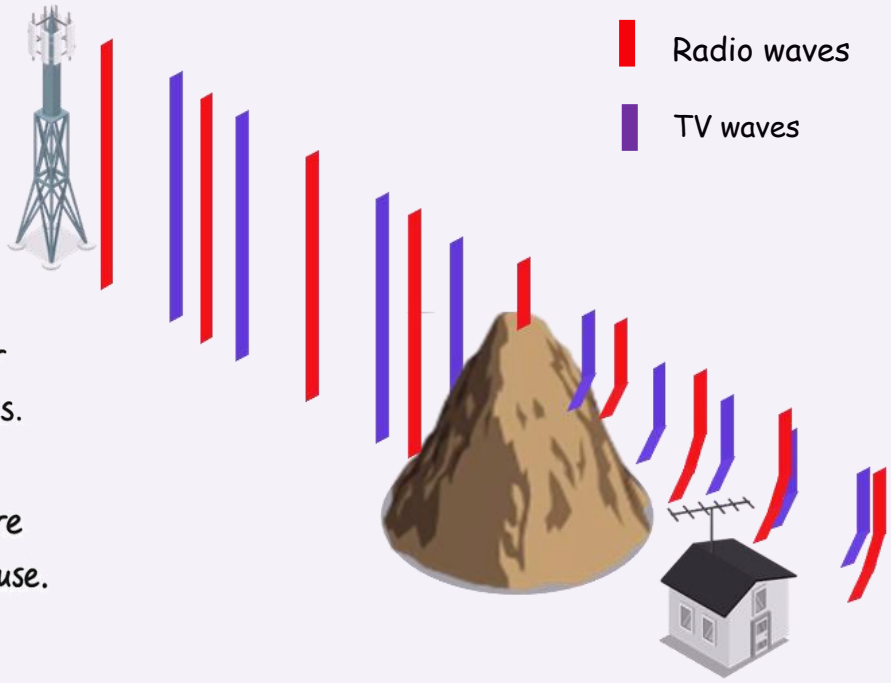


Large Gap

Worked Example:

In the image below the house is able to receive a clear radio signal however the TV signal is less clear.

Explain why this is the case.



The radio waves have a longer wavelength than the TV waves.

This means they diffract more and more easily reach the house.

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Electromagnetic Spectrum

- Knowledge of the relative frequency and wavelength of bands of the electromagnetic spectrum.

- Knowledge of typical sources, detectors and applications for each band in the electromagnetic spectrum.

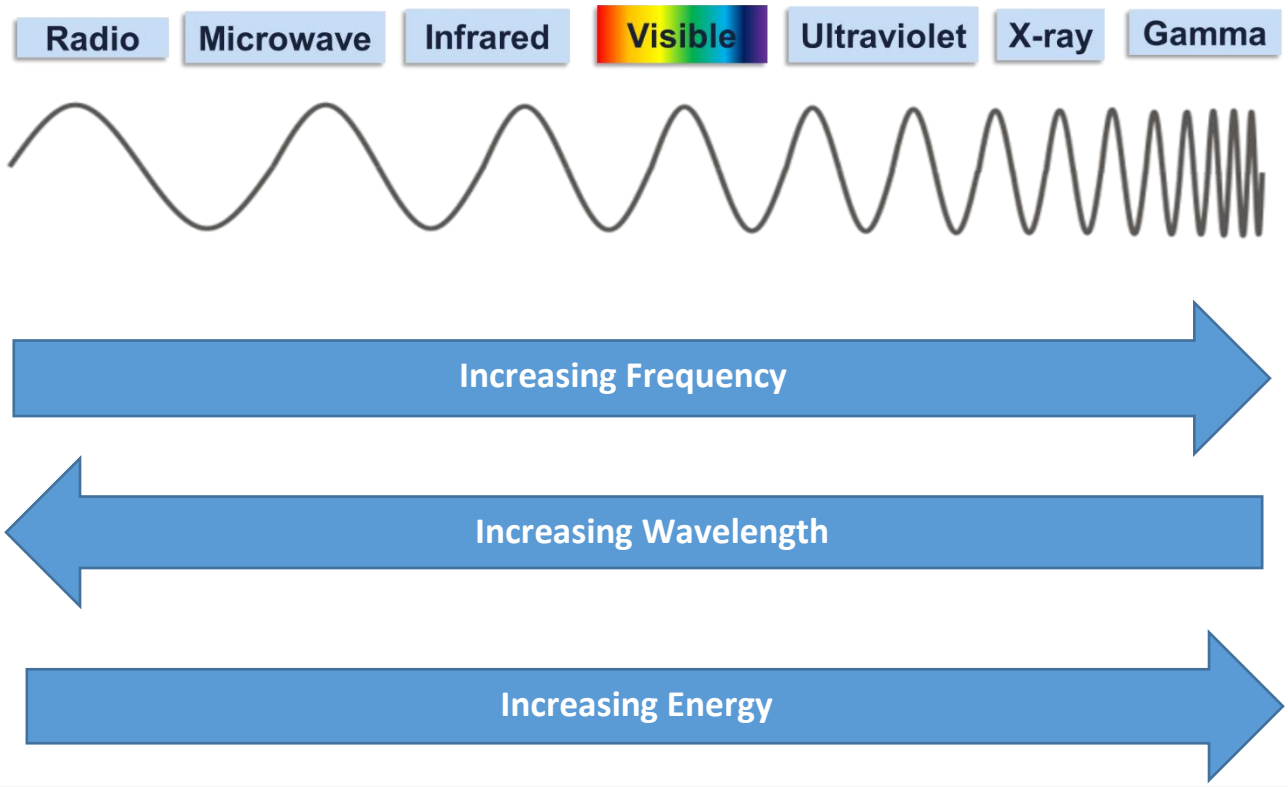
- Knowledge that all radiations in the electromagnetic spectrum are transverse and travel at the speed of light.

1.2 Electromagnetic Spectrum

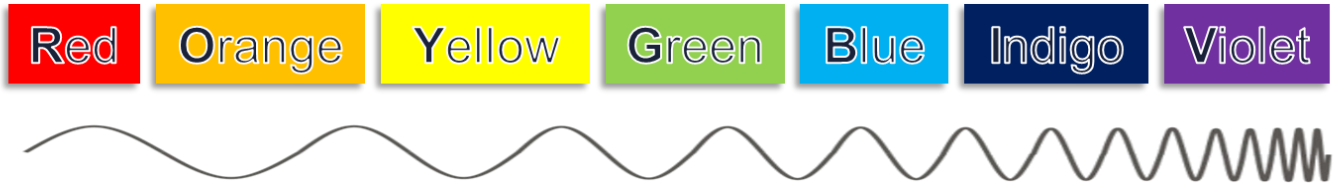
The electromagnetic spectrum is a range of transverse waves which travel at **$3x10^8$ ms^{-1}** in a vacuum.

Electromagnetic waves do not consist of vibrating particles, but instead are vibrations in electrical and magnetic fields.

The order of the EM spectrum:



The visible light spectrum can be separated further into the colours of the rainbow. A useful way to remember the order of these colours is **ROYGBIV**:



Red light has the longest wavelength and violet has the shortest.

Unlike sound waves, electromagnetic waves can travel in a vacuum (at the speed of light). When electromagnetic waves travel through other materials such as solids and liquids their speed may change.

Sources, detectors and applications:

Each member of the electromagnetic spectrum has its own sources, detectors and applications:

Radio waves:



Source: Electrical circuits

Detector: Antenna/aerial

Application: Communications

Microwaves:



Source: Electrical circuits

Detector: Antenna/aerial

Application: Communications, heating food

Infrared:

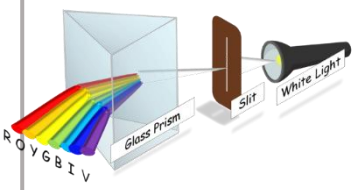


Source: warm objects

Detector: CCD

Application: TV remotes, treating muscle injuries

Visible Light:

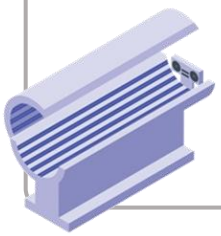


Source: The sun, lamps

Detector: The retina, CCD

Application: Photography

Ultraviolet:



Source: The sun, lamps

Detector: CCD

Application: Producing vitamin D

X-ray:



Source: very fast electrons striking a metal surface

Detector: CCD

Application: detecting broken bones

Gamma Rays:



Source: radioactive nuclei decaying

Detector: Geiger-Muller Tube

Application: sterilisation, medical traces

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Refraction of Light

- Knowledge that refraction occurs when waves pass from one medium to another.

- Description of refraction in terms of change of wave speed, change in wavelength and change of direction (where the angle of incidence is greater than 0°), for waves passing into both a more dense and a less dense medium.

- Identification of the normal, angle of incidence and angle of refraction in ray diagrams showing refraction.

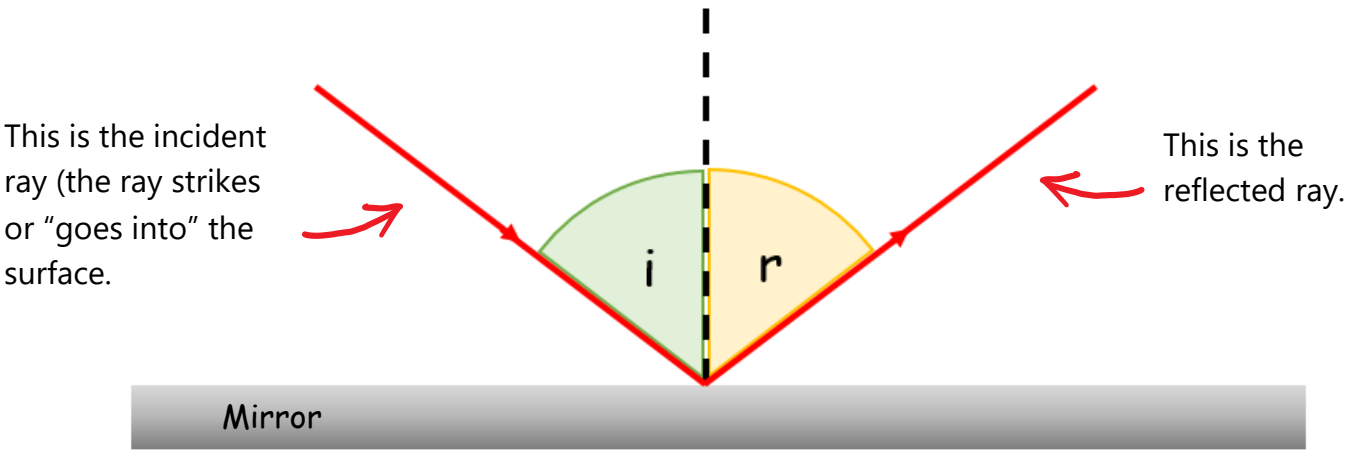
1.3 Refraction of Light

Light travels in straight lines called rays.

We use "ray-diagrams" to represent the path that light takes.

Reflection:

When light hits certain materials, it will reflect and "bounce" of the surface:



Key:			
	The normal	i	Angle of Incidence
	Ray of light	r	Angle of Reflection

Note: The normal is a line at right angles to the surface of the material.

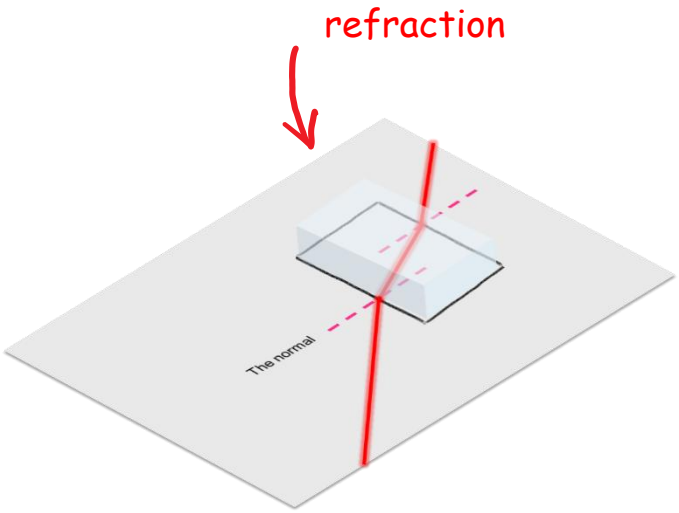
Law of Reflection:

The angle of incidence (i) is equal to the angle of reflection, (r).

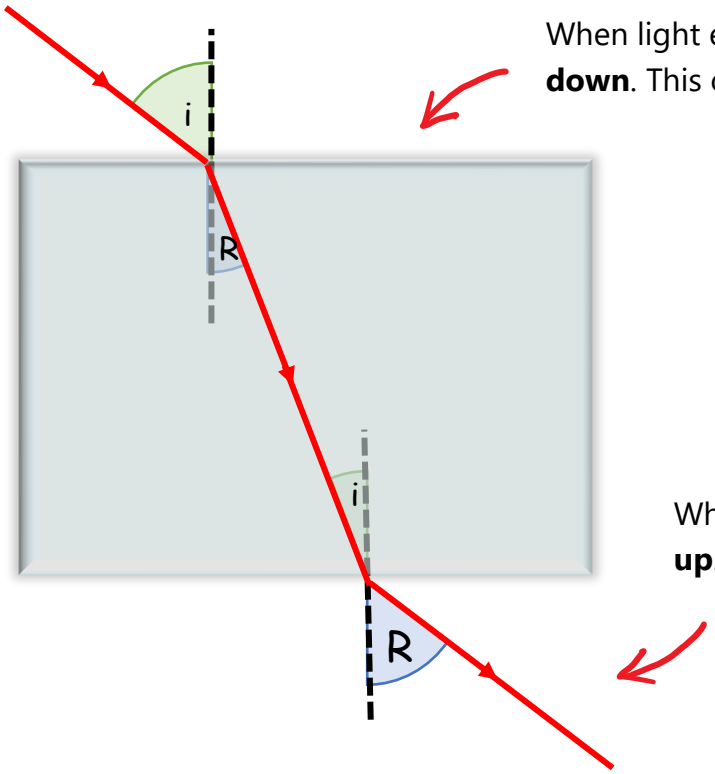
$$i = r$$

Refraction

Refraction: when light passes from one material to another material with a different density its speed (and wavelength) will change.



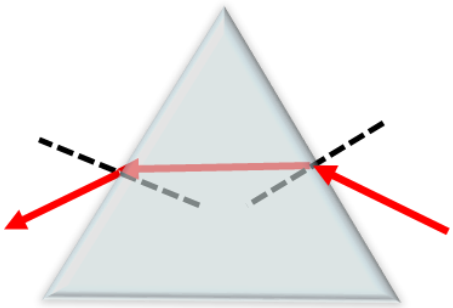
Refraction Diagrams:



When light enters a more dense material, it **slows down**. This causes it to bend **towards the normal.**

When light enters a less dense material, it **speeds up**. This causes it to bend **away from the normal.**

Key:			
	The normal		Angle of Incidence
	Ray of light		Angle of Refraction

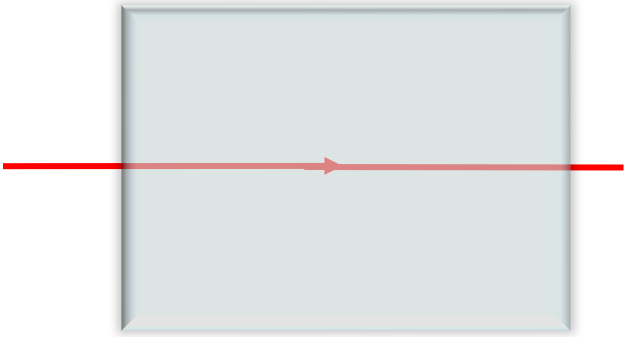


The above rules apply to any shape and/or medium (glass, Perspex water ect.)

For the triangle on the left, the light first bends towards the normal (it slows down in glass) and then bends away from the second normal (it speeds up as it moves back into air).

When Light does not bend:

If the light travels along the normal (as seen in the diagram on the right), the ray will pass straight through the material. This only happens when the angle of incidence = 0°

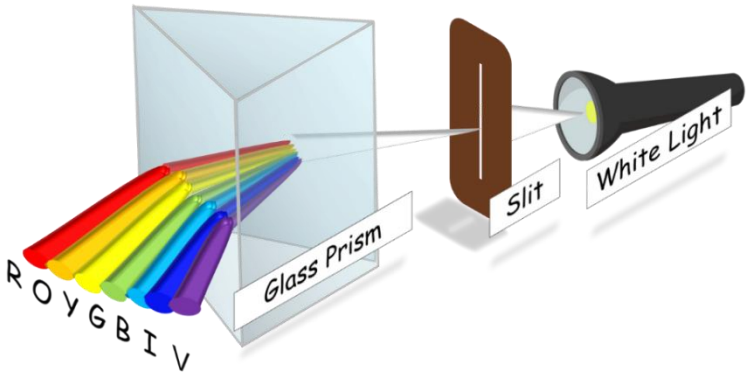


Refraction still occurs in this case as the light is changing speed.

Refracting white light:

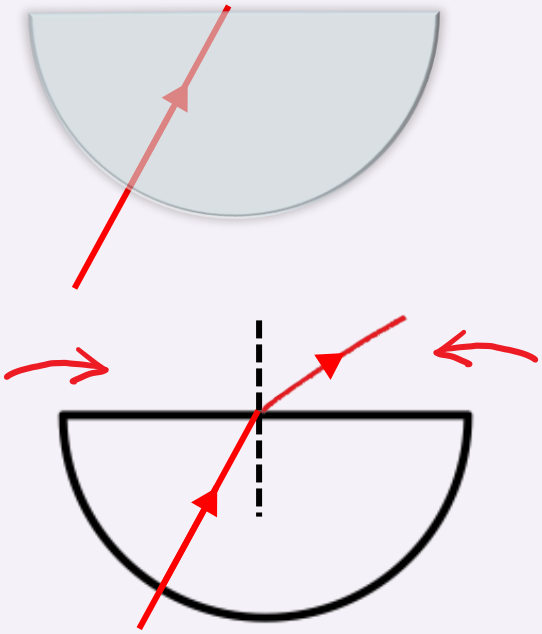
During refraction, a wave's wavelength decreases if its speed slows down in a new medium, while its frequency remains constant.

This change in wavelength is why different colours of light, which have different wavelengths, bend at different angles when passing through a prism, creating a rainbow.



Worked Example:

Copy and complete the diagram below to show the path of the ray of red light through and out of the glass blocks



Solution:

Step 1: draw the normal at 90° to the surface

Step 2: the light bends away from the normal when it speeds up

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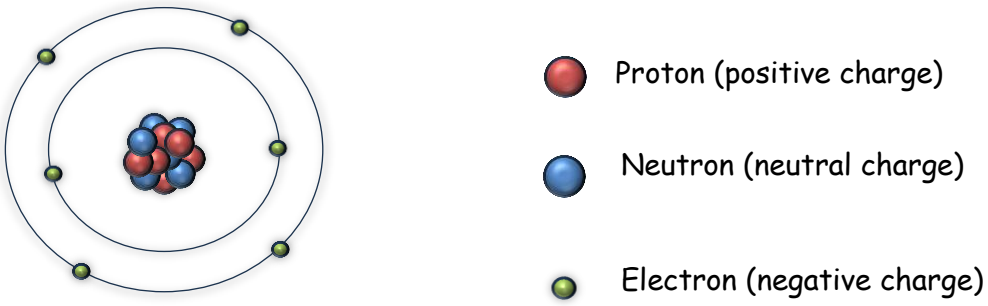
Nuclear Radiation

- [ ] Knowledge of the nature of alpha (α), beta (β) and gamma (γ) radiation.
- [ ] Knowledge of the term 'ionisation' and the effect of ionisation on neutral atoms.
- [ ] Knowledge of the relative ionising effect and penetration of alpha, beta and gamma radiation.
- [ ] Definition of activity in terms of the number of nuclear disintegrations and time.
- [ ] Use of an appropriate relationship to solve problems involving activity, number of nuclear disintegrations and time.
- [ ] Knowledge of sources of background radiation.
- [ ] Knowledge of the dangers of ionising radiation to living cells and of the need to measure exposure to radiation.
- [ ] Use of appropriate relationships to solve problems involving absorbed dose, equivalent dose, energy, mass and weighting factor.
- [ ] Use of an appropriate relationship to solve problems involving equivalent dose rate, equivalent dose and time.
- [ ] Comparison of equivalent dose due to a variety of natural and artificial sources.
- [ ] Knowledge of equivalent dose rate and exposure safety limits for the public and for workers in the radiation industries in terms of annual effective equivalent dose.
- [ ] Awareness of applications of nuclear radiation: electricity generation, cancer treatment and other industrial and medical uses.
- [ ] Definition of half-life.
- [ ] Use of graphical or numerical data to determine the half-life of a radioactive material.
- [ ] Description of an experiment to measure the half-life of a radioactive material.
- [ ] Qualitative description of fission, chain reactions, and their role in the generation of energy.
- [ ] Qualitative description of fusion, plasma containment, and their role in the generation of energy.

1.4 Radiation

Atoms are the smallest possible particles of the elements which make up everything around us. Nuclear radiation occurs when the nucleus of atoms are unstable

Atoms are made of the following:



The nucleus of the atom is the centre of an atom and is made of protons and neutrons. The nuclei of an atom becomes stable after nuclear radiation is emitted.

Ionising Radiation

Ionisation is the additional or removal of electron(s) from an atom.

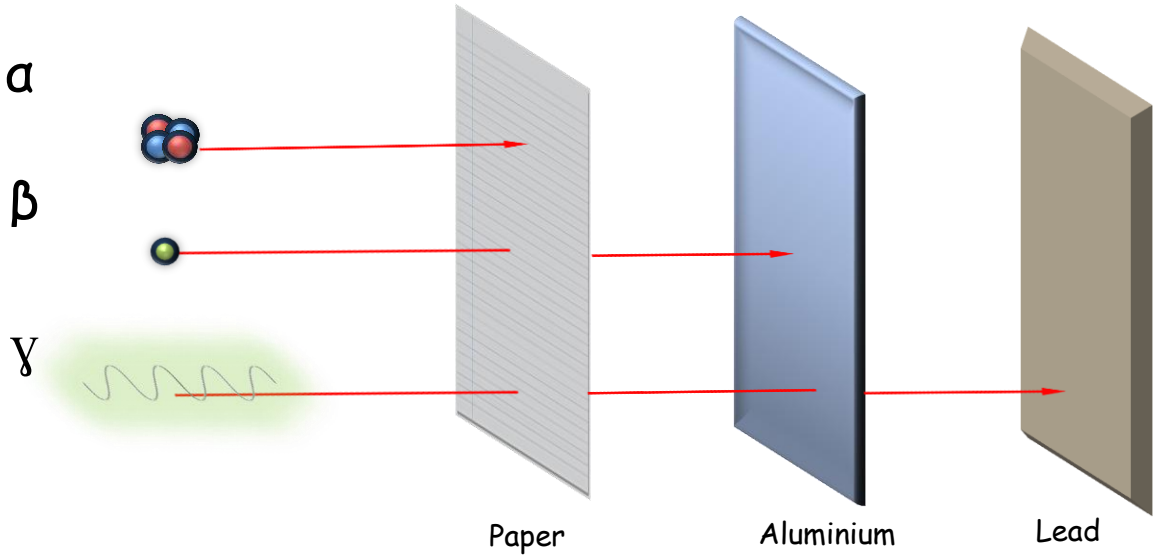
There are 3 types of ionising radiation:

Alpha, α — An alpha particle is a **helium nucleus**, it is made of 2 protons and 2 neutrons they are positively charged, relatively and heavy. They are the most ionising

Beta, β — A beta particle is a **fast moving electron** released from the nucleus, they are negatively charged, fast and light.

Gamma, ɣ — Gamma rays are **Electromagnetic Waves**, not particles. This means that they have no mass and no charge. They are the least ionizing.

The following shows the relative penetration of each type of ionising radiation:



Activity

When a radioactive source decays, it emits a ray or a particle. This is a random process.

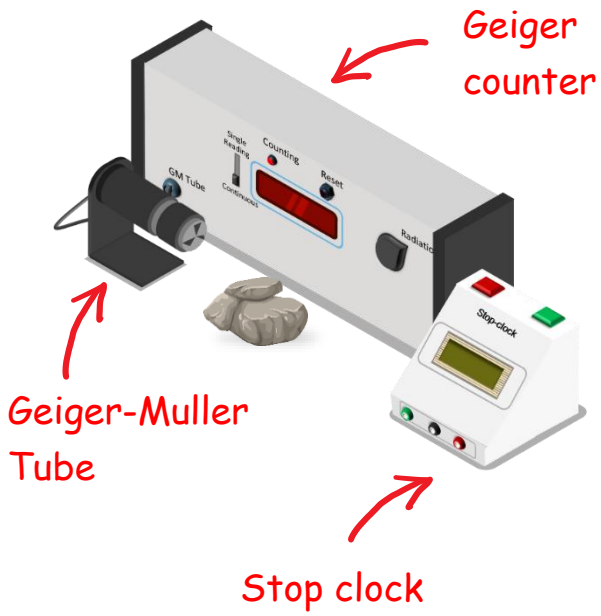
Activity is the number of decays per second.

It can be calculated using:

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

A = activity (Bq); N = number of decays; t = time (s)

Activity can be measured with a Geiger-Muller Tube connected to a counter:



Worked Example:

A radioactive source decays 4000 times in 2 minutes.

Calculate the activity of the source.

Solution:

$A = ?$

$N = 4000$

$t = 2 \text{ minutes} = 120 \text{ s}$

Convert 2 minutes into seconds:

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

$$A = \frac{4000}{120}$$

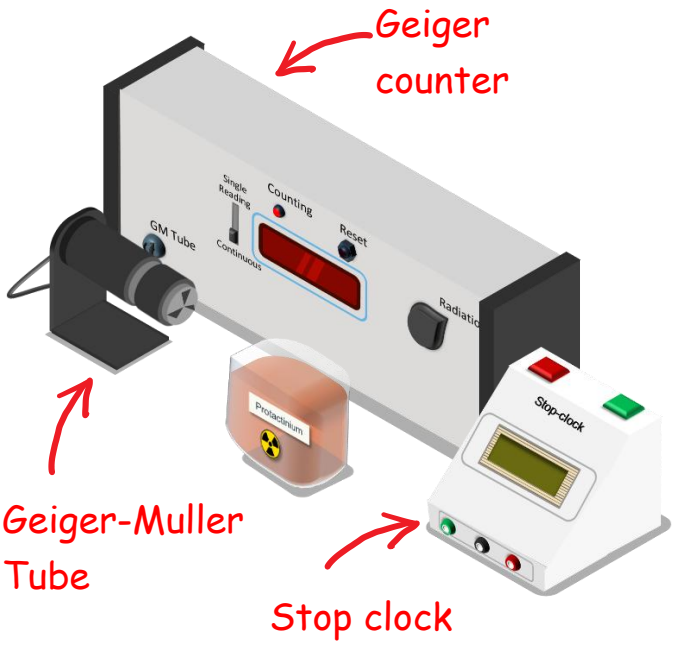
$$A = 33 \text{ Bq}$$

Half-Life

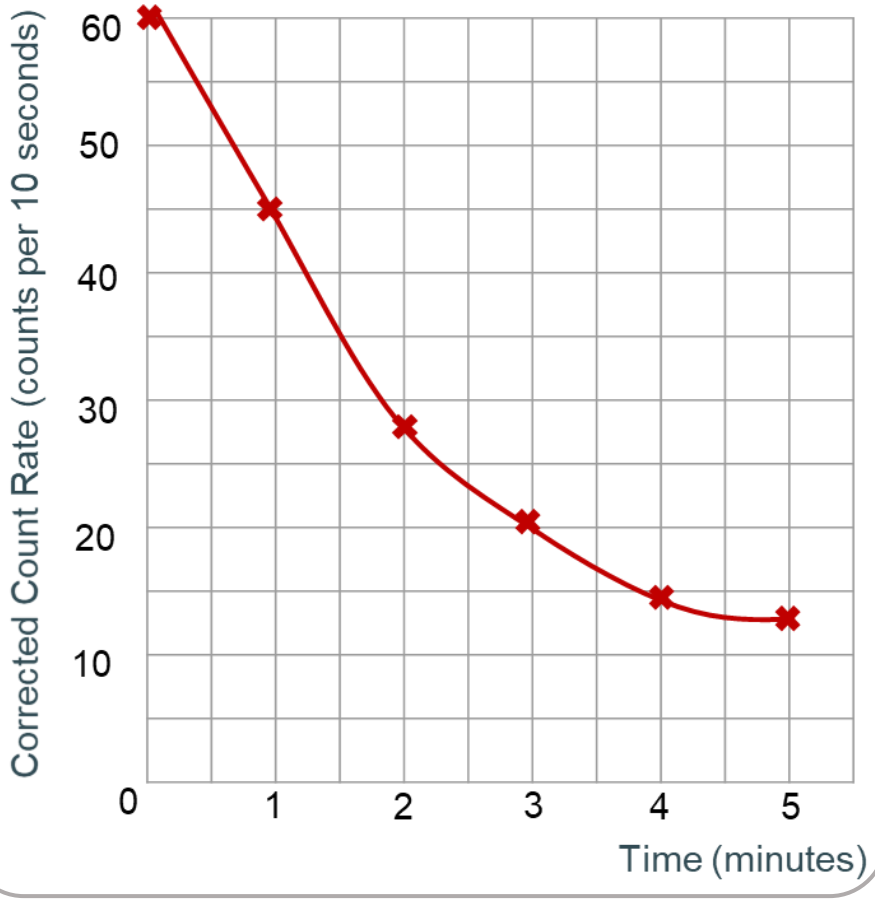
Radioactive decay is a random process. This means that for a radioactive source, it can never be predicted when an atom is about to decay. Because any particular radioactive source has so many nuclei it is possible to determine when half of all the nuclei for a particular source will have decayed. This is called half-life.

The half-life: the time for the activity of a radioactive source to fall to half its original value.

Measuring half-life:

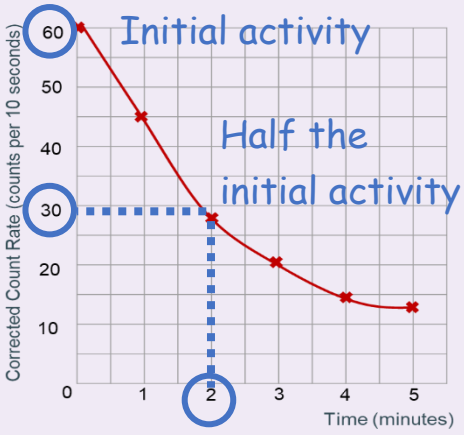


1. Measure the background count in 10s.
2. A Geiger-Muller tube and counter are used to measure the number of decays of a radioactive source over 10s.
3. The activity/count rate of the source is noted every 60 s.
4. Count rate **must** be corrected for background radiation.
5. A graph of count rate against time is plotted:



Worked Example:

Determine the half-life from the graph.



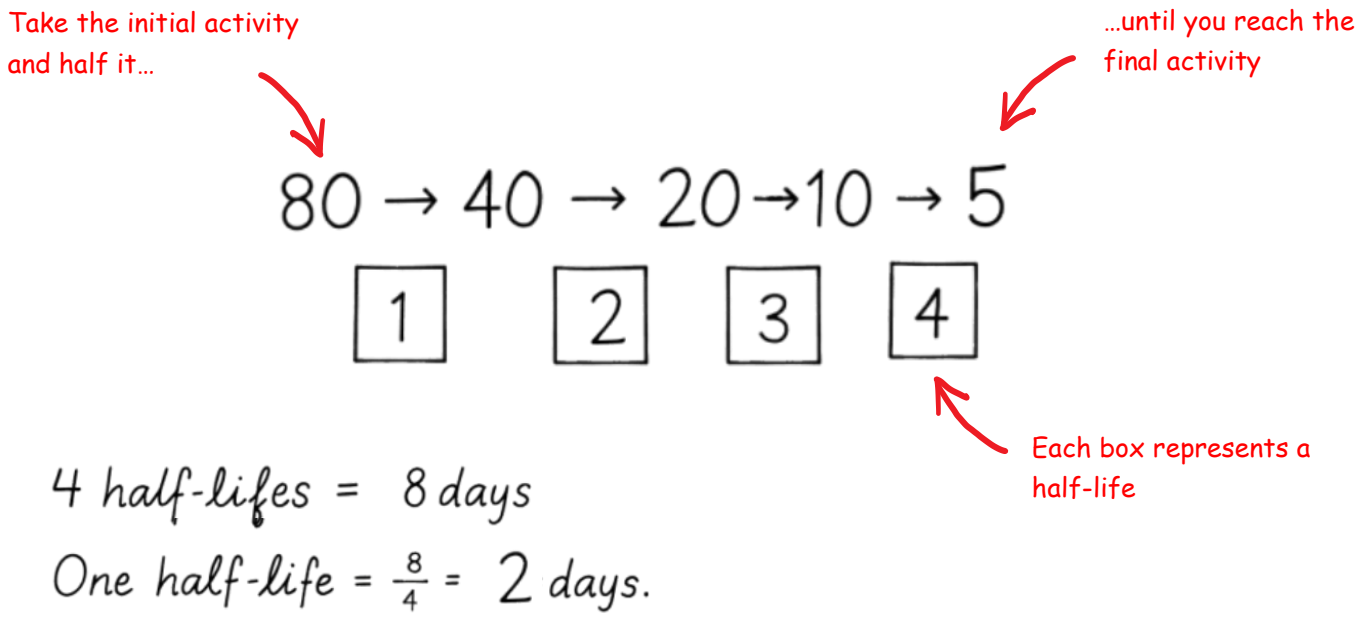
Half-life = 2 minutes

Half-life Numerical Method:

Half-life problems can also be solved with numerical solutions, sometimes referred to as the "box method":

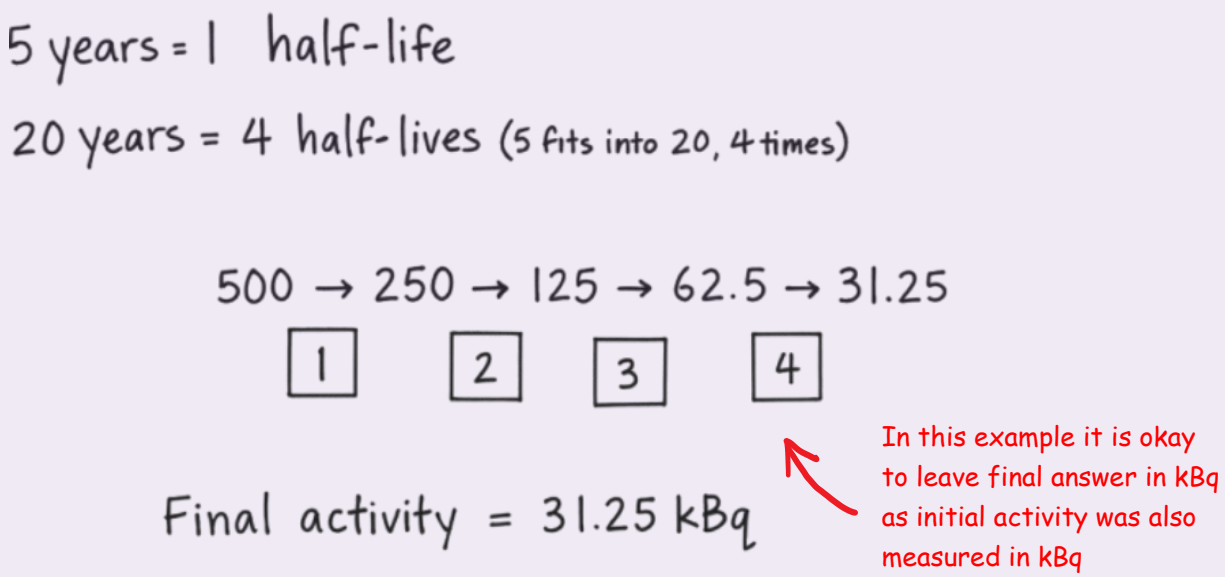
Take a source that falls from 80 MBq to 5 MBq in 8 days.

We can **<u>determine</u>** its half-life by using the following technique:



Worked Example:

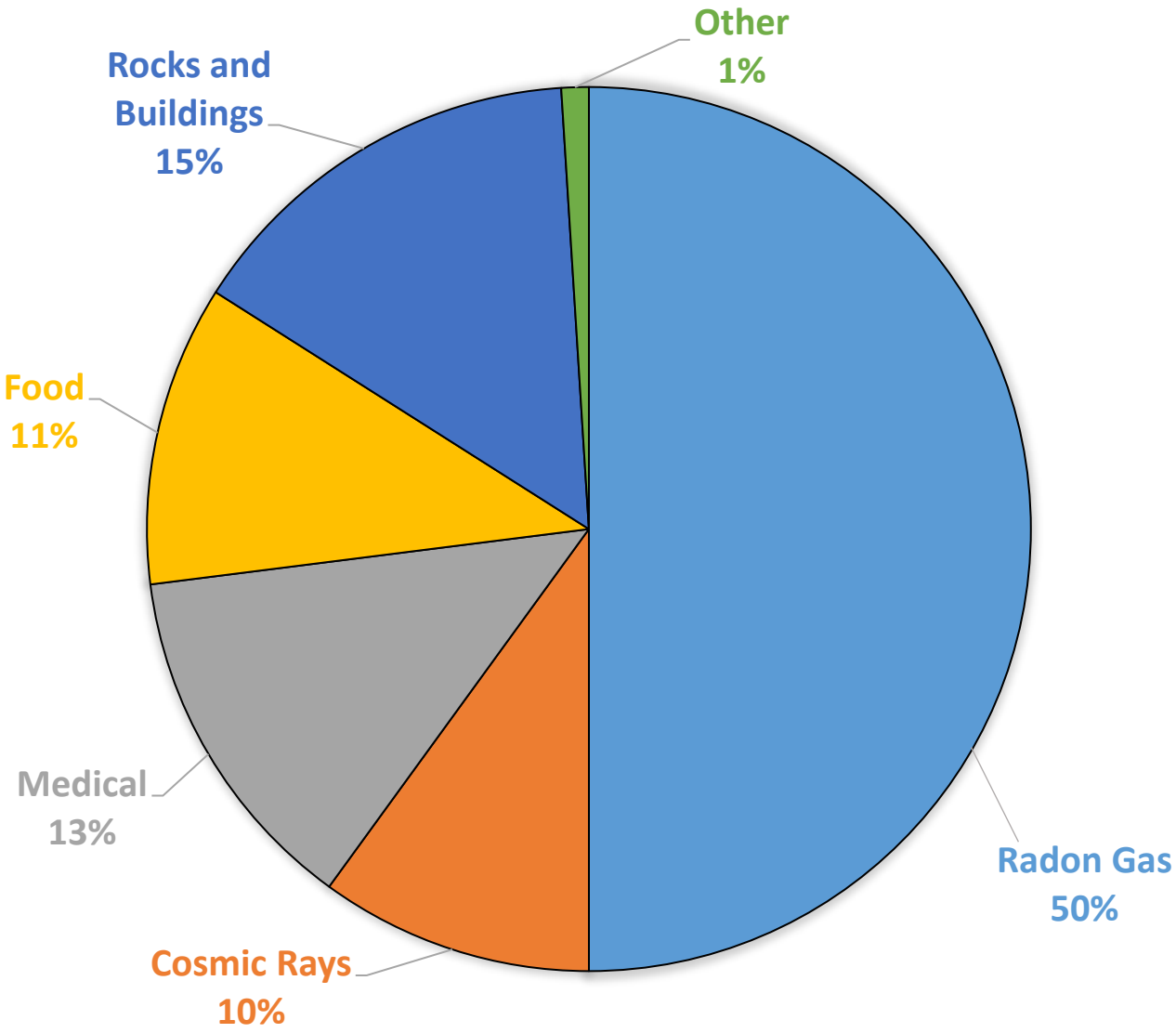
The half-life of Cobalt-60 is 5 years. If the source, 20 years ago, had an activity of 500 kBq, **determine** the activity now.



Background Radiation

Some ionising radiation is always present and everyone is exposed to it. We call this background radiation, and it comes from both **natural** and **artificial** radioactive sources.

The following pie chart shows sources of background radiation:



Artificial sources are those in which human activity has played a part. These include radioactive waste from nuclear power stations and radioactive fallout from nuclear weapons testing. However the overall contribution of most of these sources is too small to appear on the chart above.

In total artificial sources account for about 15 per cent of the average background radiation dose most of which come from medical uses such as X-rays.

The Biological Effects of Radiation

All living things are made of cells. Ionising radiation can kill or change the nature of healthy cells. This can lead to different types of cancer. The risk of biological harm from an exposure to radiation depends on:

1. the absorbed dose of radiation
2. the kind of radiation
3. the body organs or tissue exposed



Absorbed Dose

When ionising radiation (alpha, beta, gamma or other types) strikes the human body, the energy of the radiation is absorbed by the body.

Absorbed dose can be calculated using the following formula:

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

D: absorbed dose (Gy)
E: energy (J)
m: mass (kg)

Worked Example:

Calculate the absorbed dose if a 300 g sample receives 2.7 J of energy.

Solution:

$D = ?$

$E = 2.7\ J$

$m = 300\ g = 0.3\ kg$

Mass **always** gets converted from grams to kilograms

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

$$D = \frac{2.7}{0.3}$$

$$D = 9\ Gy$$

Equivalent Dose

The body tissue or organs may receive the same absorbed dose from alpha or gamma radiation, but the biological effects will be different.

To solve this problem a weighting factor, (w_r) is used. This is a number given to each kind of radiation as a measure of its biological effect.

When scientists try to work out the effect on our bodies of a dose of radiation they prefer to talk in terms of **equivalent dose.**

Type of radiation	*Radiation weighting factor*
alpha	20
beta	1
fast neutrons	10
gamma	1
slow neutrons	3
X-rays	1

From the data sheet

Equivalent dose can be calculated using:

$$H = D \times w_r$$

H: equivalent Dose (Sv)

D: absorbed Dose (Gy)

w_r: weighting factor

Worked Example:

A medical physicist receives an absorbed dose of 0.20 Gy of X-ray radiation.

Calculate the equivalent dose received by this worker.

Solution:

$H = ?$

$D = 0.20$ Gy

$w_r = 1$

From the data sheet

$H = D \times w_r$

$H = 0.20 \times 1$

$H = 0.2$ Sv

Reducing Equivalent Does

The following can be done to reduce the equivalent dose:

1. Use shielding, eg. sealed lead containers. Wear protective lead aprons.
2. Keep as far away from a radioactive source as possible.
3. Limit the exposure time.

UK Annual Limits

In the UK the average background radiation: 2·2mSv.

The following are quoted limits per year :

- Effective dose for member of the public: 1 mSv.
- Effective dose for radiation worker: 20 mSv.

Equivalent Dose Rate

Equivalent Dose Rate takes into account the relative risks from exposure of different organs of the body. It is the equivalent dose rate that is used to indicate the risk of health from exposure to ionising radiations.

It can be calculated using the following formula:

equivalent dose rate → $\dot{H} = \frac{H}{t}$ ← equivalent dose; time

The units of equivalent dose rate can be: mSv/h, mSv/yr, etc

Worked Example:

In a year a worker receives the following exposures to radiation; 30 mGy of gamma radiation and 400 µGy of fast neutrons. **Calculate** is her total equivalent dose rate for the year.

Step 1: Work out total equivalent dose by working out each equivalent dose and **then** adding them

Gamma: $H = Dwr = 30 \times 10^{-3} \times 1 = 30 \times 10^{-3}$

Fast neutrons: $H = Dw_r = 400 \times 10^{-6} \times 10 = 4 \times 10^{-3}$

Total equivalent dose: $30 \times 10^{3} + 4 \times 10^{3} = 34\ mSv$

Step 2: Use the total equivalent dose to work out the equivalent dose rate

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

$\dot{H} = \frac{34}{1}$ ← Number of years

$\dot{H} = 34\ mSvyr^{-1}$

Applications of Nuclear Radiation

Nuclear Radiation has multiple uses within society:

Treating Cancer



Radiotherapy is the treatment of cancers by radiation. Cancers are growths of cells which are out of control. The object of the radiation treatment is to cause damage to the cancer cells which stops them reproducing. The tumour then shrinks. Unfortunately, healthy cells can also be damaged by radiation. This means the amount of radiation has to be very accurately calculated and the radiation must be aimed very accurately at the tumour.

Sterilising Instruments



Gamma radiation can kill cells. This can be used to kill bacteria on instruments leaving them sterile. The instruments are wrapped up inside a package and exposed to a heavy dose of radiation, which kills all germs inside the pack. The package does not need to be opened until it is required for use. So it stays sterile.

The Gamma Camera

A radiopharmaceutical is used which acts as a tracer. The advantage of the radiopharmaceutical is that the radiation can be detected outside the body. It is injected into the blood and provides a trace of the inside of the body, the kidney, which is viewed with a special camera called a gamma camera which detects the radiation passing from the body. Gamma is chosen since alpha or beta would be absorbed by tissue and would not be detected outside the body.

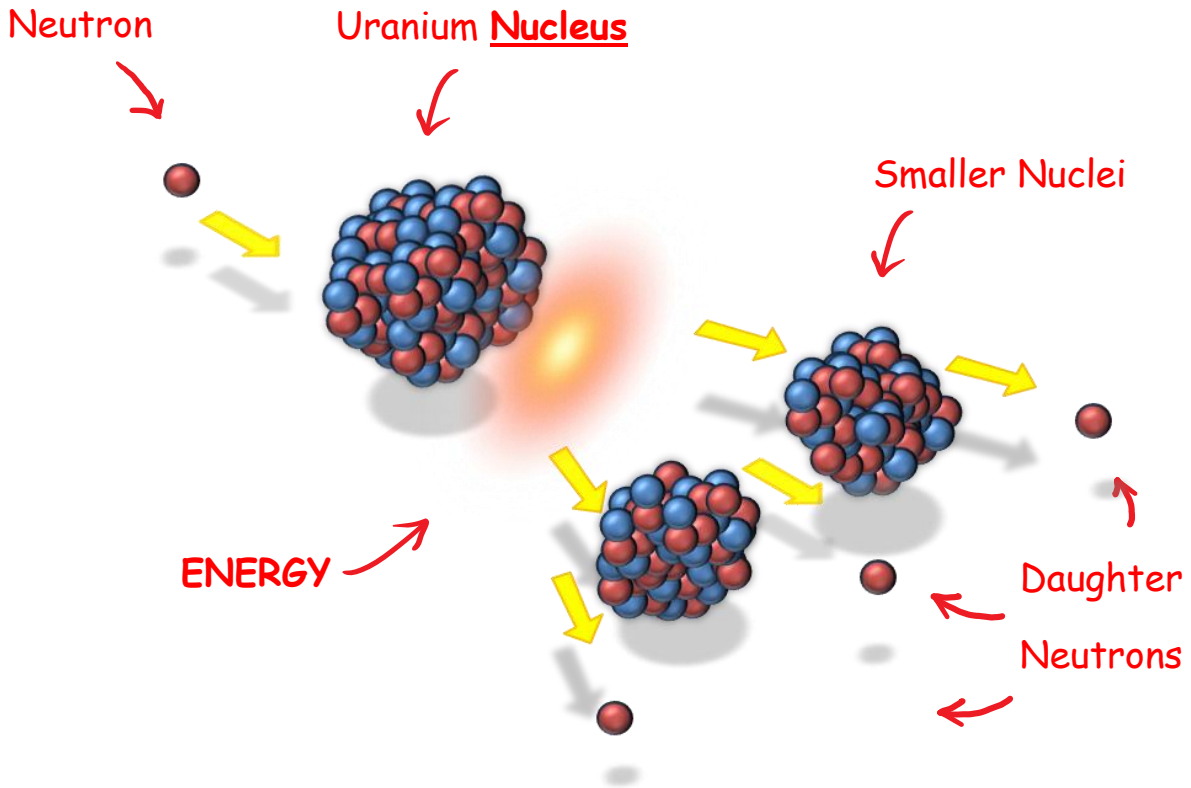
Electricity Generation

Nuclear power is a major source of energy. These generally involve nuclear fission reaction to produce large amounts of energy (see Nuclear Fission). Scientists are looking into nuclear fusion as an option as well however it generally is in efficient as the reaction takes more energy than it produces.

Nuclear Fission

Nuclear fission: the splitting of a large unstable nucleus. Can be induced by bombarding nucleus with a neutron. This releases energy.

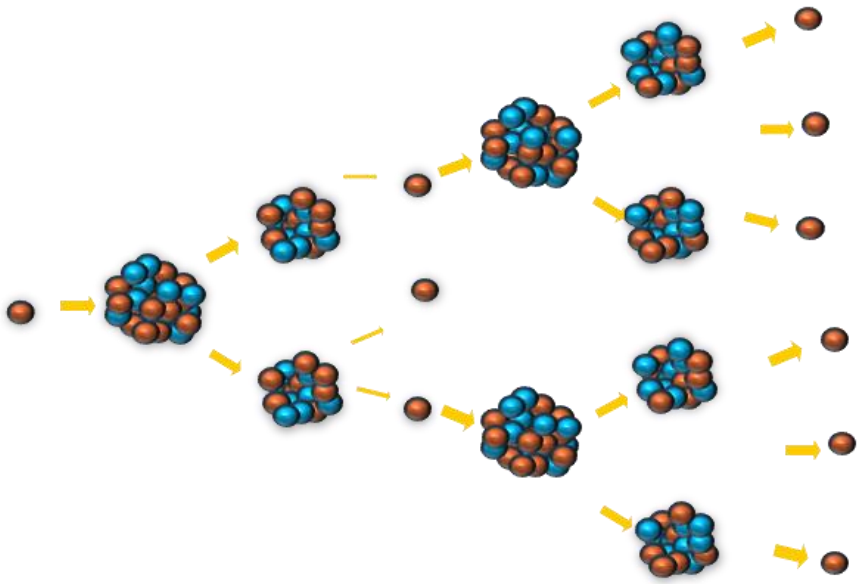
Nuclear fission is used in the production of **Nuclear Power**.



This single reaction can turn it into a continuous generation of energy in a process called a **chain reaction:**

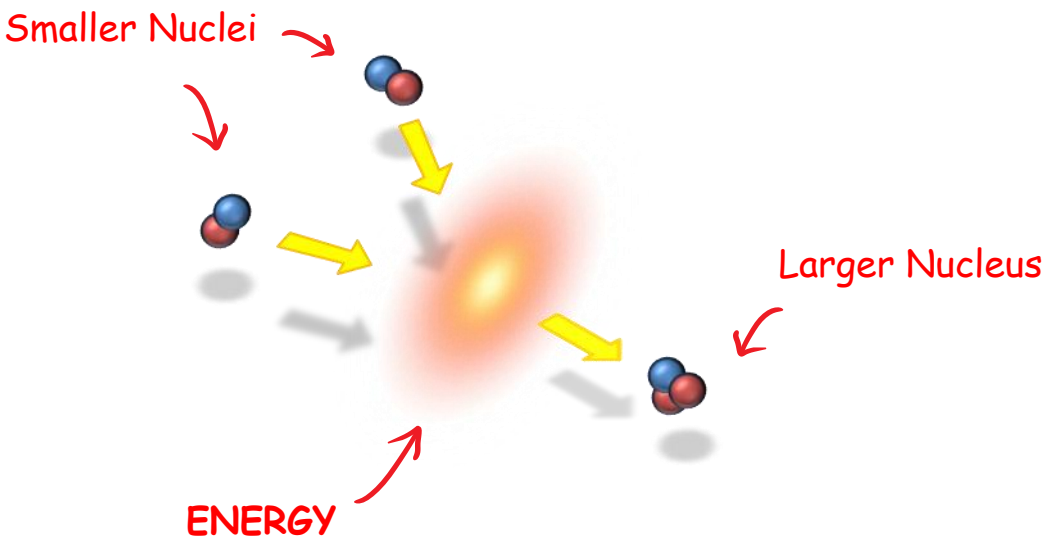
During this process, neutrons released in one fission reactions can go on to cause further fission reactions.

This process repeats, releasing energy each time.



Nuclear Fusion

Nuclear Fusion: occurs when two light nuclei combine to form a nucleus of larger mass number.



During fusion **a lot** of energy is released from a small amount of mass (even more than fission!).

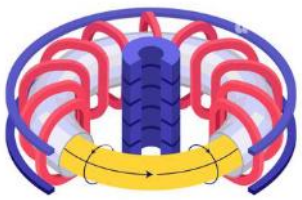
All of the energy from the Sun and stars is produced due to nuclear fusion – in the cores of stars the temperatures are so high and the pressures so immense that light nuclei (such as hydrogen) are fused together.



Nuclear Fusion on Earth

To sustain nuclear fusion on Earth we would need to create conditions similar to those that occur in the core of stars (very high temperature and pressure).

This is difficult – gases heated to such high temperatures are likely to melt whatever container they are in. *Plasma containment* is one method of heating these gases - when the gases become so hot they experience ionisation and turn into *plasma* which we can use magnets or lasers to control.



TEST YOURSELF