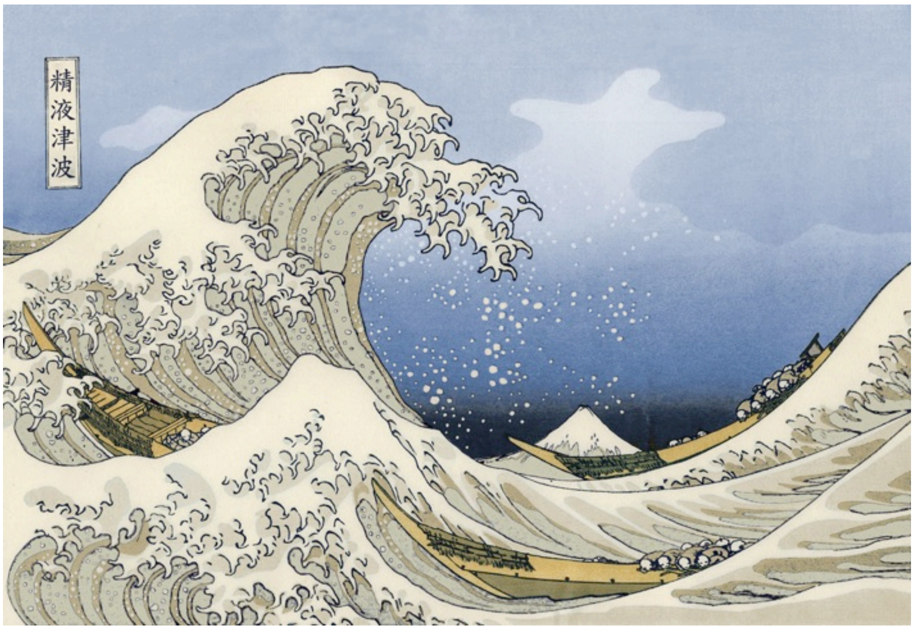
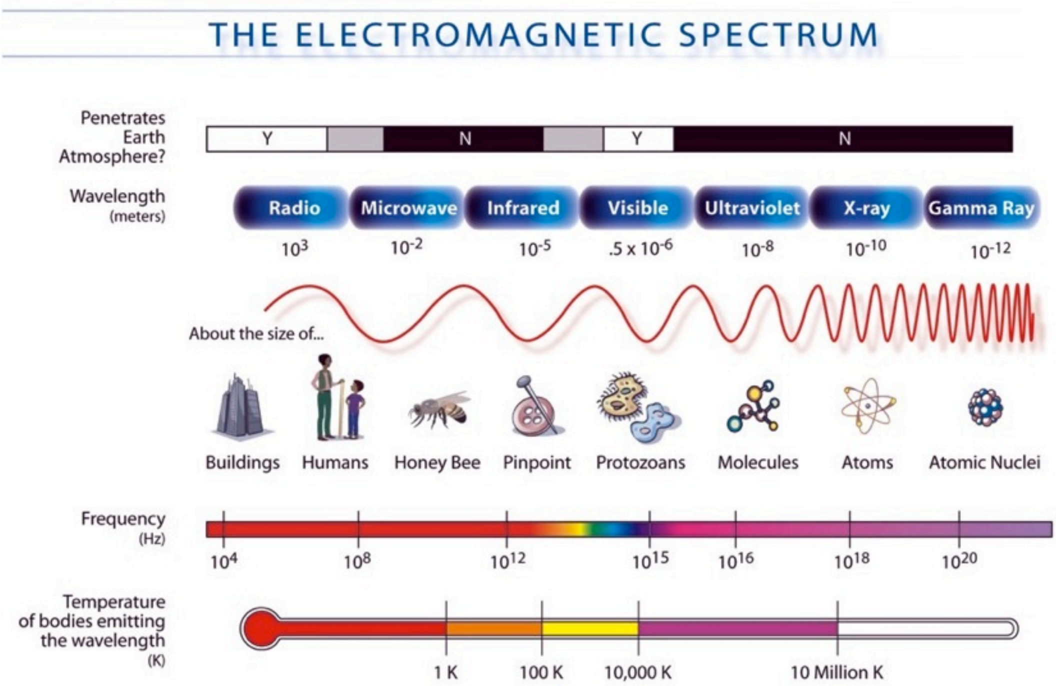
National 5 Physics

Waves





Throughout the Course, appropriate attention should be given to units, prefixes and scientific notation.

Prefix	Symbol	Notation	Operation
tera	T	10^{12}	x 1,000,000,000,000
giga	G	10^{9}	x 1,000,000,000
mega	M	10^{6}	x 1,000,000
kilo	k	10^{3}	x 1,000
centi	c	10^{-2}	/100
milli	m	10^{-3}	/1,000
micro	µ	10^{-6}	/1,000,000
nano	n	10^{-9}	/1,000,000,000
pico	p	10^{-12}	/1,000,000,000,000

In this section the prefixes you will use most often are milli (m), micro (µ), kilo (k), mega (M) and giga (G). It is essential that you use these correctly in calculations.

In Physics, the standard unit for time is the **second (s)** and therefore if time is given in milliseconds (ms) or microseconds (µs) it must be converted to seconds.

Example 1
a) A wave takes 40 ms to pass a point. How many seconds is this?

40 ms = 40 milliseconds = 40 x 10^{-3} s = 40/1 000 = 0.040 seconds.

b) A faster wave travels past in a time of 852 µs, how many seconds is this?

852 µs = 852 microseconds = 852 x 10^{-6} s = 852/1 000 000 = 0.000852 seconds.

In Physics, the standard unit for distance is the **metre (m)** and therefore if distance is given in kilometres (km) it must be converted to metres.

Example 2
A wave travels 26.1 km in 0.5 ms. How far in metres has it travelled?

26.1 km = 26.1 kilometres = 26.1 x 10^{3} m = 26.1 x 1 000 = 26 100 metres.

This unit involves calculations which use the term frequency, frequency has units of **hertz** (Hz) although often we meet the terms Megahertz and Gigahertz.

Example 3
A wave has a frequency of 99.5 MHz. How many Hz is this?

99.5 MHz = 99.5 Megahertz = 99.5 x 10^{6} Hz = 99.5 x 1 000 000 = 99 500 000 Hertz.

National 5 Physics

Waves

Contents

1. Wave parameters and behaviours

1.1. Energy can be transferred as waves.
1.2. Determination of frequency, wavelength, amplitude and wave speed for transverse and longitudinal waves.
1.3. Use of the relationship between wave speed, frequency, wavelength, distance and time.
1.4. Diffraction and practical limitations.
1.5. Comparison of long wave and short wave diffraction.

$$d = v\ t$$

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

$$v = f\,\lambda$$

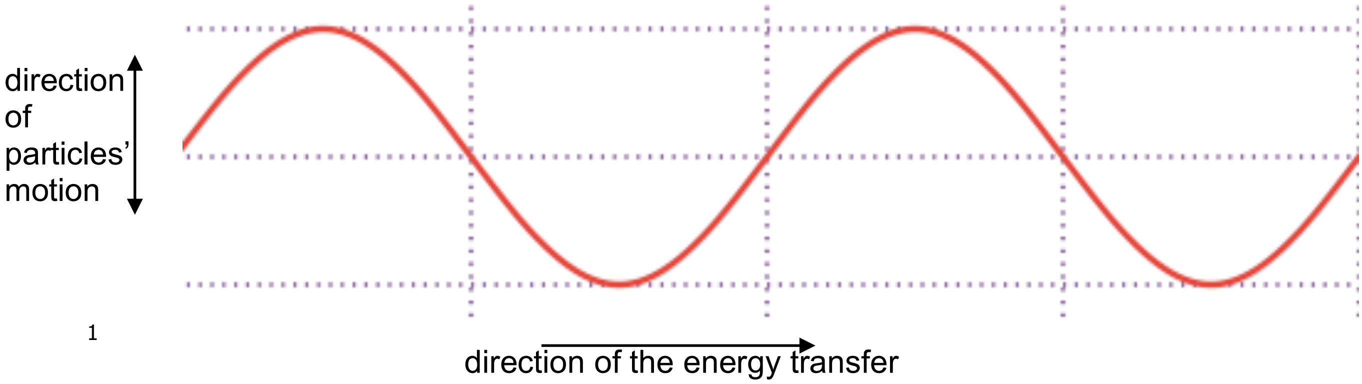
Wave parameters and behaviours

Types of wave

Waves are used to transfer energy. The substance the wave travels through is known as the medium. The particles of the medium oscillate around a fixed position but the energy travels along the wave. For example, consider waves at the beach. Seawater will move up and down as a wave passes through it but as long as the wave does not "break" there is no overall movement of any water.

There are two different types of waves you will meet in this course, transverse waves and longitudinal waves

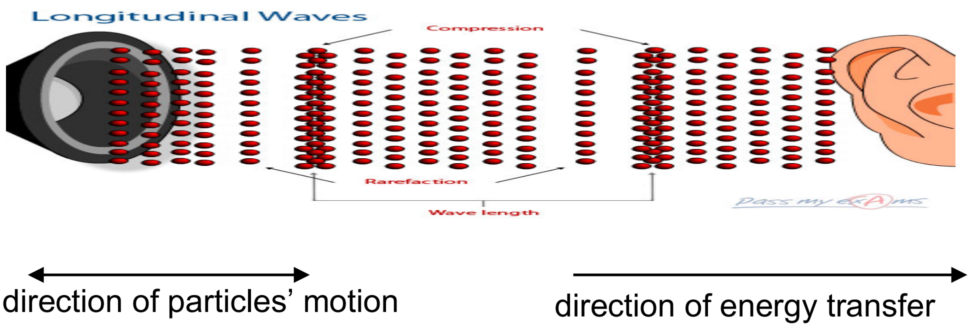
In **transverse** waves the particles oscillate (vibrate) at right angles to the direction of energy transfer



[1]

Examples are water waves, waves in a string, light, gamma rays, X-rays and all the other members of the Electromagnetic Spectrum (see below)

In **longitudinal** waves the particles oscillate in the same direction as the motion of the wave



Sound is an example of a longitudinal wave. Air particles are either squashed together to form a region of increased pressure or they are moved apart to make a region of decreased pressure.

[1] http://upload.wikimedia.org/wikipedia/commons/7/77/Waveforms.svg

Examples of Waves

All waves travel through some medium. As the wave travels it disturbs the medium through which it moves.

Mechanical Waves

Mechanical waves travel through a medium which is made up from some physical matter with particles (or molecules) in it. For example, when a water wave passes a particular point, some of the water bobs up and then down. For sound travelling through air it is the air particles that vibrate. The typical speed of a sound wave in air is 340 m/s although this varies a bit as the temperature and humidity of the air changes.

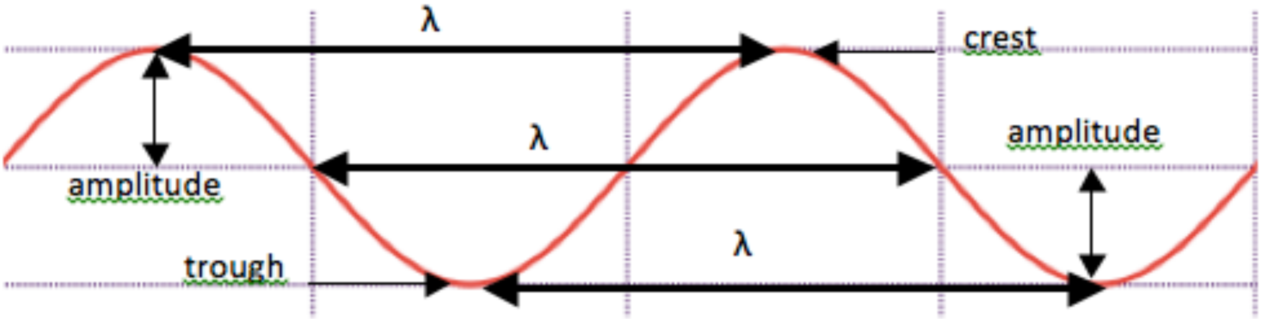
Electromagnetic Waves

Electromagnetic waves travel through two media, electric and magnetic fields. These waves cause disturbances in the electric and magnetic fields that can exist in all space. They do not need any particles of matter in order to travel, which is why light can travel through a vacuum. Different examples of electromagnetic waves are gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, TV waves and radio waves. They all travel at the same speed in a vacuum (3×10^8 m/s). This is usually referred to as the **speed of light** and is given the symbol ***c***. This very fast speed is the fastest that anything can travel.

Gravitational Waves

Research scientists are currently investigating a theory of gravity that involves gravitational waves. It has not been proven yet.

Properties of waves



Several important features of a wave are shown in the diagram. These are explained in the following table

Wave property	Symbol	Definition	Unit	Unit symbol
Crest		highest point of a wave		
Trough		lowest point of a wave		
Wavelength	λ	horizontal distance between successive crests or troughs	metre	m
Amplitude	A	half the vertical distance between crest and trough	metre	m
Wave Speed	v	distance travelled per unit time	metres per second	m/s
Period	T	the time it takes one wave to pass a point	seconds	s
Frequency	f	number of waves produced in one second	hertz	Hz

Wave Formulae

Wave Speed

The **distance** travelled by a wave travelling at a **constant speed** can be calculated using:

$$d = v\ t$$

Symbol	Name	Unit	Unit Symbol
d	Distance	metre	m
v	Velocity or Speed	metres per second	m/s
t	Time	Seconds	s

Worked Examples

1. The crest of a water wave moves a distance of 4.0 metres in 10 seconds. Calculate the speed of this wave.

$$d = v\ t$$

$$4 = v \times 10$$

$$v = 4 / 10$$

$$v = 0.40 \text{ m/s}$$

Wave speeds can vary greatly from a few metres per second up to the speed of light. For example sound waves travel in air at around 340 m/s. The actual speed of a sound wave will depend on environmental factors like temperature and pressure. Light waves travel in air at 300, 000, 000 m/s (or 3×10^8 m/s). So light travels approximately 1 million times faster than sound in air.

Wave Frequency

The frequency of a wave is defined to be:

$$frequency = \frac{number\ of\ waves}{time\ for\ the\ waves}$$

Now consider the case for just one wave. The number of waves is one and the time taken is the Period. Hence,

$$frequency = \frac{1}{Period}$$

Using symbols, this becomes

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

Symbol	Name	Unit	Unit Symbol
f	Frequency	hertz	Hz
T	Period	second	s

Worked Examples

1. A certain breed of bat emits ultrasounds with a period of 23 μs. Calculate the frequency of the ultrasound.

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

$T = 23 \times 10^{-6}$ s

f = ?

$$f = \frac{1}{23 \times 10^{-6}}$$

f = 43.5 kHz

2. Given that a wave has a frequency of 50 Hz, calculate its period.

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

T = ?

f = 50 Hz

$$50 = \frac{1}{T}$$

T = 0.02 s

The Wave Equation

The other main formula related to waves is derived from the relationship between distance, speed and time.

distance = speed x time

For just one wave, the distance becomes one wavelength and time becomes one period.

wavelength = speed x period

But period = $\frac{1}{f}$

Therefore, wavelength = speed x $\frac{1}{f}$ or $\lambda = \frac{v}{f}$

this can be rearranged to give an equation called the **wave equation**.

$$v = f\lambda$$

Symbol	Name	Unit	Unit Symbol
v	Velocity or Speed	metres per second	m/s
f	Frequency	hertz	Hz
λ	Wavelength	metre	m

Worked Example

Microwaves have a frequency of 9.4 GHz. Calculate their wavelength.

$v = 3 \times 10^8$ m/s
$f = 9.4 \times 10^9$ Hz
$\lambda = ?$

$v = f\lambda$

$3 \times 10^8 = 9.4 \times 10^9 \lambda$

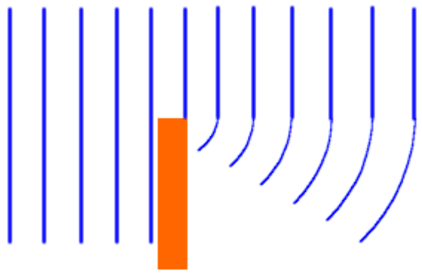
$\lambda = 3 \times 10^8 / 9.4 \times 10^9$

$\lambda = 0.032$ m

Diffraction

Waves can 'spread' in a rather unusual way when they reach a gap in a barrier or the edge of an object placed in the path of the wave - this is called **diffraction**.

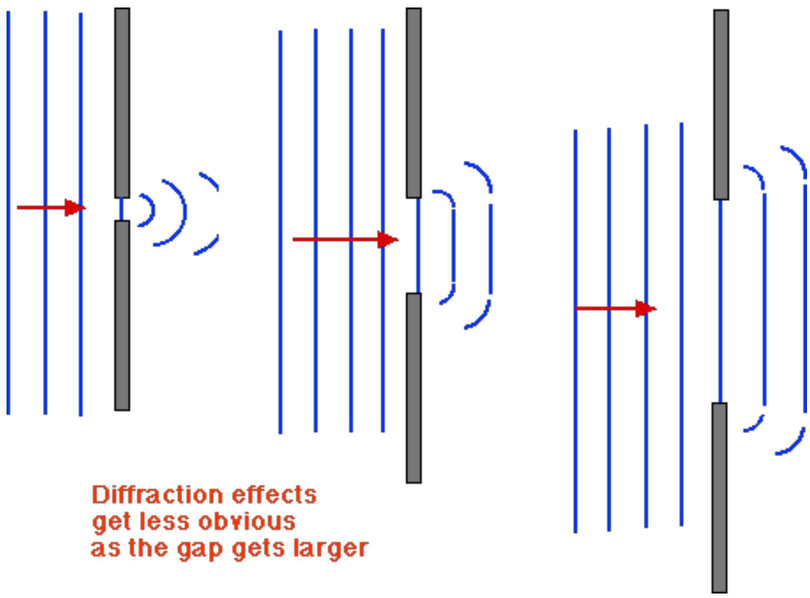
Diffraction can be clearly observed with water waves as shown in the image to the right. Notice that the parallel crests of the water waves become circular as they spread out on passing through the gap between the two harbour walls.



Sea waves incident on a breakwater are found to spread into the region behind the wall where we would expect the sea to be flat calm. This is an example of diffraction at an edge.

Diffraction will only be significant if the size of the gap or object is matched to the size of the wavelength of the waves.

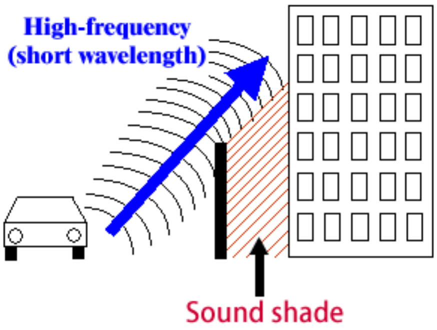
- When the size of the gap or object is **much larger than the wavelength of the waves,** the waves are only **slightly** diffracted.
- When the size of the gap or object is **nearly the same as the wavelength of the waves,** the diffraction effect is **greatest**



Waves other than water are also affected by diffraction

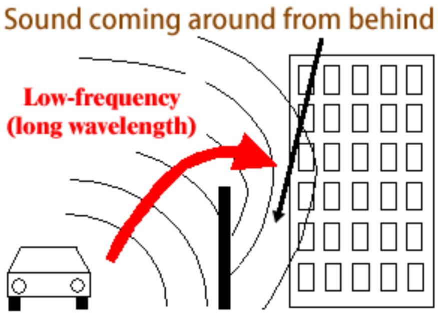
Sound

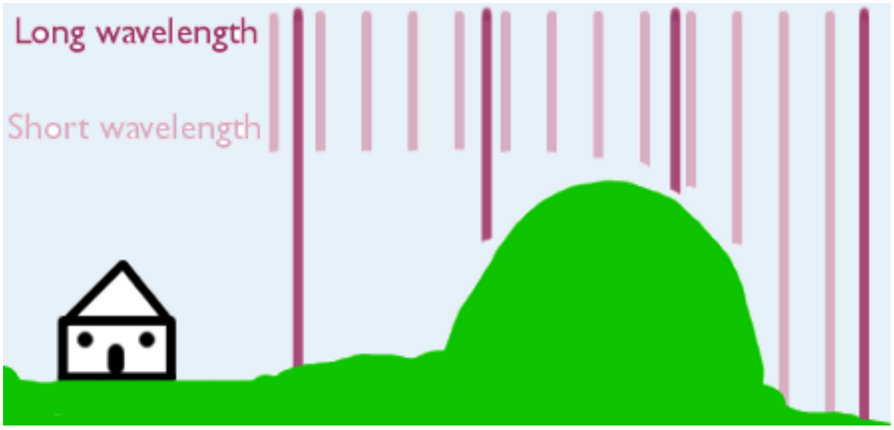
Sound can diffract through a doorway or around buildings. Lower pitched sounds travel better than high-pitched sounds. This is because low-pitched sounds have a long wavelength compared with the width of the gap, so they spread out more.



Ultrasound

Ultrasound is sound with a high frequency. It has a very short wavelength compared with most structures in the body, so there is very little spreading. This makes sharp focusing of ultrasound easier, which is good for medical scanning.





Radio waves

Long wave radio signals are much less affected by buildings and tunnels than short wave radio signals or VHF radio signals. Because of diffraction, long wave radio signals (e.g. Radio 4, λ=198 m) can sometimes be received in the shadow of hills when the equivalent VHF broadcast can not.

Light

Light has a very short wavelength compared with most everyday gaps such as windows and doors. There is little obvious diffraction, so it produces sharp shadows.

2. Electromagnetic spectrum
    2.1. Relative frequency and wavelength of bands of the electromagnetic spectrum with reference to typical sources and applications.
    2.2. Qualitative relationship between the frequency and energy associated with a form of radiation.
    2.3. All radiations in the electromagnetic spectrum travel at the speed of light.

$$v = f\lambda$$

$$E \; \alpha \; f$$

Electromagnetic spectrum

Frequency and Wavelengths

Electromagnetic waves travel through two media, electric and magnetic fields. These waves cause disturbances in the electric and magnetic fields that can exist in all space. They do not need any particles of matter in order to travel, which is why they can travel through a vacuum. Electromagnetic waves travel at a very high speed. In a vacuum this speed is three hundred million metres per second – i.e. **300 000 000 m/s or 3 x 10^8 m/s**. This is usually referred to as the speed of light and is given the symbol ***c***. This is a universal speed limit – nothing can travel faster than c.

Remember that the wave equation states

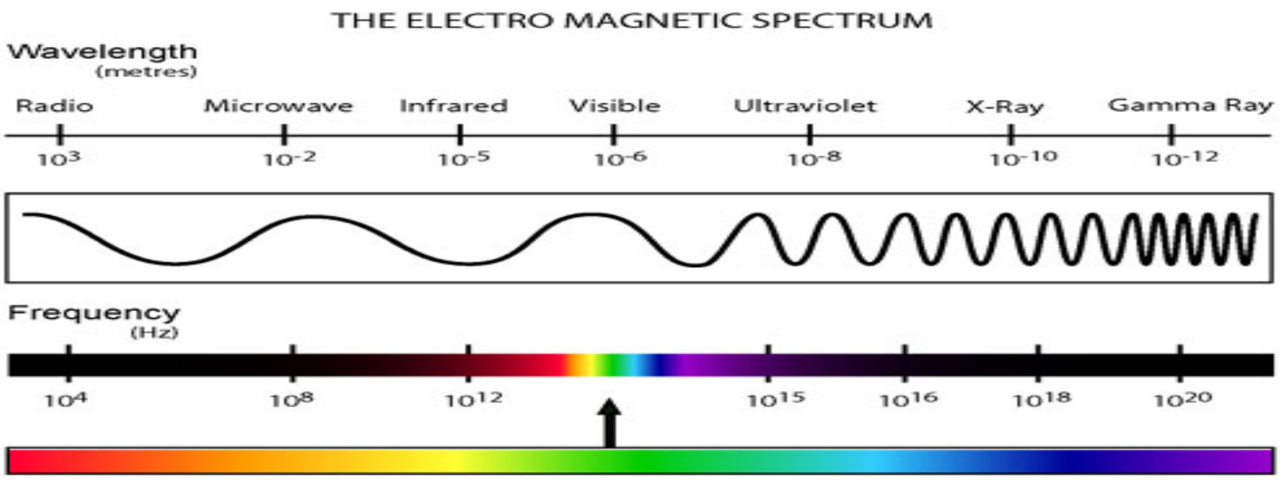
$$v = f\lambda$$

So if v is fixed, it is possible to have a whole family of electromagnetic waves whose frequencies are different but are always related by this equation, e.g. as f doubles, so λ halves such that the equation

$$c = f\lambda$$

is always true.

This family of waves is known as the electromagnetic spectrum and consists of Radio Waves, Microwaves, Infrared, Visible Light, Ultraviolet, X-Rays and Gamma Rays. The image below shows the spectrum arranged in order of increasing frequency (i.e. decreasing wavelength).



Notice how small the section is for visible light compared to the width of the whole spectrum. The colour order of the visible spectrum is expanded in the lowest section of the image and is shown in the decreasing wavelength or increasing frequency order

Red – **O**range – **Y**ellow – **G**reen - **B**lue – **I**ndigo - **V**iolet (**ROY G BIV**)

Uses and sources of electromagnetic radiation

Each member of the electromagnetic spectrum transfers energy from source to receiver/detector and as such may be called electromagnetic radiation. radiation and a typical use for each of them.

Type	Source	Typical use
Gamma Radiation	Nuclear decay, Cosmic Rays & some Stars	Killing cancer cells
X-Rays	Man-made sources & some Stars	Medical images of bones
Ultraviolet Radiation	Ultra-Hot objects, Electrical discharges/sparks, Starlight	Sunbeds
Visible Light	Very-Hot objects (lamps), Electrical discharges/sparks, Starlight	Seeing
Infrared Radiation	All hot objects, Starlight	Optical fibre communication, Remote controls, "Night" vision
Microwaves	Electrical circuits, some Stars	Cooking, Mobile Phone signals
Radio Waves	Electrical circuits, some Stars	Television signals

Frequency and Energy

A beam of electromagnetic radiation delivers energy in 'packets' called photons.
The **energy** delivered by each photon **increases with** the **frequency** of the electromagnetic waves. This means that gamma photons have the most energy, and radio photons the least.

Energy of the photon is directly proportional to frequency:

$$E \propto f$$

This important relationship is studied in greater detail in the Higher Physics course.

3. Light

- 3.1. Reflection including identification of the normal, angle of incidence and angle of reflection.
- 3.2. Refraction of light including identification of the normal, angle of incidence and angle of refraction.
- 3.3. Description of refraction in terms of change of wave speed.
- 3.4. Ray diagrams for convex and concave lenses

Light

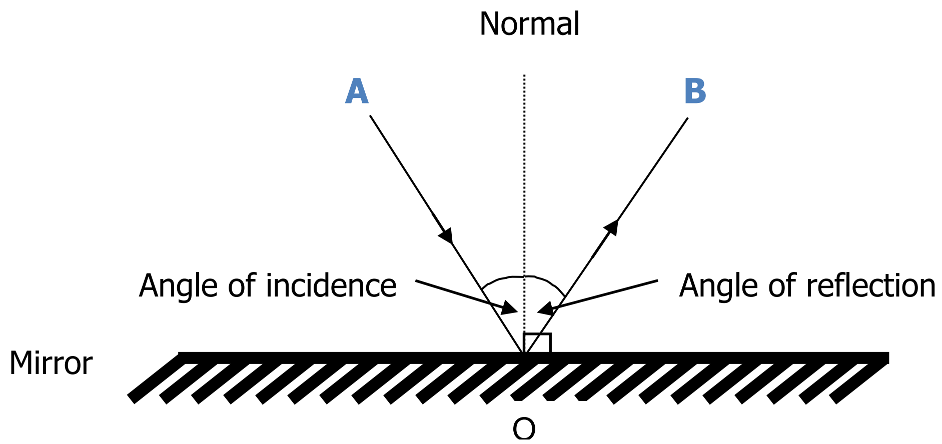
Wave behaviours

It has already been shown that waves **diffract**, or spread out, when they meet a gap or edge of an object. In addition, waves can be shown to **reflect and refract**. The next two topics of this unit cover reflection and refraction. It is particularly useful to study the reflection and refraction of visible light waves, though any waves can exhibit these phenomena.

Reflection

The diagram below shows the path of a ray of light when reflected off a mirror.
Some simple rules:

- A **ray** is a line with an arrow to show the wave direction.
- The **normal is a dotted line drawn at 90^o to the mirror** at the point where the ray of light hits the mirror.
- All angles are measured **between the ray and the normal.**
- The incoming ray is called the **incident ray** and this makes the **angle of incidence** with the normal.
- The outgoing ray is called the **reflected ray** which travels at the **angle of reflection** to the normal.

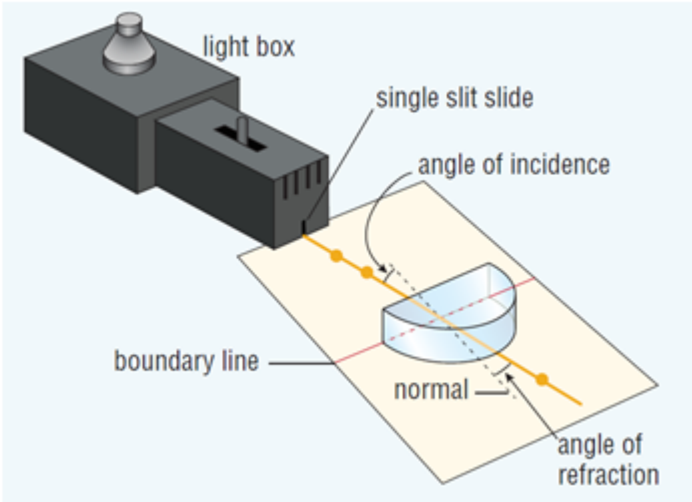


It is very important to **always put arrows** on any diagram that contains rays of light. Otherwise you would not be able to tell in which direction the light was travelling.

Refraction

The wave speed depends on the medium in which the wave travels. When a wave changes medium it's changes speed. This change of speed is called **refraction**.

In the diagram below the incident light is shown passing from air into a semicircular glass block.

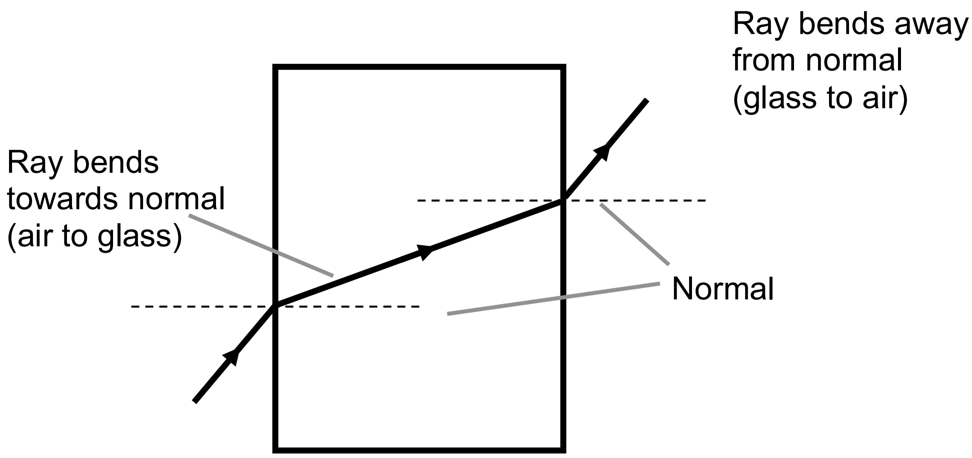


In addition to changing speed the wave changes direction inside the glass block. This change of direction only happens when the angle of incidence is non-zero, i.e. the incident ray is not along the normal. Both these changes are due to refraction.

Remember that the speed of light in a vacuum is the fastest speed possible. The speed of light in air is almost the same as in vacuum. The **light slows down as it enters the glass** and speeds up again as it leaves.

For **refraction**:

- Bigger speed = Bigger Angle between the ray and the normal
- Smaller speed = Smaller Angle between the ray and the normal



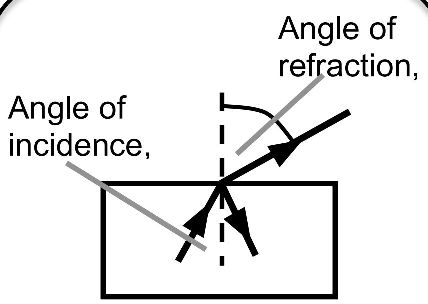
Total Internal Reflection and Critical Angle

There is a link between refraction and a phenomenon called **Total Internal Reflection.**

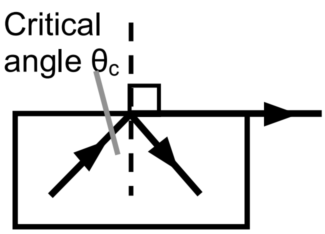
It can be shown that:

- when light travels from glass into air the direction of travel is changed (refracted) away from the normal.
- when the angle of refraction is exactly 90^0 then the angle of incidence is know as the **Critical Angle** (θ_c).
- when the angle of incidence is less than the critical angle most of the light will be refracted out into the air and some will be reflected inside the glass.
- when the angle of incidence is bigger than the critical angle the light does not pass into the air. **All** the light is **reflected** (not refracted) back into the glass.

Total Internal Reflection is used in optical instruments including periscopes, binoculars and fibre optics.



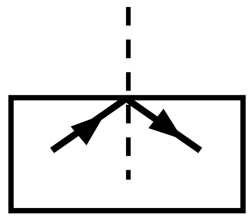
Angle of incidence is less than the critical angle.
($\theta_i < \theta_c$)



Angle of incidence is equals the critical angle.

Angle of refraction = 90^0

($\theta_i = \theta_c$)



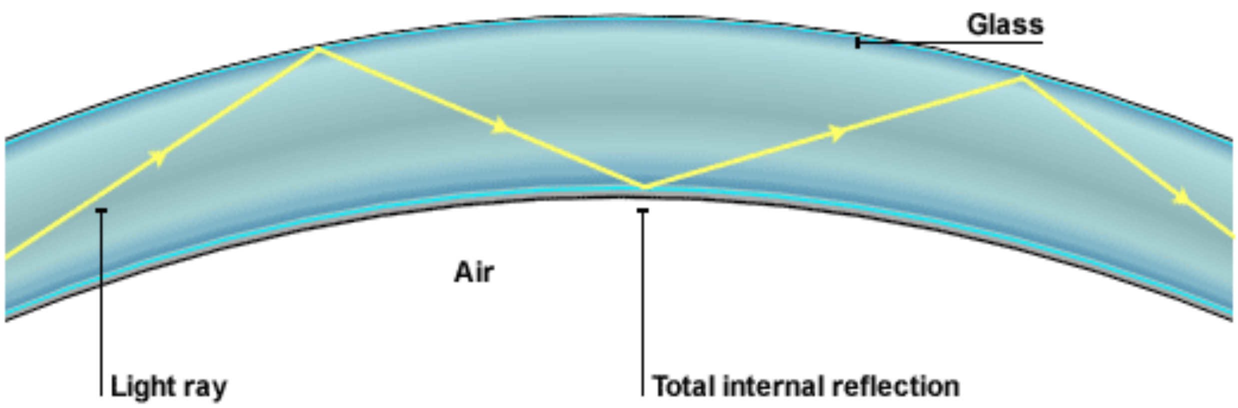
Angle of incidence is greater than the critical angle.

Ray undergoes total internal reflection.

($\theta_i > \theta_c$)

Fibre Optics

A fibre optic is a thin thread of glass. Light entering at one end always strikes the outer edges of the glass at **large angles of incidence** so that the light is always totally internally reflected back into the glass. Consequently the light never escapes and is trapped inside the glass fibre.



The fibre can be made pliable enough so that it can bend round corners. Thus, light inside the fibre optic can be made to bend round corners.

This is extremely useful:

- In medicine it is used in a "fibrescope" that allows a doctor to see inside a patient's body without having to cut them open.
- In telecommunications it is used to send pulses of laser light from one place to another, allowing enormous amounts of information to be transmitted very quickly.

Slow Down – Speed of Light in an Optic Fibre

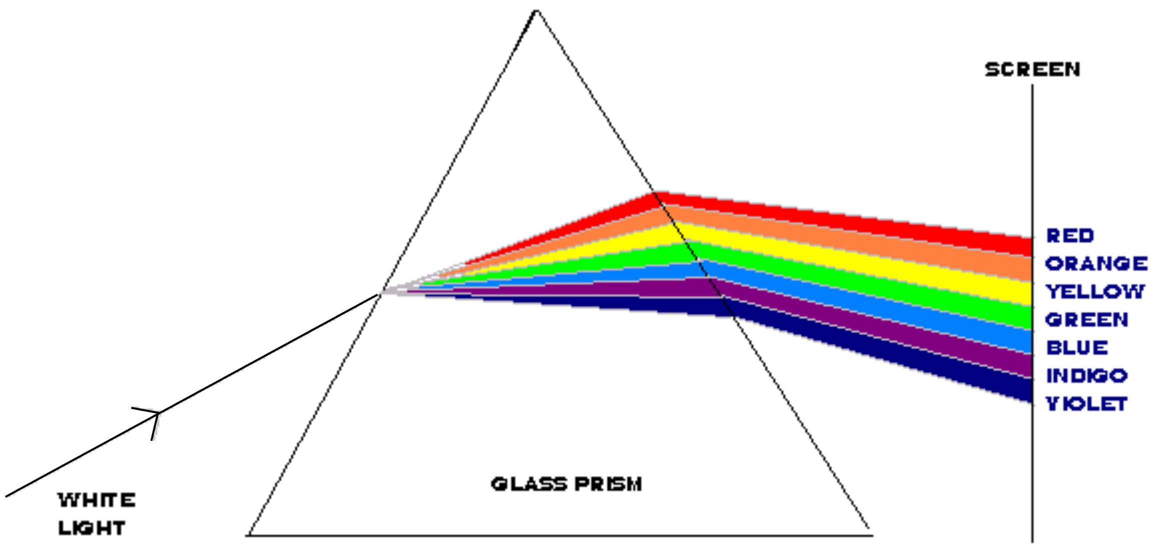
Speed of light inside a fibre optic is **2×10^8 m/s**.

If fibre optics are used in telecommunications then the information transmitted along the fibres as pulses of light will lose much less energy than if the information was transmitted using cables. As a result booster stations are required less frequently.

Refraction and frequency

The splitting of white light into different colours happens because each colour has its own unique frequency. *(All colours of light travel at the same speed)*

The amount of refraction (bending) depends on the frequency of the light and so each colour is bent by different amounts.



Dispersion of light by a prism

- **Red light** has the **lowest frequency** and so is **bent the least**.
- **Violet light** has the **highest frequency** and so is **bent the most**.

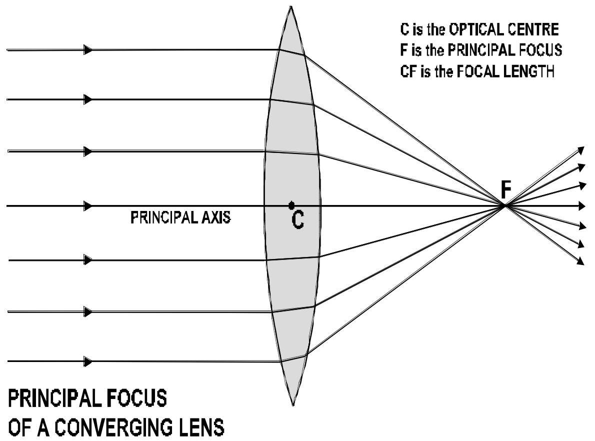
Colour	Red	Orange	Yellow	Green	Blue	Indigo	Violet
Wavelength (nm)	650	590	570	510	475	445	400
Frequency (THz)	462	508	526	588	382	674	750
Speed (m/s)	3×10^8	3×10^8	3×10^8	3×10^8	3×10^8	3×10^8	3×10^8

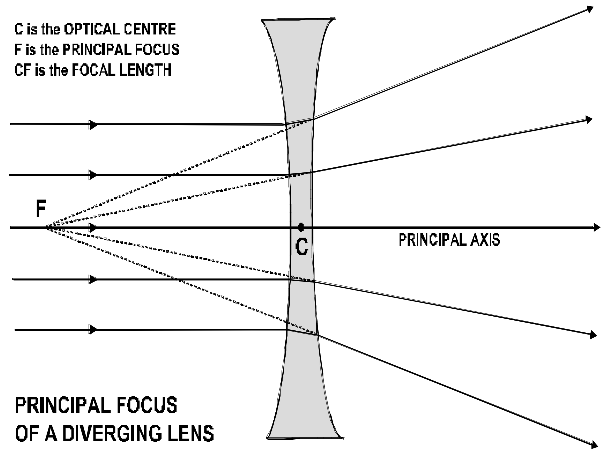
Lenses

We may make use of refraction to create lenses which alter the shape of a beam of light. There are two different types of lens.

- **Converging:** this type of lens focuses rays together**.**
- **Diverging:** this type of lens spreads rays out.

The diagrams below show rays of light approaching these two types of lens.

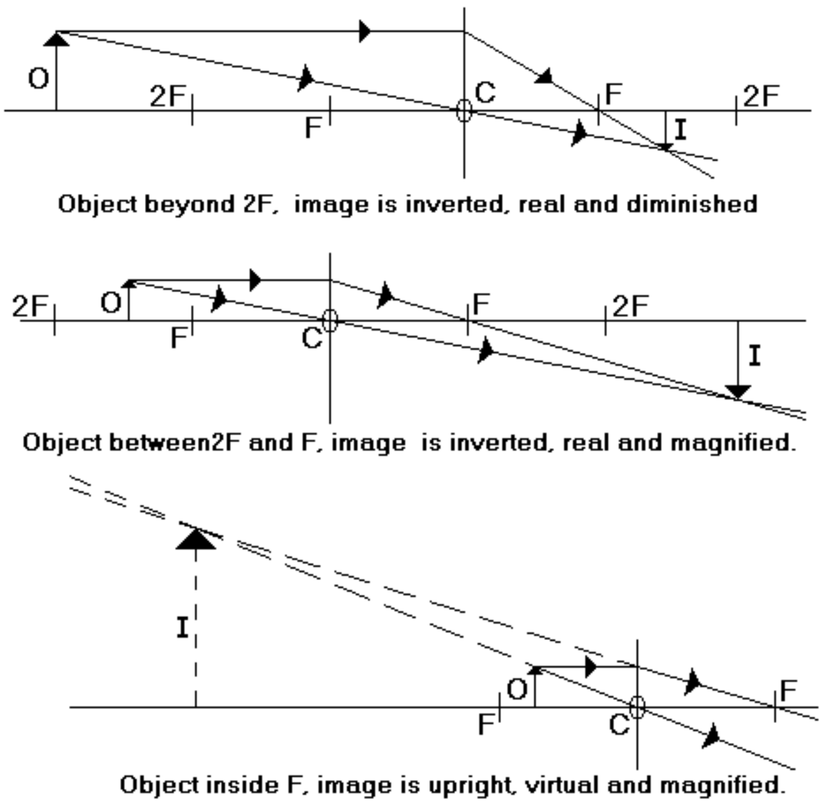




If the rays entering a lens are parallel then where they cross over is called the **principle focus.**

The distance from the centre of the lens to the principle focus is called the **focal length**.

The greater the curvature of the lens, the shorter the focal length of the lens



Images formed by convex lenses.

Tutorial Questions

The Nature of Waves

1. Explain, using a diagram, the difference between a transverse and longitudinal wave.

2. What type of waves are the following:
   - i) sound waves
   - ii) water waves
   - iii) light waves.

3. A football is stuck, floating, in the middle of a pond. The owner finds a stick and hopes to use it to retrieve the ball. He can't decide whether to throw the stick at the ball, or use the stick to make waves in the water. Which would you recommend and why?

4. Explain why sound travels quicker in solids and liquids than gases. (Hint – think about the arrangement of particles in solids and liquids compared to gases.)

5. Explain why sound cannot travel through a vacuum, like outer space.

Speed of Waves

1. Thunder is heard 20 seconds after a lightning flash. If the speed of sound is 340 m/s, how far away is the storm?

2. Explain why, during a thunderstorm, you see the lightning before you hear the thunder.

3. On a day when the speed of sound in air is 330 m/s, how long would sound take to travel a distance of 1.6 km?

4. During a thunderstorm it is noticed that the time interval between the flash of lightning and the clap of thunder gets less. What does this tell you about the storm?

5. Ten pupils are standing on Calton Hill, looking at Edinburgh Castle. They measure the time difference between seeing the smoke from the one o'clock gun and hearing the bang. The measured times are 3.8 s, 4.2 s, 4.0 s, 3.8 s, 4.4 s, 3.8 s, 4.0 s, 4.2 s, 3.6 s, and 4.2 s.
   a) Calculate the average time for the group.
   b) Calculate the distance from the Castle to Calton Hill if the speed of sound is 330 m/s.

6. An explosion in Grangemouth could be heard in South Queensferry one minute later. Given they are 20 km apart, calculate the speed of sound in air.

7. On a day when the speed of sound is 330 m/s, how long would the sound take to travel a distance of 14.85 km?

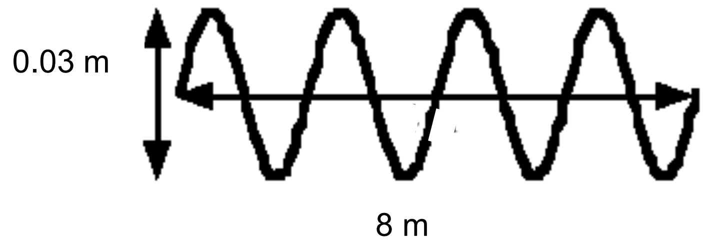
8. In a race the runners are different distances away from the starter. They will hear the starting horn at different times. Using the speed of sound as 340 m/s, calculate the time difference in hearing the horn for two runners who are 5 m and 15 m from the starter.

9. Calculate how long it would take light to travel from the sun to the earth, a distance of 1.49×10^8 km.

10. How long will it take a radio signal to travel from Britain to Australia, a distance of 1.8×10^4 km.

Wave Formulae

1. The diagram below represents a wave 0.2 s after it has started.



   Calculate the following quantities for this wave:
   a) wavelength
   b) amplitude
   c) frequency
   d) speed.

2. A swimming pool is to have a wave-making machine installed. The time taken for a wave to travel the length of the 50 m pool has to be 20 s and the wavelength has to be 4 m.
   a) Calculate the speed of the waves.
   b) Calculate the required frequency of the waves.

3. Wave A has a wavelength of 6 cm and a frequency of 50 Hz. Wave B travels 250 m in 1 minute 40 seconds. Which wave travels faster and by how much?

4. 40 waves are found to pass a point in 20 s. If the waves have a wavelength of 0.015 m, calculate their speed.

5. Calculate the wavelength of a wave of frequency 0.1 Hz and speed 5 m/s.

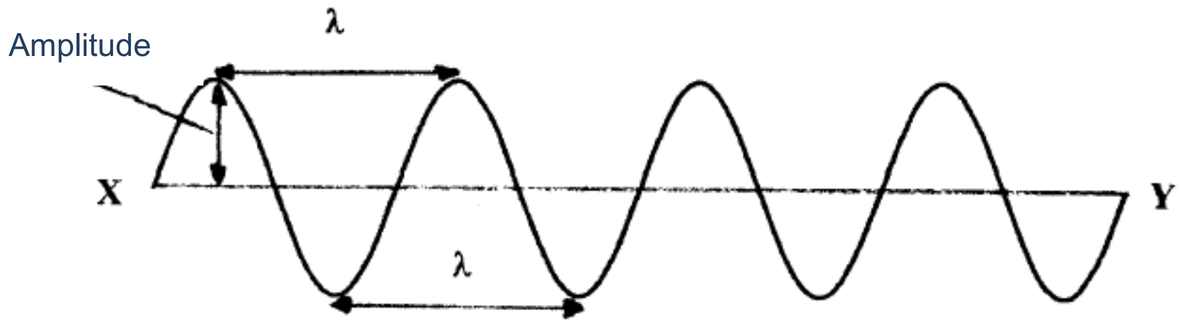
6. State what is meant by the period of a wave.

7. If the speed of a water wave is 0.6 m/s and the wavelength of each wave is 6 cm, calculate
   a) the frequency
   b) the period of the wave.

8. Waves of wavelength 5 cm travel 120 cm in one minute. Find their
   a) speed
   b) frequency
   c) period.

9. A sound generator produces 25 waves every 0.1 s. If the speed of sound is 330 m/s, find:
   a) the frequency
   b) the period of the waves
   c) the wavelength of the sound.

10. In the diagram below the distance between X and Y is 10 m.



If 20 waves pass a particular point in 5 s, find
   a) the wavelength
   b) the frequency and
   c) the period of the wave.

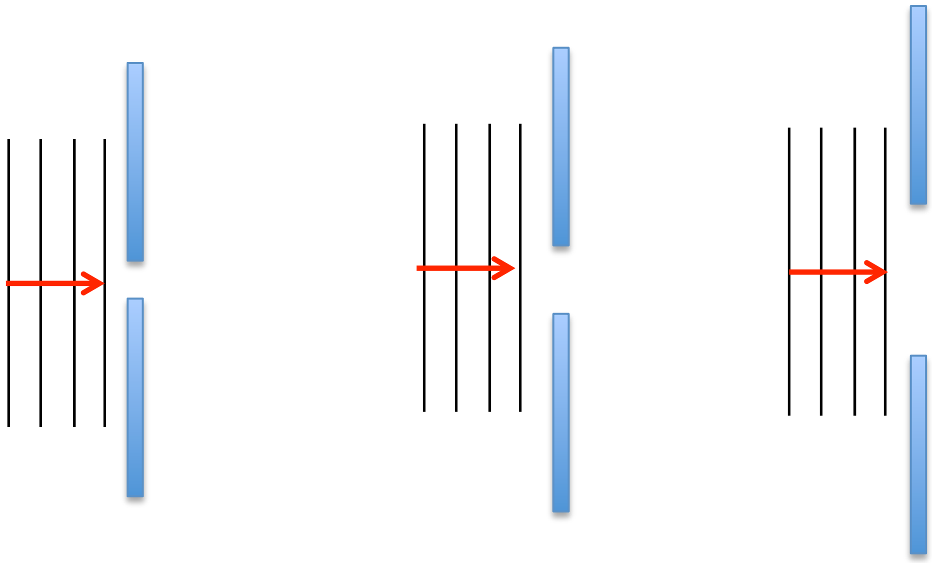
11. Tsunami is the name given to the very long waves on the ocean generated by earthquakes or other events which suddenly displace a large volume of water. The wave speed depends upon wavelength and the depth of the water for tsunamis at sea. Characteristic data is shown in the table.

Depth (metre)	Velocity (km/h)	Wavelength (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

Find the largest and smallest frequency for these tsumani waves.

Diffraction

1. Sketch the diffraction patterns formed in the following circumstances;



2. Elephants can communicate with each other across distances of several kilometres, even when there is dense vegetation in the way and they cannot see each other. They do this by making low pitched noises. How does the sound get through? Why would this not work for high-pitched sounds?

Electromagnetic Spectrum

1. Complete the following paragraph.

   The part of the electromagnetic spectrum with the longest wavelength is........1........ Between X-ray and visible light in the electromagnetic spectrum is ....2........ Radiation. Some radioactive isotopes emit ....3......... radiation. Signals can be sent from remote controls to a television by ....4....... Radiation.

2. Name a type of electromagnetic radiation that
   a) is visible to the eye
   b) is emitted by hot objects
   c) is diffracted by hills
   d) is used for imaging inside the body
   e) causes tanning
   f) kills bacteria
   g) is used by mobile phones
   h) can cook food
   i) has the highest energy
   j) has the lowest energy associated with it.

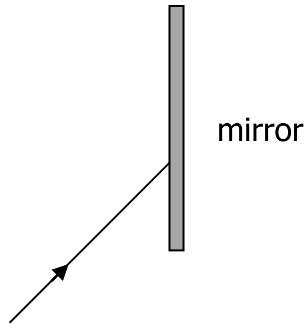
3. How far will radio waves travel in a) 2 ms b) 0.25 ms c) 1 μs.

4. Calculate the wavelength of the electromagnetic waves whose frequencies are a) 5 GHz b) 4 MHz c) 200 GHz.

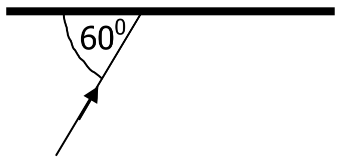
5. Calculate the transmission frequency of Radio Scotland broadcasting on 810 m on the Medium waveband. Give your answer in MHz.

Reflection Tutorial

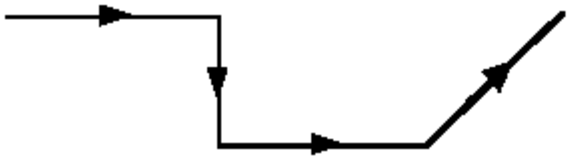
1. Complete the diagram below, labelling clearly
   a) the angle of incidence
   b) the angle of reflection
   c) the normal.



   d) What is the angle of reflection in the diagram below?



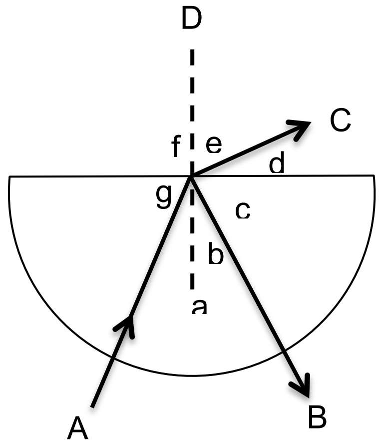
2. The diagram shows the path of a ray of light. The direction of the ray was manipulated using mirrors, but these have been left out. Complete the diagram by placing the mirrors in exactly the correct position.



Tutorial on Refraction

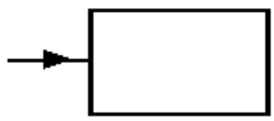
1. Identify the following on the diagram shown.

   i. the incident ray
   ii. the reflected ray
   iii. the refracted ray
   iv. the normal
   v. the angle of incidence
   vi. the angle of refraction
   vii. the angle of reflection.

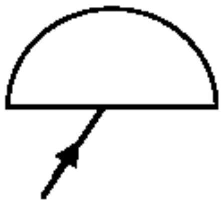


2. Complete the following diagrams to show how the rays would pass through the glass objects.

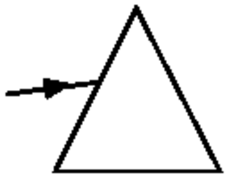
a)



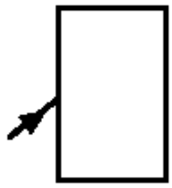
b)



c)



d)



e) For d) above, how would your diagram be different if the ray was passing into a block filled with water rather than solid glass?

Total Internal Reflection and Critical Angle

1. Describe an experiment to demonstrate total internal reflection. You should include a list of apparatus, a diagram, and an explanation of how you would use the equipment.

2. Explain, with the aid of a diagram, what is meant by 'the critical angle'.

3. a) Describe the principle of operation of an optical fibre transmission system.

   b) Optical fibre systems use repeater stations. What is the purpose of repeater stations?

   c) Light signals travel through glass at a speed of 2×10^8 m/s. How long would it take to travel between two repeater stations which were 100 km apart?

Solutions to numerical problems

The Nature of Waves

-

Speed of Waves

1. 6 800 m
2.
3. 4.8s
4.
5. a) 4.0 s
   b) 1 320 m
6. 330 ms^{-1}
7. 45 s
8. 0.3 s
9. 497 s (or 8.3 minutes)
10. 0.06 s

Wave Formulae

1. a) 2 m
   b) 0.015 m
   c) 20 Hz
   d) 40 ms^{-1}.
2. a) 2.5 ms^{-1}
   b) 0.625 Hz.
3. Wave A by 0.5 ms^{-1}
4. 0.03 ms^{-1}
5. 50 m
6. -
7. a) 10 Hz
   b) 0.1 s
8. a) 0.02 ms^{-1}
   b) 0.4 Hz
   c) 2.5 s
9. A sound generator produces 25 waves every 0.1 s. If the speed of sound is 330 m/s, find:
   a) 250 Hz
   b) 0.004 s
   c) 1.32 m
10. a) 2.5 m
    b) 4 Hz
    c) 0.24 s
11. 3.435 Hz, 3.313Hz

Diffraction

1. -
2. -

Electromagnetic Spectrum

1. -
2. -
3. a) 600 km b) 75 km c) 300 m
4. a) 0.06 m b) 4 75 m c) 0.0015 m.
5. 0.37 MHz

Reflection Tutorial

1. -
2. -

Tutorial on Refraction

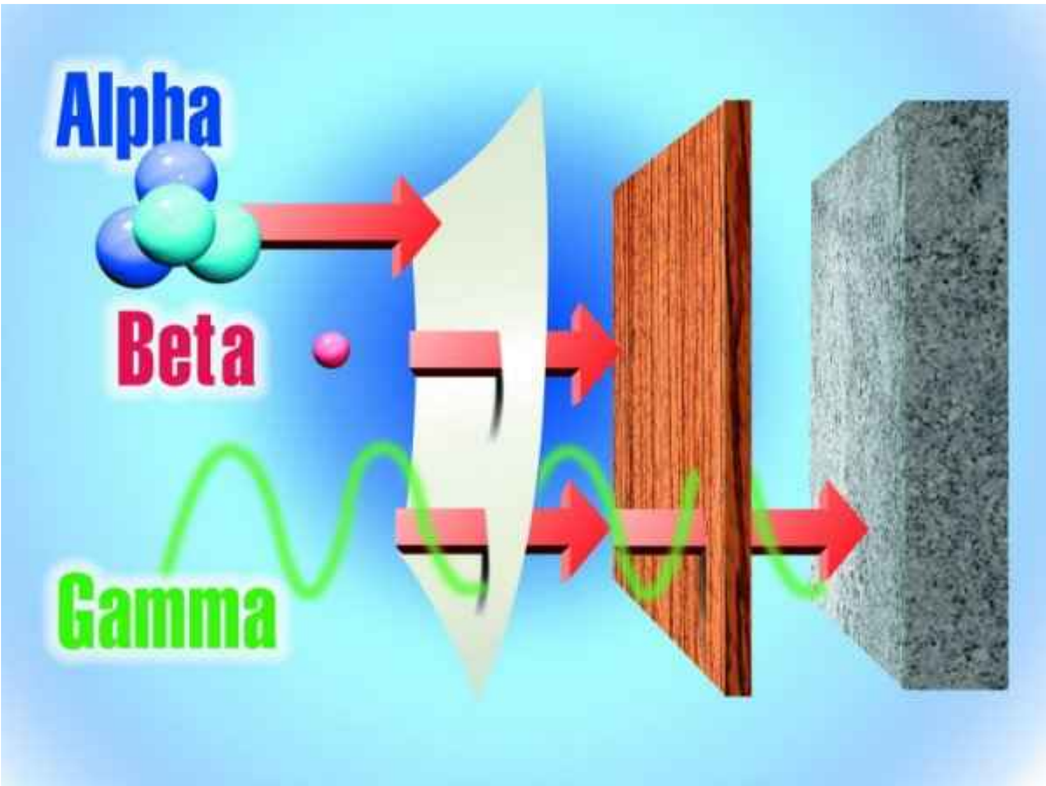
1. -
2. -

Total Internal Reflection and Critical Angle

1. -
2. -
3. a) -
   b) -
   c) 5×10^{-4} s

National 5 Physics

Radiation



Throughout the Course, appropriate attention should be given to units, prefixes and scientific notation.

Prefix	Symbol	Notation	Operation
tera	T	10^{12}	x 1,000,000,000,000
giga	G	10^{9}	x 1,000,000,000
mega	M	10^{6}	x 1,000,000
kilo	k	10^{3}	x 1,000
centi	c	10^{-2}	/100
milli	m	10^{-3}	/1,000
micro	μ	10^{-6}	/1,000,000
nano	n	10^{-9}	/1,000,000,000
pico	p	10^{-12}	/1,000,000,000,000

In this section the prefixes you will use most often are milli (m), micro (μ), kilo (k), mega (M) and giga (G). It is essential that you use these correctly in calculations.

In Physics, the standard unit for time is the **second (s)** and therefore if time is given in milliseconds (ms) or microseconds (μs) it must be converted to seconds.

Example 1
a) A wave takes 40 ms to pass a point. How many seconds is this?

40 ms = 40 milliseconds = 40 x 10^{-3} s = 40/1 000 = 0.040 seconds.

b) A faster wave travels past in a time of 852 μs, how many seconds is this?

852 μs = 852 microseconds = 852 x 10^{-6} s = 852/1 000 000 = 0.000852 seconds.

In Physics, the standard unit for distance is the **metre (m)** and therefore if distance is given in kilometres (km) it must be converted to metres.

Example 2
A wave travels 26.1 km in 0.5 ms. How far in metres has it travelled?

26.1 km = 26.1 kilometres = 26.1 x 10^{3} m = 26.1 x 1 000 = 26 100 metres.

This unit involves calculations which use the term frequency, frequency has units of **hertz** (Hz) although often we meet the terms Megahertz and Gigahertz.

Example 3
A wave has a frequency of 99.5 MHz. How many Hz is this?

99.5 MHz = 99.5 Megahertz = 99.5 x 10^{6} Hz = 99.5 x 1 000 000 = 99 500 000 Hertz.

National 5 Physics

Dynamics and Space

Contents

Nuclear radiation

3.5. The nature of alpha, beta and gamma radiation: relative effect of ionisation, absorption, shielding.
3.6. Background radiation sources.
3.7. Absorbed dose, equivalent dose and comparison of equivalent dose due to a variety of natural and artificial sources.
3.8. Applications of nuclear radiation.
3.9. Activity in Becquerels.
3.10. Half-life and use of graphical or numerical data to determine the half-life.
3.11. A qualitative description of fission and fusion, emphasising the importance of these processes in the generation of energy.

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

$$H = D\,\omega_R$$

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

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

The nature of Nuclear radiations

Atoms

Every substance is made up of atoms.

Atoms are the smallest possible particle of the simple substances (the elements – see periodic table) that make up everything around us. Each element is made up of the one kind of atom. All atoms of one element are identical to one another, but they are different to atoms of other elements. This is because they are made from different combinations of **electrons, protons and neutrons.**

Inside each atom there is a small dense central part called the nucleus. The nucleus contains two particles:

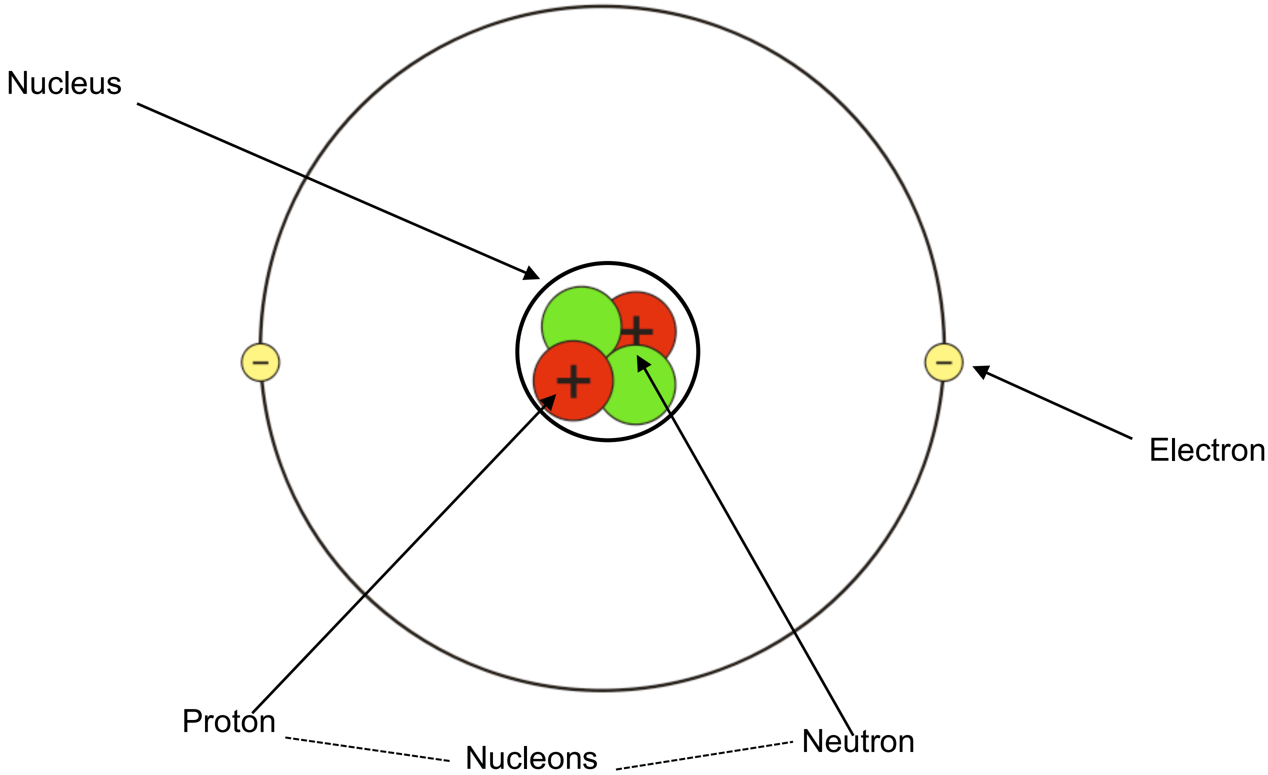
- **protons**: these have a positive charge
- **neutrons**: these have no charge.

Together protons and neutrons are called **nucleons.**

Surrounding the nucleus are negatively charged **electrons.** The electrons go round the nucleus in orbits. An **uncharged** atom will have the same number of protons and electrons. Sometimes different atoms are combined together to form compounds.

Example - Helium

This has two neutrons and two protons in the nucleus, and as it is uncharged there will be two electrons orbiting the nucleus.
This can be represented as:



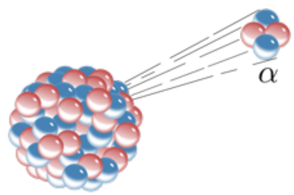
Nuclear Radiation (Alpha, Beta And Gamma)

There are some atoms which have unstable nuclei. (*Nuclei is the plural of nucleus).*
Everything in nature prefers to be in a stable state of minimum energy. The unstable nuclei are unstable because they have too much energy. They get rid of this energy by emitting some form of radiation (either particles or electromagnetic waves). This radiation is **nuclear radiation** because it comes from the **nucleus** of an atom. These atoms are said to be **radioactive**.
There are three types of nuclear radiation:

- α (alpha) particles
- β (beta) particles
- γ (gamma) rays

When α, β or γ are emitted from the nucleus energy is also released. This energy is usually absorbed by the medium through which the radiation is passing.

Alpha particles α



They consist of 2 neutrons and 2 protons and are therefore positively charged with a charge of +2e (where e is the size of the charge on an electron, i.e 1.6×10^{-19} C). So they have the same structure as the nucleus of a helium atom.

Symbol: ${}^{4}_{2}\alpha$

Beta particles β

They are fast moving electrons with a charge of -1e. Note that they come **from the nucleus** of an atom. They are caused by the break up of a neutron into a positively charged proton and a negatively charged electron.

Symbol: ${}^{0}_{-1}\beta$

Gamma rays γ

They are caused by energy changes in the nucleus. Gamma rays are high frequency waves which are part of the electromagnetic spectrum.
Often the gamma rays are sent out at the same time as alpha or beta particles. Gamma rays have neither mass nor charge but carry energy from the nucleus leaving the nucleus in a more stable state.

Symbol: γ

Ionising effect of Nuclear Radiation

Ionisation

If the number of electrons is equal to the number of protons then the **Atom** is uncharged and is electrically neutral.
However, atoms can gain or lose electrons, this increases or decreases the negative charge.

- Ionisation is the addition or removal of an electron from an **Atom** to create an **Ion**.
- Losing an electron creates a **Positive Ion**.
- Gaining an electron creates a **Negative Ion**.

Alpha or beta particles are charged. When they pass nearby other atoms they tend to cause it to lose electrons so that it becomes ionised. Gamma rays do not directly ionise other atoms, although they may cause atoms to emit other particles which will then cause ionisation. As a result, nuclear radiation is sometimes **Ionising** Radiation.

Because of the differences in the charges they carry, the ionising effect of the three types of nuclear radiation is different.

- α particles: highly ionising
- β particles: ionising
- γ rays: very weakly ionising

Penetrating ability and Absorption

The penetrating ability and ionising ability of nuclear radiation are linked. The radiation continues to penetrate matter until it has dissipated all of its energy.

Alpha particles are the least penetrating, as they are the most highly ionising. They are absorbed by 10 cm of air; 0.01 mm lead or a sheet of paper. This means that if a given number of alphas are fired at a target they will all cause ionisation near the surface of the material, resulting in the effects of the radiation being concentrated in a small volume. The double charge and relatively high mass of the alpha explains why the impact on matter is so great.

Beta particles can penetrate quite deeply into matter before its energy has been absorbed. Its penetrating power is therefore moderate (absorbed by 1m air, 0.1 mm lead or 3mm aluminium sheet). Beta particles have only about 1/8000 of the mass of an alpha particle and only half of the charge. Therefore its interaction with matter as it passes through is far less severe and so the effects of its interaction (ionisation) are much more spread out.

Gamma Rays have an ionising ability so low that they penetrate very deeply into matter before most of the energy has been absorbed. Their penetrating ability is therefore very high (about 99.9% is absorbed by 1 km of air or 10 cm lead). Gamma rays are pure energy - no charge and no mass - therefore their interaction with matter is much less than the other two.

Summary of nuclear radiation properties

	Alpha particle	Beta particle	Gamma ray
Mass *(amu)*	4	1/2000	0
Charge	+2e	-1e	0
Speed	slow	fast (almost speed of light)	very fast (speed of light)
Ionising ability	high	medium	0
Penetrating power	low	medium	high
Stopped by:	paper	aluminium	lead

1 amu = 1 atomic mass unit (1.66×10^{-27} kg): 1 e = electron charge (1.6×10^{-19} C)

Sources of Nuclear Radiation

Nuclear radiation is a naturally occurring phenomenon and so the sources of this radiation are all around us. This is known as **Background Radiation.**

Background radiation is made up of natural and artificial (man-made) sources. The majority of the background is natural. Artificial sources of background account for about 15% of the total and most of this comes from medical examinations, such as X-rays and other scans.

Natural Sources

Naturally occurring nuclear radiation comes from radioactive substances including the ground, the air, building materials and food. Radiation is also found in the cosmic rays from space.

Source	Type of Radiation
Cosmic Rays	Radiation that reaches the Earth from outer space
Animals	All animals emit natural levels of radiation
Rocks	Some rocks give off radioactive radon gas
Soil and Plants	Radioactive materials from rocks in the ground are absorbed by the soil and hence passed on to plants

Dosimetry

Absorbed Dose (D)

Damage can be done to the body due to the energy absorbed from nuclear radiation as it penetrates the body.
The greater the absorbed energy, the greater the damage is likely to be. The absorbed dose, D, is defined as the energy absorbed per unit mass of the absorbing material

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

Symbol	Name	Unit	Unit Symbol
D	Absorbed dose	gray	G
E	Energy absorbed	joule	J
m	Mass	kilogram	kg

Equivalent Dose (H)

As we have seen above, the different types of nuclear radiation have different penetrating and ionising powers. In order to compare the effects of the same absorbed dose but with different radiation types it is necessary to weight these differing penetrating and ionising powers. This is done using a number known as Radiation **Weighting Factor (ω_R).** The radiation weighting factor is simply a scale factor, which indicates the ability of a particular type of radiation to cause damage.

Equivalent Dose, H, combines the Absorbed Dose information with the Radiation Weighting Factor to give a more accurate "picture" of the potential harm that could be done by radiation using the equation.

$$H = D\,\omega_R$$

Symbol	Name	Unit	Unit Symbol
D	Absorbed dose	gray	G
H	Equivalent dose	sievert	Sv
ω_R	Weighting Factor	n/a	

Radiation Weighting Factor (ω_R)

Do not forget that biological harm from exposure to radiation depends on:

- the absorbed dose
- the kind of radiation (e.g. α particles are highly ionising)

These two are combined in the Equivalent Dose value in Sieverts.

Radiation Type	ω_R
X-rays	1
γ- rays	1
β particles	1
thermal neutrons	3
fast neutrons	10
α particles	20

The overall biological effect must also take account of the body organs or tissues exposed.

Equivalent Dose Rate

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.

The equivalent dose rate is defined by the equation

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

Symbol	Name	Unit	Unit Symbol
H	Equivalent dose	sievert	G
H	Equivalent dose rate	sievert per second	Sv/s
t	Time of exposure	seconds	s

Equivalent dose rate can be quoted in a variety of units -sieverts/millisieverts/microsieverts per second/minute/hour. Make sure that the units you use in any problem are consistent.

Dose from natural background radiation

Radiation has always been present all around us. In fact, life has evolved in a world containing significant levels of ionising radiation. It comes from space, the ground, and even within our bodies. The doses due to natural background radiation vary depending on location and habits.

Dose from cosmic radiation

Regions at higher altitudes receive more cosmic radiation. The worldwide annual average equivalent dose from cosmic rays is about 0.40 mSv, although this varies from 0.30 mSv (sea level) to 0.84 mSv at the top of Mount Lorne, Yukon (2000 m). Air travel also increases exposure to more cosmic radiation, adding a further average annual dose of 0.018 mSv per person in the developed world.

Dose from terrestrial radiation

There are also natural sources of radiation in the ground. The worldwide average effective dose from the radiation emitted from the soil (and other materials that come from the ground) is approximately 0.5 mSv a year. However, the dose varies depending on location and geology, with doses reaching as high as 260 mSv in Northern Iran or 90 mSv in Nigeria.

Dose from inhalation

Radon gas, which is produced by the earth, is present in the air we breathe. Radon gas naturally disperses as it enters the atmosphere from the ground. However, when radon gas enters a building (through the floor from the ground), the concentration tends to build up. The worldwide average annual effective dose of radon radiation is approximately 1.2 mSv.

Dose from ingestion

There are a number of sources of natural radiation that penetrate our bodies through the food we eat, the air we breathe and the water we drink. Potassium-40 is the main source of internal irradiation (found in Brazil nuts, Lima Beans, Bananas, Carrots, Potatoes, Lo-Sodium Salt). The worldwide average effective dose from these sources is approximately 0.3 mSv a year.

Dose from artificial background radiation

Most artificial sources are related to medical procedures. The table shows the absorbed doses involved. Notice that the highly medically effective procedures such as CT scanning come at a "cost" of radiation exposure.

Nuclear weapon testing, the Chernobyl disaster and Nuclear Power generation add a further 7.2 μSv to the worldwide average equivalent dose.

Study Type	Dose (mSv)
Dental X-ray	0.01
Chest X-ray	0.1
Screening mammography	3
Adult abdominal CT	10
Neonatal abdominal CT	20

Medical Uses of Nuclear Radiation[2]

It can be seen from the annual equivalent dose numbers above that the primary source of artificial nuclear radiation is in medicine — for diagnosis and therapy. Both are intended to benefit patients and, as with any use of radiation, the benefit must outweigh the risk.

Diagnosis

Most people at some time in their lives have an X ray examination to help diagnose disease or damage in the body. A much less common diagnostic procedure involves the introduction of radionuclides inside patients so that detectors outside the body can be used to observe how organs are functioning. Radiation doses are generally low, although they can be appreciable in certain procedures.

Therapy[3]

Much higher doses are required to treat malignant diseases or malfunctioning organs sometimes in combination with other forms of treatment.

- **outside the body** (external radiotherapy) - using X-rays, electrons or, in rare cases, other particles such as protons; external radiotherapy is usually given once a day as a course of treatment over a number of days or weeks
- **within the body** (internal radiotherapy, also known as brachytherapy) - either by drinking a liquid that is absorbed by the cancerous cells or by putting radioactive material into, or close to, the tumour, usually for a small number of treatments (brachytherapy) or by injecting or drinking a liquid that is absorbed by the cancerous cells - for example, radioiodine for thyroid cancer.

[2] http://www.iaea.org/Publications/Booklets/RadPeopleEnv/indx.html
[3] http://www.nhs.uk/conditions/Radiotherapy/Pages/Introduction.aspx

Industrial Uses of Nuclear Radiation

In industry, radiation is used in quality control of materials, measuring the level of containers, or monitoring the thickness or consistency of paper, for example. Devices which monitor industrial processes consist of radiation sources and detectors. When the material between the radioactive source and the detector changes thickness or density, the level of radiation detected also changes. The process can be controlled by weakening or strengthening the signal from the detector.

Radiography

This is a method of non-destructive testing, used to check for flaws in metal structures and welding seals, among others. The principle is the same as in medical imaging: radiation passes through the object to be tested and exposes the X-ray film placed behind it. Dark patches in the developed film reveal flaws. Radiography devices create radiation using either X-ray machines, or for thicker material, a gamma source or linear accelerator.

Tracers

Radioactive isotopes are used as tracers in many biochemical and physical examinations. The path of material marked with radioactive tracers is monitored with a detector. Radioactive isotopes of carbon and hydrogen can be used to examine the path of nutrients into plants, for example. Also radioisotopes are used to detect leaking pipes. To do this, a small amount of a gamma emitter is injected into the pipe. The radiation is then detected with a GM counter above ground.

Sterilisation

Gamma rays can be used to kill bacteria, mould and insects in food. This process prolongs the shelf life of the food, but sometimes changes the taste. Gamma rays are also used to sterilise hospital equipment, especially plastic syringes that would be damaged if heated.

Dating

Because the radioactive half-life of a given radioisotope is not affected by the environment radioactive samples continue to decay at a predictable rate, i.e. any radioactive nucleus acts as a clock. Organic materials may be dated using Carbon-14 content whilst longer-lived isotopes in rocks and minerals provide evidence of long timescales in geological processes.

Activity

Some materials are radioactive because their nuclei are unstable. It is impossible to tell when a particular nucleus will break apart. What we can measure is the number of nuclei (N) in a quantity of a radioactive substance that will decay in a particular time (t). The activity of any radioactive substance is the rate at which it decays and is defined by the equation

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

Symbol	Name	Unit	Unit Symbol
A	Activity	becquerel	Bq
N	Total count	n/a	
t	Time	second	s

Activity is measured in becquerel (Bq) where one Bq is one nucleus decaying every second. Activity relates to a quantity of a radioactive substance. It is meaningless to refer to the 'activity of uranium oxide' for example, since the activity depends on how much of the substance is present. Radioactive decay happens spontaneously. The number of nuclei in a quantity of radioactive substance still to decay depends on how many have already decayed. Because of these factors, activity is not constant over time.

Background Activity

Radiation from natural sources and man made sources are around us all the time. This is called Background Activity - it's very low level, usually less than 1 Bq. However, if you were to measure the activity of a source, you would also be measuring the background activity. To ensure that you calculate the correct activity for a source, the average background activity must first be measured and then deducted from the measured activity.

Measuring Activity

The ionising effect of radiation is used in the Geiger-Muller (GM) tube as a means of detecting the radiation. The GM tube is a hollow cylinder filled with a gas at low pressure. The tube has a thin window made of mica at one end. There is a central electrode inside the GM tube. A voltage supply is connected across the casing of the tube and the central electrode as shown in the following diagram. When nuclear radiation enters the tube it produces ions in the gas allowing it to conduct which produces a voltage pulse. Each voltage pulse corresponds to one ionising radiation entering the GM tube. The voltage pulse is amplified and counted. The greater the amount of radiation, the more ionisation in the tube so the greater the rate of counts. The activity of a substance is the number of counts or ionisations per second.

Half-life ($t_{1/2}$)

Radioactive decay involves a change from a high energy state to a lower energy state for the individual atoms involved. As a result of decay then there are fewer high energy, radioactive atoms. This means the overall activity will decrease over time as fewer candidate atoms are available to decay.

Radioactive decay is a random process. This means that for a radioactive source, it is not possible to predict when an atom will decay. Each atom has an equal probability to be the next atom to decay. In any radioactive source, the activity decreases with time because the number of unstable atoms gradually decreases leaving fewer atoms to decay.

The **half-life** of a radioactive source is **the time for the activity to fall to half its original value**. Half-life is measured in units of time. This may be seconds, minutes, days or years.

Using a graph of activity versus time, it is possible to calculate the half-life of a radioactive source.

The count rate drops from 80 to 40 in two days. In the next two days, it drops from 40 to 20 - it halves. In the two days after that, it drops from 20 to 10 - it halves again - and so on. So the half life,
$t_{1/2}$ = 2 days

$t_{½}$ should be the same value no matter which starting activity is selected.

Corrected count rate

When making accurate measurements of the decay of a radioactive source you must always use the corrected count rate. This is the count rate that is due to the source alone and not including any background radiation.

From the diagram it can be seen that incorrectly using the total count curve gives an erroneously large value for $t_{1/2}$

corrected count = total count – average background count

Examples

1. A Geiger-Muller tube and ratemeter were used to measure the half-life of radioactive caesium-140. The activity of the source was noted every 60 s. The results are shown in the table. By plotting a suitable graph, find the half-life of caesium-140.

Time (s)	0	60	120	180	240	300	360
Corrected count rate (counts/s)	70	50	35	25	20	15	10

From ***the best-fit line*** on the graph the time taken to fall from

- 70 counts/s to 35 counts/s = 125 s
- 35 counts/s to 17.5 counts/s = 125 s

Average half-life of caesium-140 = 125 s.

2. The activity of a source falls from 80 MBq to 5 MBq in 8 days. Calculate its half-life.

Count Rate (MBq)	Number of $t_{1/2}$
80	0
40	1
20	2
10	3
5	4

There are 4 x $t_{1/2}$ in 8 days. Therefore $t_{1/2}$ = 8/4 = 2 days

Or

80 40 20 10 5

This takes 4 half-lives (count the arrows) = 8 days.
So one half-life, $t_{1/2}$ = 8/4 = 2 days

Nuclear Fission and Fusion

Nuclear Power Stations

A nuclear power station is similar to a coal or oil fired power station, but the fuel used to produce the heat is uranium or plutonium. The particles (or atoms) of the uranium or plutonium are spilt into smaller particles in a nuclear reactor.
This is called FISSION. *(See later notes).*

When the atoms split a large amount of heat is produced, which is used to turn water into steam. In turn the steam is used to spin a turbine, which turns a generator to produce electricity.

Although nuclear power stations can produce large amounts of electricity, with no further use of fossil fuels there are other dangers involved.

Advantages of Using Nuclear Power to Produce Electricity

- Fossil fuels are running out, so nuclear power provides a convenient way of producing electricity.

- A nuclear power station needs very little fuel compared with a coal or oil-fired power station. A tonne of uranium gives as much energy as 25000 tonnes of coal.

- Unlike fossil fuels, nuclear fuel does not release large quantities of greenhouse gases or sulphur dioxide (a cause of acid rain) into the atmosphere.

- A country may not want to be reliant on imports of fossil fuels. If a country has no fossil fuels of its own it might use nuclear power for security reasons.

Disadvantages of Using Nuclear Power to Produce Electricity

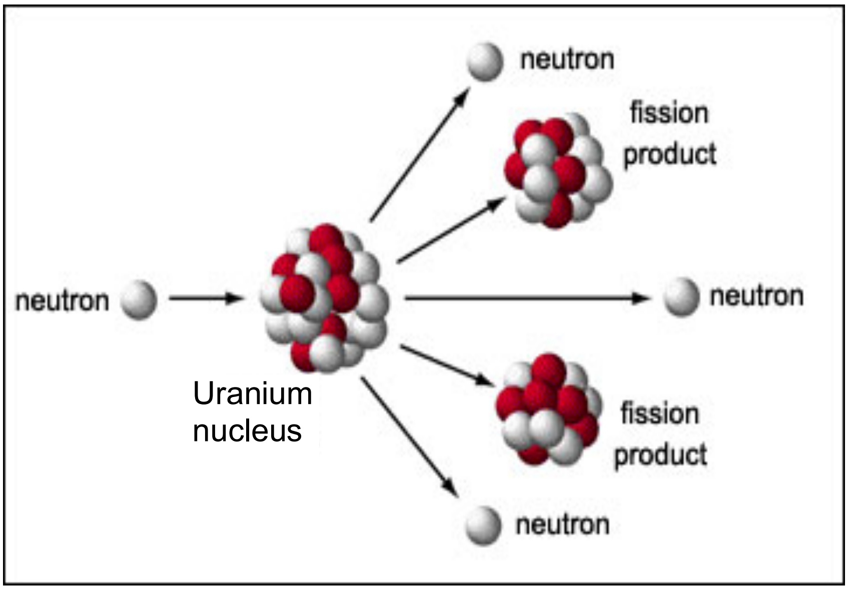
- A serious accident in a nuclear power station is a major disaster. British nuclear reactors cannot blow up like a nuclear bomb but even a conventional explosion can possibly release tonnes of radioactive materials into the atmosphere. (The Chernobyl disaster was an example of a serious accident.)

- Nuclear power stations produce radioactive waste, some of which is very difficult to deal with. Nobody wants radioactive waste stored near them.

- After a few decades nuclear power stations themselves will have to be decommissioned.

Nuclear Fission

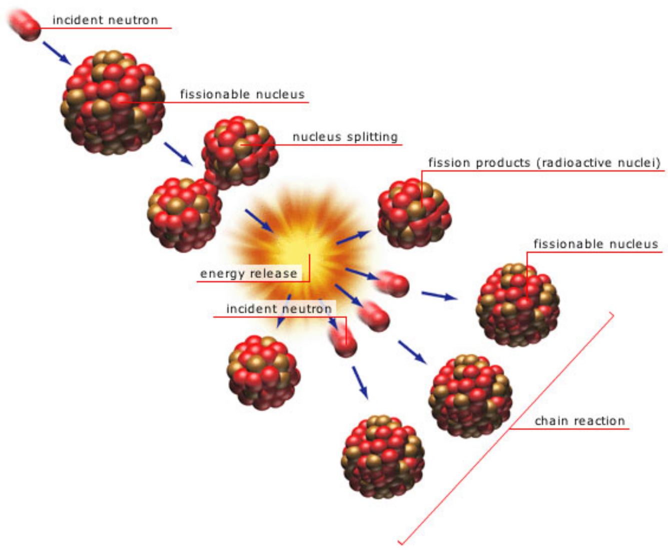
Nuclear fission is the process in which one nucleus splits into more than one nuclei, leading to formation of other elements and the release of energy in the process. There are two types of nuclear fission: spontaneous and stimulated fission. Some heavy nuclei are not stable so they will undergo **spontaneous fission** and give lighter nuclei.



Sometimes fission is **stimulated** by collisions with other particles. For example, the fission of uranium 235 in nuclear reactors is started by the collisions with neutrons. If a neutron is fired into the nucleus of a uranium 235 atom, the atom will split into two new nuclei emitting further neutrons and releasing energy in the form of heat (i.e. the kinetic energy of the emitted nuclei).

This splitting of the atom is known as **STIMULATED NUCLEAR FISSION. The new nuclei are known as fission fragments.** The emitted neutrons hit other atoms causing them to split.

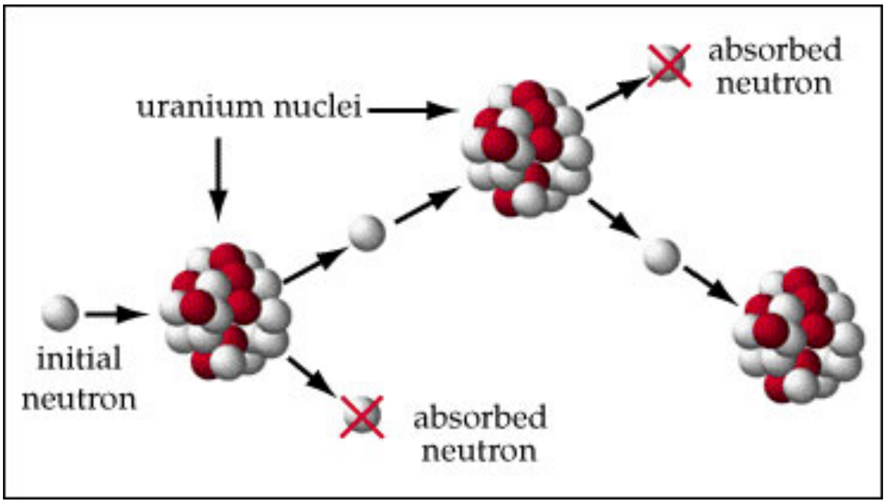
If this process keeps going, a **CHAIN REACTION** results giving out huge amounts of energy in a way which is difficult to control.



In a **nuclear reactor**, the chain reaction is controlled by **control rods** and the **moderator.**

Fission reactions take place only if the neutrons are travelling slow enough to be ‘captured’ by the atom. **Collisions with the moderator** will **slow down** the **fast neutrons** and **allow more fission** to take place. **Control rods** absorb neutrons. This will allow the reactor to produce energy at a steady rate.

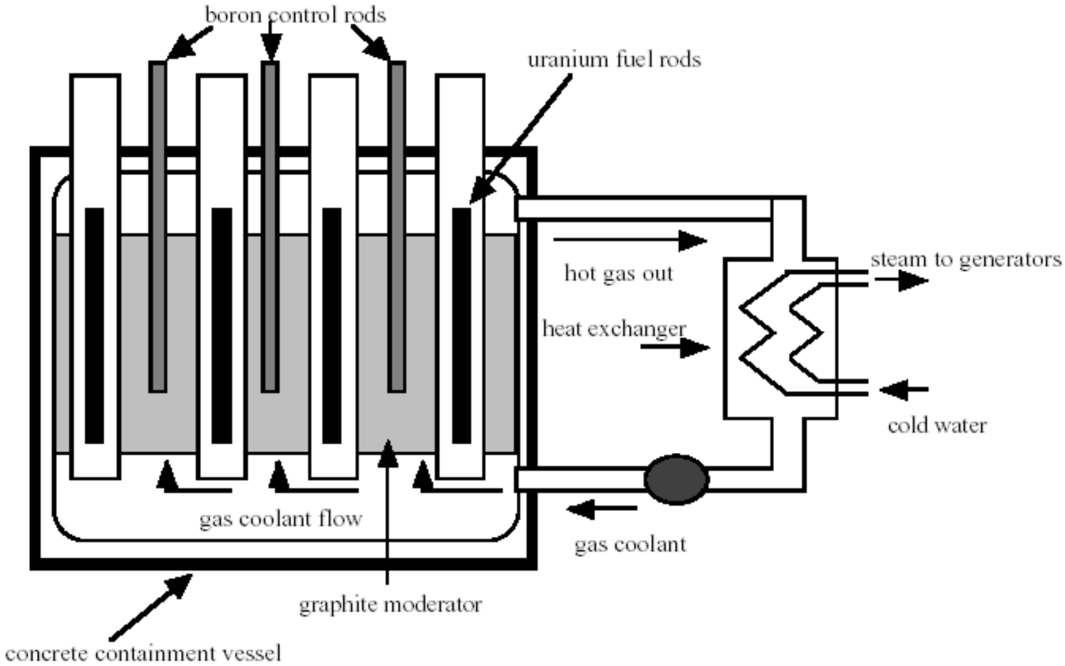
In a controlled chain reaction, on average only one neutron from each fission will strike another nucleus and cause further stimulated fission to occur.



In an uncontrolled chain reaction all the neutrons from each fission strike other nuclei producing a large surge of energy. This occurs in atomic bombs.

The Nuclear Reactor

There are five main parts of a reactor as shown in the diagram below:



- The **fuel rods** are made of uranium-238 enriched with uranium-235. They release energy by fission.

- The **moderator**, normally made of graphite, has the fuel rods embedded in it. The purpose of the moderator is to **slow down** the neutrons that are produced in fission, since a nucleus is split more easily by slow moving neutrons.

- The **control rods** are normally made of boron, and they control the rate of production of energy. The boron rods **absorb** neutrons, so by lowering the control rods into the reactor, the reaction can be slowed down. In the event of an emergency the control rods are pushed right into the core of the reactor and the chain reaction stops completely.

- A **cooling system** is needed to cool the reactor and to transfer heat to the boilers in order to generate electricity. The diagram shows the original British gas-cooled reactor design which used carbon dioxide gas as a coolant. Other systems have used water and some even use liquid sodium metal as the coolant material.

- The **containment vessel** is made of thick concrete which acts as a shield to absorb neutrons and other types of radiation.

Radioactive Waste

Nuclear power stations unfortunately produce dangerous radioactive waste materials, some of which have half-lives of hundreds of years. When the used fuel is taken out of the reactor core, all the dangerous waste materials must be safely stored until its radioactivity reaches a safe level.
These waste products are first set in concrete and steel containers then buried deep under ground or dropped to the bottom of the sea.

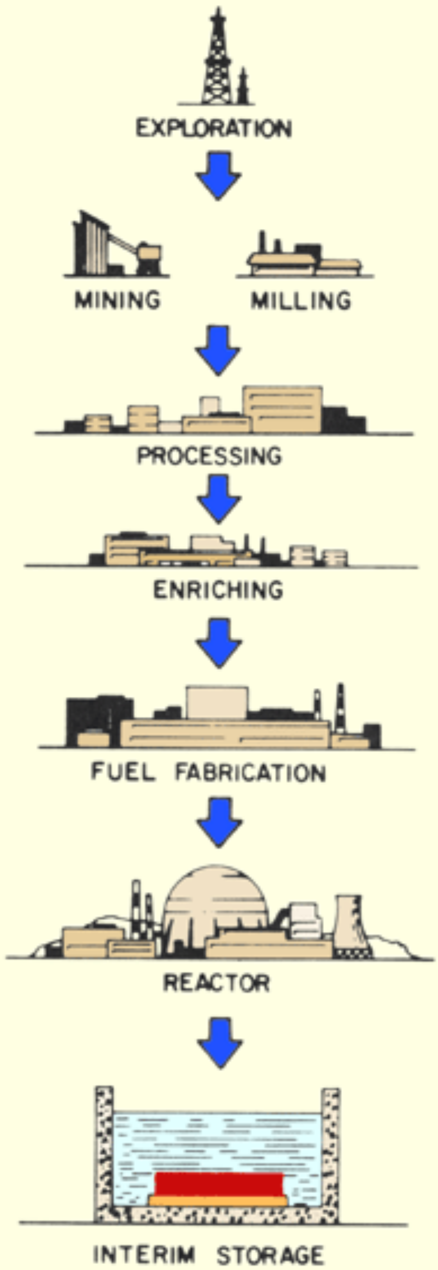
These types of disposals are very controversial. Some scientists believe the containers will keep the radioactive material safe for a long time; other scientists are worried that the containers will not remain intact for such a long time.

Most recently the British government has decided to dig up radioactive waste buried in the 1960's near Dounreay in Scotland for fear of radioactive leakage.

There is also the controversial issue of transportation of the waste fuel products. Some towns and cities (there was a sign as you enter Dundee from the north) have declared themselves nuclear free zones.

As a result no trains or lorries can travel within their boundaries if they are transporting nuclear waste. One big question that has never been fully answered is the safety of the waste products whilst they are in transit.

Waste products from nuclear power stations can be reprocessed, but again this is controversial as one of the uses of reprocessed plutonium is weapon grade plutonium which could be used in nuclear weapons.



The nuclear fuel cycle, carrying uranium from the mine to spent fuel storage in water pools.

It is not the remit of this course to take a stand one way or the other on the use of fission reactions in producing energy. For every positive reason there seems to be a convincing negative reason.

Nuclear Fusion

Where nuclear fission is the splitting of large, heavy nuclei into smaller, lighter fragments nuclear fusion is the process in which the nuclei of light elements combine, or fuse together, to give heavier nuclei.

An example of a fusion reaction is that of two deuterium nuclei fusing together to give a helium nucleus. Deuterium is an isotope of hydrogen ($^{2}_{1}H$). The reaction is as follows:

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{4}_{2}He + energy$$

Fusion reactions are accompanied by a much greater mass to energy conversion than in fission reactions. Nuclear fusion is difficult to achieve, as it requires extremely high temperatures. This is because the small nuclei are positively charged and therefore repel each other. The high temperature means that they have enough kinetic energy to overcome their electrostatic repulsion.

Nuclear fusion occurs naturally in stars where the gravitational attraction of the large mass making up the star gives rise to such high temperature and pressure that the fusion process becomes possible. So the energy we receive from the sun is from nuclear fusion. Our nearest star, the Sun, is made up mainly of mostly hydrogen and helium. Within the sun the temperature is millions of degrees Celsius, there is the constant fusion of small nuclei into larger nuclei.

The fusion process in stars is the method by which all of the elements in the Universe were formed from the original simple particles present after the Big Bang. This is known as **nucleosynthesis** (the creation of new heavier nuclei from lighter ones) and continues over the star's life cycle producing heavier and heavier elements. A limit is reached when Iron (26 protons) is produced, as the energy required to fuse elements heavier than Iron is greater than that available from the fusion reaction.

Man-made Nuclear Fusion

On Earth, attempts have been made to create nuclear fusion reactors for use in electrical power generation but the technology to achieve the extremely high temperatures and pressures is very expensive and difficult to create.

Compared to nuclear fission, nuclear fusion reactors:

- Release even more energy per kg of fuel
- Make less radioactive emissions as many of the products are stable (e.g. ^{4}He)
- Use 'cleaner' fuel: isotopes of hydrogen, which can be made from water and lithium

Magnetic containment: the TOKAMAK

ITER (**International Thermonuclear Experimental Reactor**) is a joint international research and development project that aims to demonstrate the scientific and technical feasibility of fusion power. ITER is being constructed in Europe, at Cadarache in the South of France.

ITER will use the reaction between two hydrogen (H) isotopes: deuterium (D,$^{2}_{1}H$) and tritium (T, $^{3}_{1}H$). The D-T fusion reaction produces the highest energy gain at the 'lowest' temperatures. It requires nonetheless temperatures of 150,000,000° C to take place - ten times higher than the H-H reaction occurring at the Sun's core. At these extreme temperatures, electrons are separated from nuclei and a gas becomes a **plasma -** a hot, electrically charged gas. In a star as in a fusion device, plasmas provide the environment in which light elements can fuse and yield energy. In ITER, the fusion reaction will be achieved in a **TOKAMAK** device that uses magnetic fields to contain the charged particles of the plasma in a doughnut shaped ring inside a vacuum chamber.

The fusion between deuterium and tritium (D-T) will produce one helium nuclei, one neutron, and energy.

$$^{2}_{1}\boldsymbol{H} + ^{3}_{1}\boldsymbol{H} \rightarrow ^{4}_{2}\boldsymbol{He} + ^{1}_{0}\boldsymbol{n} + \boldsymbol{energy}$$

The helium nucleus is electrically charged and so will remain confined within the plasma by magnetic fields of the TOKAMAK. Around 80% of the energy liberated by the fusion is carried as kinetic energy of the neutron. As this is electrically neutral its travel is unaffected by magnetic fields and so these neutrons will be absorbed by the surrounding walls of the TOKAMAK, transferring their energy to the walls as heat.

Inertial Confinement Fusion:

Researchers in the US are trialling a different system called Inertial Confinement Fusion (ICF) which uses small pellets of hydrogen fuel in lithium cases. Intensely powerful LASERs are focused on the pellets, starting a fusion reaction. These are in effect tiny nuclear fusion bombs. A continuous series of pellets would be detonated, with the heat produced being used to produce electricity.

The reactor chamber in ICF is called a hohlraum – a hollow area or cavity – which contains the tiny, 2mm diameter fuel pellets. Once illuminated by the proposed 192 laser beams concentrated onto the target fuel pellet is compressed and heated to ignition temperature within 20 billionths of a second.

To date continuous controlled fusion in a reactor has still not been achieved !

Nuclear Radiation

1. An atom contains electrons, protons and neutrons. Which of these particles
    a) are outside the nucleus
    b) are uncharged
    c) have a negative charge
    d) are nucleons
    e) are much lighter than the others?

2. Complete the table below.

Name	Symbol	Charge	What is it?
Alpha particle			
	β	-1	
Gamma ray			An electromagnetic wave

3. How is an ionised material different from a material that is not ionised?

Absorption of Radiation

1. The figure below shows a Geiger tube used to detect radiation from a radioactive source.

The following measurements were made using the apparatus above.

	Counts in 300 seconds			
	Readings			Average
1 No source present	102	94	110	
2 Source present at fixed distance from tube				
a) No lead plate present	3466	3420	3410	
b) Thick lead plate present	105	109	89	
c) Aluminium sheet in place of the thick lead sheet	1834	1787	1818	

a) Complete the table by calculating the average readings.

b) Why are the readings on each line not the same?

c) What can you say from the table about the effect on the radiation of:

   i. The lead plate?

   ii. The aluminium plate?

d) Why is it possible to say from the readings that:

   i. gamma radiation is emitted by the source?

   ii. alpha and beta radiation might be emitted by the source?

e) What further tests could you make using this arrangement to find out whether or not the source emits alpha radiation?

2. Complete the sentences below with either **alpha, beta** or **gamma.**

_____________ radiations are easiest to absorb because they are larger than ___________ radiations and so have more collisions with other particles. ___________ radiations are high energy electromagnetic waves and it takes a very dense material to absorb all their energy.

3. The table below represents data obtained from an absorption experiment using three separate radioactive sources (background count = 20 counts per minute).

Absorber	Count rate (counts per minute)		
	Source A	*Source B*	*Source C*
air	3125	900	420
paper 1 mm	3130	880	38
aluminium	3000	380	20
10 mm lead	1900	20	21

a) What effect did paper have on each of the three sources?
b) Use the data in the table to try to identify the type of radiation from each source.

4. Describe how you would show experimentally that radium emits three different kinds of radiation.

5. Beta particles can be stopped by a few centimetres of air or by a few micrometres of aluminium. Explain this.

Absorbed Dose

1. 12J of energy are absorbed by 2.5kg of body tissue. Calculate the absorbed dose.

2. 0.3kg of body tissue receives an absorbed dose of 6Gy. Calculate the energy absorbed the tissue.

3. A cancer tumour absorbs 15 J of energy and therefore receives 300 Gy absorbed dose. Calculate the mass of the tumour.

4. The unit for absorbed dose is the gray, Gy. Give another unit for absorbed dose.

Equivalent Dose

Use the following values for radiation weighting factor in the questions below.

Radiation type	W_R
X-rays	1
Gamma rays	1
Beta particles	1
Thermal neutrons	3
Fast neutrons	10
Alpha particles	20

1. What does the "Radiation Weighting Factor" give us a measure of?

2. In the course of his work an industrial worker receives an equivalent dose of 200 mSv. Determine the absorbed dose if he is exposed to alpha particles.

3. An unknown radioactive material has an absorbed dose of 500 mGy and gives a equivalent dose of 1 mSv. Calculate the radiation weighting factor of the material.

4. A patient receives a chest X-ray with an equivalent dose of 2.0 mSv. Calculate the absorbed dose of the patient.

5. A lady has a dental X-ray which produces an absorbed dose of 0.3 mGy. Calculate the equivalent dose of this X-ray.

6. A worker spends some time in an area where she is exposed to the following radiations:
   thermal neutrons = 8 mGy
   fast neutrons = 40 mGy
   (a) Calculate the equivalent dose for each type of neutron.
   (b) What is the total equivalent dose for the exposure?

7. A nuclear worker is exposed to a radioactive material producing an absorbed dose of 10 mGy. She finds that the material emits particles with a radiation weighting factor of 3. Calculate the equivalent dose for this exposure.

8. A physics teacher uses a gamma source in an experimental demonstration on absorption. The teacher receives an equivalent dose of 0.5 mSv. Calculate her absorbed dose.

9. (a) Alpha particles produce a equivalent dose of 50 mSv from an absorbed dose of 2.5 mGy. Calculate the radiation weighting factor of the alpha particles.

   (b) Why does exposure to the same dose of alpha radiation increase the risk of cancer more than X-rays or gamma rays?

Uses of Radiation

1. By considering the penetrating ability of each form of radiation explain why only gamma radiation can be used from outside the body to treat cancerous cells deep inside the body.

2. Gamma radiation is used to sterilize articles after they have been pre-packed in plastic packets.
    a. Why is the gamma radiation still effective on these articles?
    b. Why could syringes not be made of plastic materials before gamma rays were used for sterilization?
    c. Why is it better and cheaper to sterilise medical instruments by using radiation rather than heat or chemicals?

3. The brain can suffer from cancer called glioblastoma. Doctors can treat patients by injecting the patient with boron-10 and then irradiating the patient with. This process produces two particles, lithium and alpha particle.

    a. Explain how the alpha particle could help with the glioblastoma.
    b. Why could this process be dangerous for healthy tissue?

4. Radiation can be used to destroy tumour cells within the human body.
    a. How does the medicine make use of this fact?
    b. Explain how it is possible to leave healthy tissue unharmed.

5. A patient receives skin grafts and it is important for the surgeon to know if the blood flow to the graft is good or not. A fluid, which emits gamma radiation, is injected into the patient's bloodstream.
    a. What device could be used to detect the gamma radiation?
    b. How would the surgeon be able to tell if the skin graft had been successful?

Activity

1. Convert the following to bequerels: (a) 1 kBq (b) 1 MBq

2. What do we mean by the activity of radioactive material?

3. Calculate the missing entries in the table below (show all working).

average activity	number of decays	time
	20000	10 s
	6×10^5	10 s
	1.11×10^7	1 m
	1.50×10^7	1 m 15 s
2.5 kBq		30 s
185 kBq		2 s
3 MBq		5 s
2.5 MBq		10 m
185 kBq	925000	
1.2×10^7 Bq	5.4×10^8	

4. Describe the difference between the terms ‘activity’ and ‘count rate’.

5. The background count is measured in a science laboratory with a Geiger counter. Over a time of 15 minutes, 480 events are counted. Calculate the average background count for the laboratory in counts per minute (cpm).

Half-Life Tutorial Sheet

1. The activity of a source starts at 80 MBq. After 10 days it has fallen to 2.5 MBq. Calculate the half-life.

2. What is the half-life of a radioactive substance if its activity falls from 400 kBq to 100 kBq in 12 days?

3. What is the half-life of a radioactive isotope if the activity falls from 3 200 kBq to 200 kBq in 20 days?

4. A radioactive substance has a half-life of 6 hours. What fraction of the original activity is left after one day?

5. An isotope has a half-life of 50 s. How long does it take for the activity to fall to 1/64 of the staring value?

6. On a day when the background count is 15 counts per minute, a radioactive substance gives a count rate of 275 counts per minute. What is the half-life of the substance if the count rate, 18 minutes later is 80 counts per minute?

7. The half-life of Cobalt 60 is 5 years. A school bought a source 15 years ago of activity 300 kBq. What would be its activity now?

8. The half-life of a radioisotope is 30 days. One hundred and twenty days after its manufacture, its activity is measured at 100 kBq. Find its initial activity.

9. The half-life of Cobalt-60 is 5 years. If the source, 25 years ago, had an activity of 500 kBq, what would be the activity now?

10. The table below shows how the count rate of a source varies with time. Correction has been made for background radiation.
    a) Plot an appropriate graph and determine the half-life of the source.
    b) What will be the count rate after 5 half-life periods?
    c) Determine the fraction of the original activity which will remain after 30 minutes.

Time (minutes)	0	2	4	6	8	10
Count Rate (per second)	72	45	28	18	12	8

11. The table of results below shows how the count rate for a radioactive source varies with time. The background count was 60 counts per minute.
    (a) Plot a graph of corrected count against time.
    (b) Determine the half-life of the source.

Time (Minutes)	0	5	10	15	20
Count Rate (number of counts per minute)	1 600	1 100	750	510	350

Nuclear Reactors Tutorial Sheet

1) Use all the statements in the box below to complete the following sentence:

*In a stimulated nuclear fission event*_____________________________________

2) (a) What is a chain reaction?
   (b) Explain how a chain reaction works in a nuclear reactor and a nuclear bomb.

3) Research nuclear reactors and answer the following question.
   In a nuclear reactor what is the purpose of the following:
   (a) the concrete shield surrounding the reactor
   (b) the carbon dioxide pumped through the reactor
   (c) the graphite moderator?

4) (a)How is the temperature of a nuclear reactor controlled?
   (b) How is useful energy extracted?

5) Write down some advantages and disadvantages of using nuclear fuel to generate electricity.

6) Fission reactors produce radioactive waste. Describe some of the problems with the storage and disposal of this radioactive waste.

7) a) The fission of one U-235 nucleus releases 3.20×10^{-11} J. If one gram of U-235 contains 2.56×10^{21} atoms how much energy could be released if all the atoms were split?

   b) If 1 tonne of coal can produce 2.8×10^{10}J how much coal would be needed to produce the same amount of energy as 1 gram of U-235?

8) The plasma of light nuclei in a fusion reactor needs to be very hot. Explain why this is the case.

Solutions to numerical problems

Nuclear Radiation
1. -
2. -
3. -

Absorption of Radiation

	Counts in 300 seconds			
	Readings			Average
1 No source present	102	94	110	102
2 Source present at fixed distance from tube				
a) No lead plate present	3466	3420	3410	3432
b) Thick lead plate present	105	109	89	101
c) Aluminium sheet in place of the thick lead sheet	1834	1787	1818	1813

2. -
3. -
4. –
5. –

Absorbed Dose
1. 4.8 Gy
2. 1.8 J
3. 0.05 kg
4. -

Equivalent Dose
1. –
2. 10 mGy.
3. 0.002
4. 2.0 mGy
5. 0.3 mSv
6. (a) 24 mSv, 400 mSv (b) 424 mSv
7. 30 mSv
8. 0.5 mGy
9. (a) 20
   (b) -

Uses of Radiation

1. -
2. -
3. -
4. -
5. -

Activity

1. (a) 1 000 Bq (b) 1 000 000 Bq
2. -
3. Calculate the missing entries in the table below (show all working).

average activity	number of decays	time
200 Bq	20000	10 s
6×10^4 Bq	6×10^5	10 s
185 000 Bq	1.11×10^7	1 m
200 000 Bq	1.50×10^7	1 m 15 s
2.5 kBq	75 000	30 s
185 kBq	370 000	2 s
3 MBq	1.5×10^7	5 s
2.5 MBq	1.5×10^9	10 m
185 kBq	925000	0.2 s
1.2×10^7 Bq	5.4×10^8	0.02s

4. -
5. 32cpm

Half-Life Tutorial Sheet

1. 2 days
2. 6 days
3. 5 days
4. 1/16
5. 300 s
6. 9 minutes
7. 37.5 kBq
8. 1600 kBq
9. 15.6 kBq
10. a) approx 3 minutes

b) 2.25 per second

c) 1/1024

11. -

Nuclear Reactors Tutorial Sheet

1. -
2. -

3. -
4. -
5. -
6. -
7. a) 8.19×10^{10}
   b) 2.9 tonnes
8. -