AS Level Physics

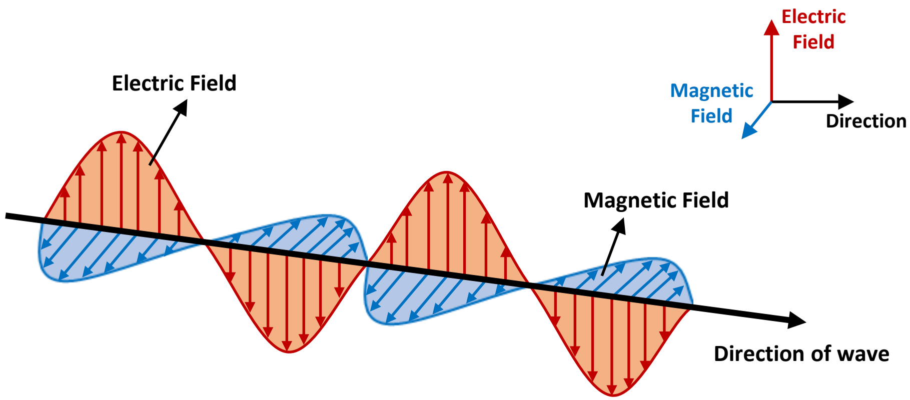
Chapter 4 – Waves

4.2.1 Electromagnetic Waves

Notes

The Nature of Electromagnetic Waves

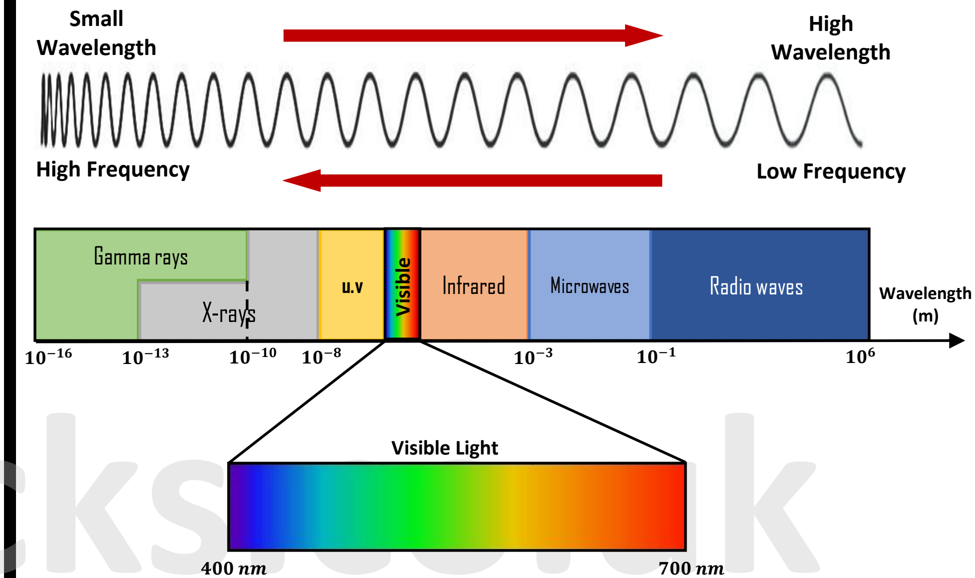
An Electromagnetic (EM) wave is made up of an alternating magnetic field in phase with an alternating electric field, both perpendicular to each other.



- EM waves are transverse waves because the vibrating electric and magnetic fields, as well as the direction of motion, are all at right angles to one other.
- Progressive EM waves, like all progressive waves, carry energy.
- EM waves, like all waves, can be reflected, refracted, diffracted, and can undergo interference.
- EM waves, like other transverse waves, can be polarised.
- EM waves, like other waves, obey $v = f\lambda$ ($v = velocity$, $f = frequency$, $\lambda = wavelength$).
- Electric, magnetic, and gravitational fields have no effect on EM waves since they have no charge.
- EM waves travel at the speed of light ($\approx 3 \times 10^8\ ms^{-1}$) in a vacuum, and at slower speeds in other mediums.

Electromagnetic Wave Spectrum

EM waves of different wavelengths act differently. The EM spectrum is divided into seven groups:



The wave properties become more obvious as the wavelength increases - for example, long radio waves can diffract around hills whereas visible light can only diffract through a very narrow slit.

Energy is directly proportional to frequency. Gamma rays have the highest energy; while radio waves the lowest. In general, the more energy (or frequency) a wave has, the more harmful it is.

For your exam you need to remember:

- The names of all the 7 regions.
- The order they appear in.
- Their approx. wavelength ranges.

Electromagnetic Wave Spectrum

Type	Approx. wavelength / (m)	Production	Penetration	Effect on human body	Uses
Radio waves	10^{-1} *to* 10^{6}	Oscillating electrons in an aerial.	Pass through matter.	No effect.	• Radio transmission.
Microwaves	10^{-3} *to* 10^{-1}	Electron tube oscillators.	Mostly pass through matter, but cause some heating.	Absorbed by water.	• Microwave cookery. • TV transmissions.
Infrared (IR)	7×10^{-7} *to* 10^{-3}	Natural and artificial heat sources.	The majority of the energy is absorbed by matter, causing it to heat up.	Excessive heating can be harmful to the body's system.	• Night-vision cameras. • Heat detectors • Remote controls • Optical fibres
Visible light	4×10^{-7} *to* 7×10^{-7}	Natural and artificial light source.	Absorbed by matter, causing some heating effect.	Used for sight. Strong bright light can damage eyes.	• Human sight • Optical fibres
Ultraviolet (UV)	10^{-8} *to* 4×10^{-7}	e.g. the Sun.	Absorbed by matter. Slight ionisation.	Tans the skin. Can cause skin cancer and eye damage.	• Sunbeds. • Security markings that show up in UV light.
X-rays	10^{-13} *to* 10^{-8}	Bombarding metal with electron.	Mostly pass through matter, but cause ionisation as they pass.	Cancer due to cell damage. Eye damage.	• To see damage to bones and teeth. • Airport security scanners. • To kill cancer cells.
Gamma rays	10^{-16} *to* 10^{-10}	Radioactive decay of the nucleus.	Mostly pass through matter, but cause ionisation as they pass.	Cancer due to cell damage. Eye damage.	• Irradiation of food. • To kill cancer cells. • Sterilisation of medical instruments.

UV Radiation

- UV radiation is classified as UV-A, UV-B, or UV-C depending on its frequency.
- UV-A has the lowest frequency and is the least harmful, but it can cause skin ageing.
- UV-B has a higher frequency and is more harmful. It can cause mutations in DNA molecules, which can lead to cancer. Sunburn is also caused by UV-B.
- UV-C is ionising because it has a high enough frequency to knock electrons off atoms. This can result in cancer, as well as mutation or destruction of cells. However, the ozone layer almost completely blocks it.
- Dark skin provides some protection from UV rays, preventing them from reaching more vulnerable tissues below.
- Sunscreens give some UV protection from the sun. The sunscreen's Sun Protection Factor (SPF) indicates how well it protects against UV-B rays. However, it provides no information on UV-A protection. To prevent UV-A, many modern sunscreens incorporate small particles of zinc oxide and titanium dioxide.

EM Waves

Exam Style Question

State two properties of electromagnetic waves which do not change across the whole of the spectrum.

Discuss two features of electromagnetic waves, other than just wavelength and frequency, which do change across the spectrum.

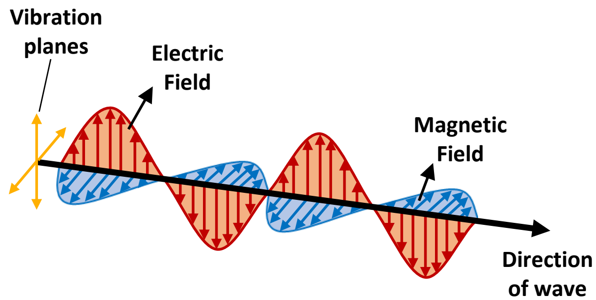
Answer:
Properties of EM waves which do not change:
- All are transverse waves and so all can be polarised under suitable conditions.
- All can travel in a vacuum at the same speed.

Features of EM waves which do change across the spectrum:
- The sensitivity of the eye to certain wavelengths.
- The heating effect of the EM waves particularly of infra-red.

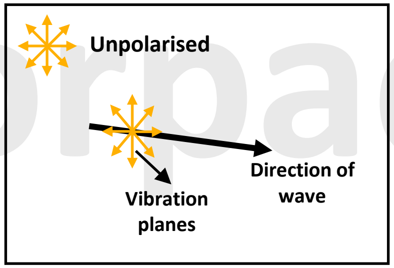
Polarisation

Light is an EM wave. A light wave is made up of varying electric and magnetic fields. These two fields vary at right angles, as they do in all EM waves.

The magnetic field vibrates in the horizontal plane, while the electric field vibrates in the vertical plane as shown opposite. You can represent the vibrations as arrows to save time when drawing the electric and magnetic fields.



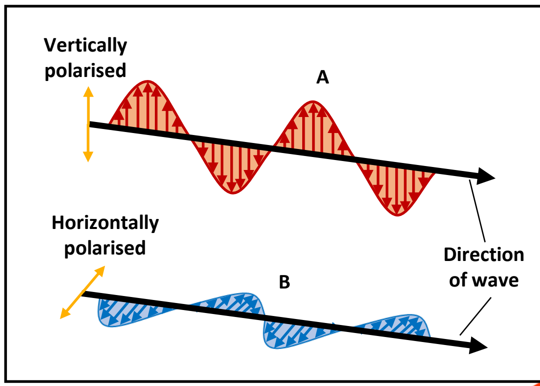
A wave that is unpolarised has vibrations in all directions that are at right angle to the wave's direction.



A plane-polarised wave is where the vibrations only occur in one plane.

E.g., in the diagram opposite:

- Wave A is vertically polarised.
- Wave B is horizontally polarised



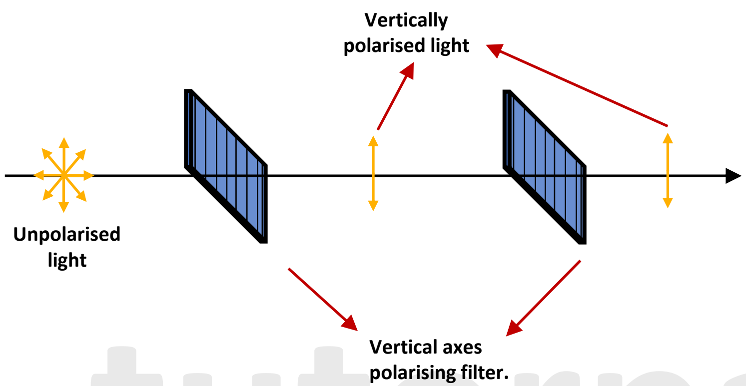
Polarisation

- Polarisation is only possible for transverse waves.
- We know EM waves are transverse because they can be polarised.
- Longitudinal waves can only vibrate in one direction – back and forth, along the direction of the motion – and hence cannot be polarised.

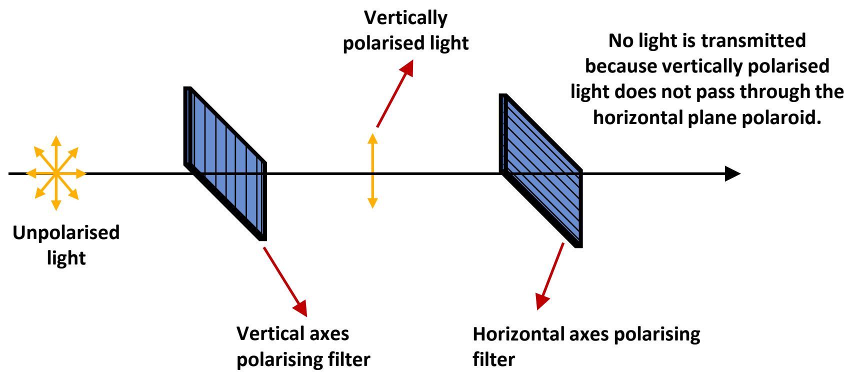
Polarising Filters

Unpolarised light is polarised by passing it through a polarising filter (a piece of Polaroid).

Light is transmitted when two polaroid's with the same vertical plane axes are placed together.



Less and less light is transmitted as the second polaroid is progressively rotated such that its polarisation axis moves from vertical to horizontal. When the axes of the two polaroid's are at right angles to one another, no light is transferred.

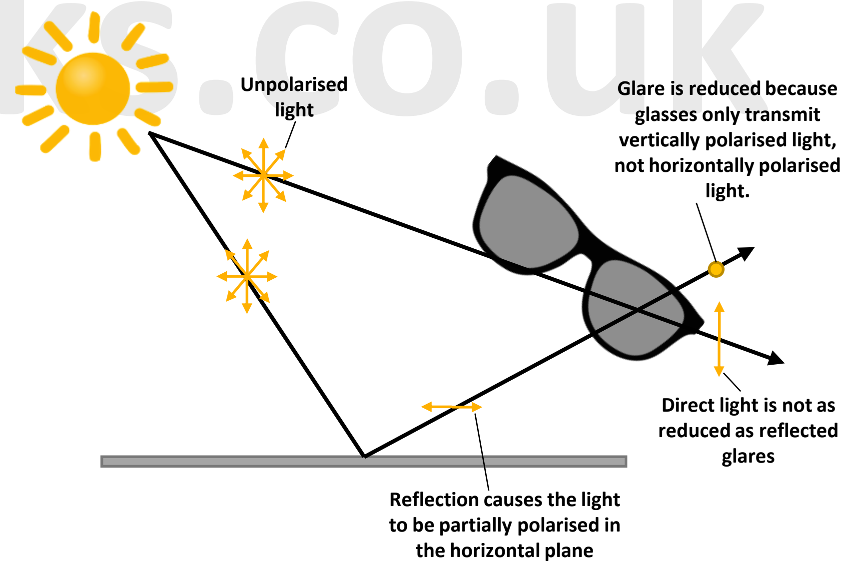


Reflected Light

Although most everyday light is unpolarised, light reflected off a surface (such as a glossy surface like water) is usually polarised (or at least partially polarised) in the horizontal plane.

Glare can be caused by reflected sunlight from a wet road surface and other vehicles. Therefore drivers can wear sunglasses with Polarised lenses, which have filters that cut out this reflected light. So the reflected light is less likely to blind the driver.

This is because the polaroid in the glasses is arranged to transmit only vertically polarised light. This helps to significantly minimise glare caused by the light that has been partially polarised in the horizontal plane.



Malus's Polarisation Law

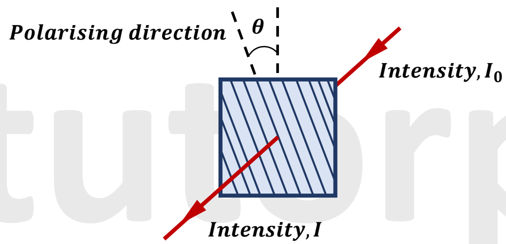
The intensity of light passing through a polarising filter depends on the angle (θ) between the direction of polarisation of the light and the axis of the filter.

$$I = I_0 \cos^2 \theta$$

Where:

I = is the transmitted intensity measured Wm^{-2}.

I_0 = is the intensity before passing through the polarising filter measured Wm^{-2}.



Malus's Polarisation Law

Worked example:

Unpolarized light with intensity I_0 passes through a vertical polariser before passing through a second polarising filter with an angle of 30 degree relative to the first one. What is the intensity of the light as it passes through the second polariser in terms of I_0?

Worked example:

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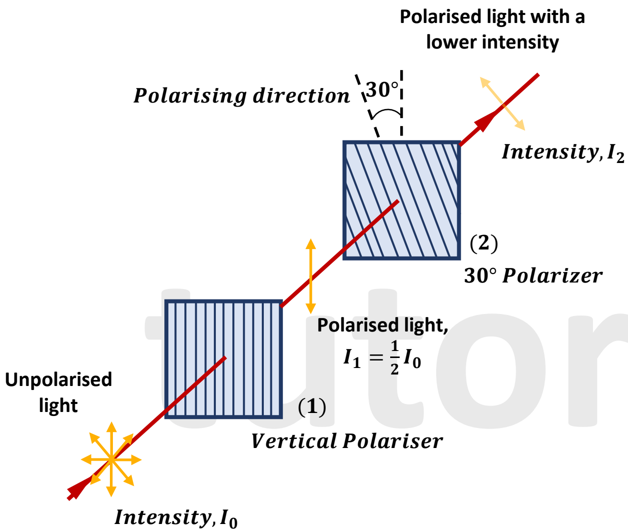


I_0 is the unpolarised light's initial intensity before going through the first vertical polariser.

The first polaroid is a vertical polariser, so the light is now polarised vertically. The intensity of the polarised light after going through the polariser is $\frac{1}{2}I_0$. We can say this polarised light has an intensity equal to I_1.

The polarised light then goes through the second polariser with filters angled at 30 degrees from vertical. We can say this polarised light has an intensity equal to I_2.

So we are determining the light's intensity after it goes through the second polariser (I_2).

Malus's Polarisation Law

To answer this question, we must apply Malus' Law:

$$I = I_0 \cos^2 \theta$$

However, in this case:

$$I_2 = I_1 \cos^2 \theta$$

Substitute 30deg into the formula:

$$I_2 = I_1 \cos^2(30)$$

$\cos(30) = \frac{\sqrt{3}}{2}$, so substitute that back in:

$$I_2 = I_1 \left(\frac{\sqrt{3}}{2}\right)^2$$

$$I_2 = I_1 \left(\frac{3}{4}\right)$$

We also know that I_1 is equal to half of the initial intensity, I_0. Therefore $I_1 = \frac{1}{2}I_0$. So we get:

$$I_2 = \left(\frac{1}{2}I_0\right)\left(\frac{3}{4}\right)$$

Therefore:

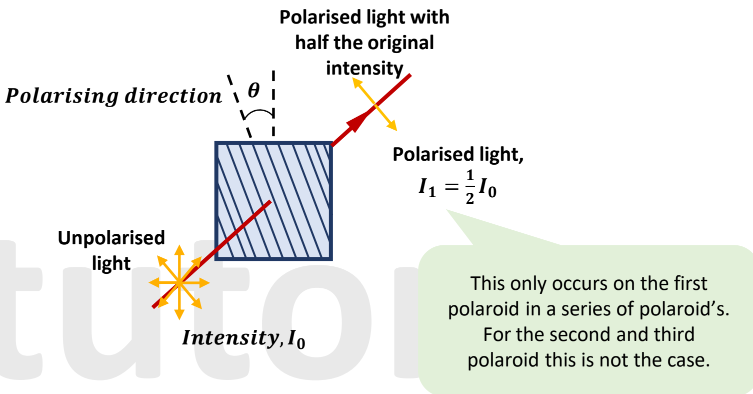
$$I_2 = \frac{3}{8}I_0$$

So, when light goes through the first polaroid, it has half of its original intensity, and when it passes through the second polaroid, it has 3/8 of its original intensity. After travelling through the polaroid's, you can see how much the light's intensity has fallen.

Malus's Polarisation Law

Remember:

When unpolarised light with initial intensity, I_0, passes through the first polaroid arranged at any angle, θ, the intensity of the polarised light is always half the initial intensity.



Malus's Polarisation Law

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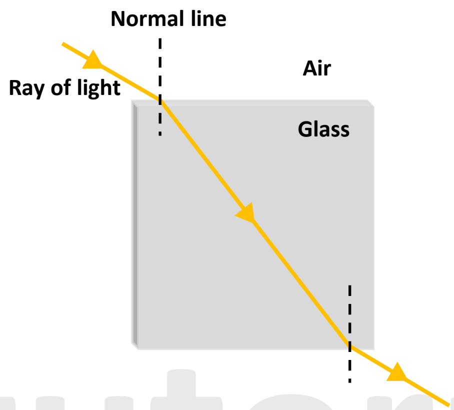
Refraction of Light

Refraction occurs when a wave passes from one medium to another and there is a change direction caused by its change in speed.



Consider the diagram above, which shows how a light ray changes direction as it enters and exits a rectangular glass block in air. When the light ray travels:

- From air to glass, it bends **TOWARDS** the normal.
- From glass to air, it bends **AWAY** from the normal.

If the incident light ray is along the normal, no refraction takes place.

Absolute Refractive Index

The refractive index of a material is an measurement of how much it slows light down.

Light travels faster in a vacuum then in other materials. This is because light interacts with the particles in the material causing it to slow down.

The higher the refractive index (or optical density) of a material, the slower light travels through it.

The absolute refractive index of a material, n, is the ratio between the **speed of light in a vacuum,** c, and the **speed of light in the given material**, v.

$$n = \frac{c}{v}$$

Where:
$n = absolute\ refractive\ index.$

$c = 3 \times 10^8$, speed of light in a vacuum measured in ms^{-1}.

v = speed of light in the given material measured in ms^{-1}.

The refractive index is always greater than or equal to one.

Air has an refractive index of 1 $(n_{air} = 1)$.

Snell's Law

We are able to predict how far light will bend when it enters a new medium.

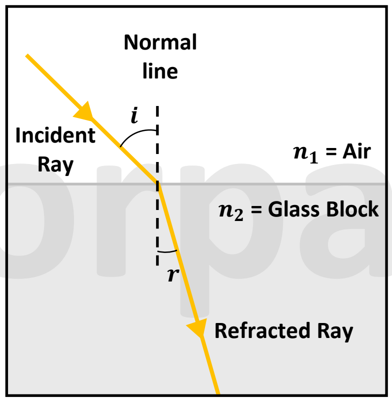
If we consider the angle of incidence as i and the angle of refraction as r, we can see that the ratio $\frac{\sin i}{\sin r}$ remains constant for all values of i and r when travelling from a vacuum into a material.

This ratio is known as Snell's Law.

We call the constant from Snell's Law the refractive index, n.

With this knowledge, we can demonstrate that:

$$n = \frac{\sin i}{\sin r} = \frac{c}{v}$$



Where:

n = absolute refractive index.

i = the angle of incidence

r = the angle of refraction

c = $3 \times 10^8\ m\ s^{-1}$, speed of light in a vacuum.

v = speed of light in that material measured in ms^{-1}.

Relative Refractive Index

The relative refractive index is the ratio of the **speed of light in material 1** to the **speed of light in material 2**.

In contrast to the absolute refractive index, which is the ratio of the speed of light in a vacuum (or air) to the speed of light in a material, the relative refractive index is between two materials.

When a wave travels from material 1 into material 2, the ratio of the sine of the angles is constant, and we use the relative refractive index, ${}_1n_2$.

$${}_1n_2 = \frac{\sin\theta_1}{\sin\theta_2} = \frac{c_1}{c_2}$$

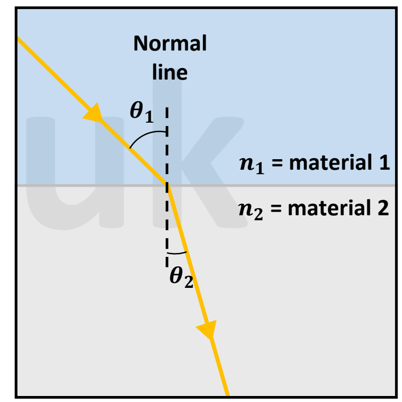
Where:

c_1 is the speed of light in material 1

c_2 is the speed of light in material 2

Also,

$${}_1n_2 = \frac{n_2}{n_1}$$



Where:

n_1 is the refractive index of material 1

n_2 is the refractive index of material 2.

With this information, we can rewrite the equation as follows:

$${}_1n_2 = \frac{\sin\theta_1}{\sin\theta_2}$$
$$\frac{n_2}{n_1} = \frac{\sin\theta_1}{\sin\theta_2}$$
$$\boldsymbol{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

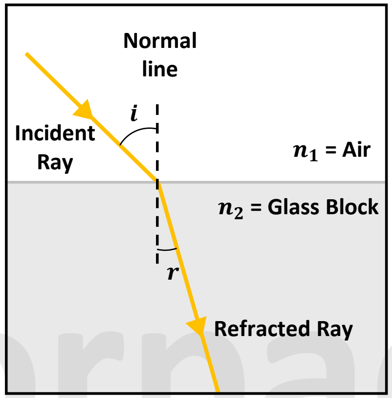
Relative Refractive Index

However, if we apply the final equation to a refraction that occurs between air and a material, we get the following:

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

Where:

n_1 = the refractive index of air which we know is 1
θ_1 = the angle of incidence, i.
θ_2 = the angle of refraction, r.
n_2 = the refractive index of the glass block



Now we can substitute all of this information into the formula above to get:

$$(1)\ \sin i = n_2 \sin r$$

Simplifying we get:

$$\boldsymbol{n = \frac{\sin i}{\sin r}}$$

Where:

$n = n_2$ = the refractive index of the glass block/material.

Here we derived the same equation we looked at in the previous page.

Refractive Index

Worked example

A light ray with an angle of incidence of 45deg is directed into a glass block of refractive index 1.5. Determine the angle of refraction of this light ray.

Solution:

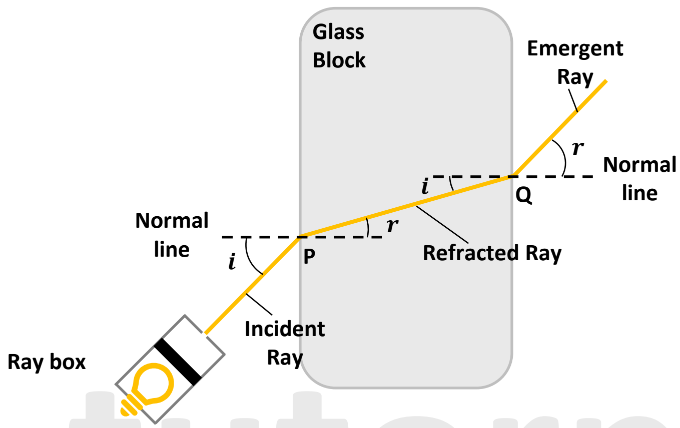
$i = 45°, n = 1.5$

Rearranging $n = \frac{\sin i}{\sin r}$ gives:

$$\sin r = \frac{\sin i}{n} = \frac{\sin 45}{1.5}$$
$$\sin r = 0.471 \ldots$$
$$\therefore\ r = 28.1°$$

Investigating the Refraction of Light by Glass

As indicated in the diagram below, use a ray box to direct a light ray into a rectangular glass block at various angles of incidence. Direct the light ray at point P or on one of the longer sides of the block.



Note: The angle of incidence, i is the angle formed by the incident light ray and the normal.

Mark the point Q where the light ray leaves the block for each angle of incidence at P. The angle of refraction r is the angle formed by the normal at P and the line PQ.

Angles of incidence and refraction for various incident light rays demonstrate that:

- At P, the refraction angle, r, is smaller than the incidence angle, i and vice versa at Q.
- For each light ray incident, the ratio of $\frac{\sin i}{\sin r}$ is the same. This is know as **Snell's Law**.

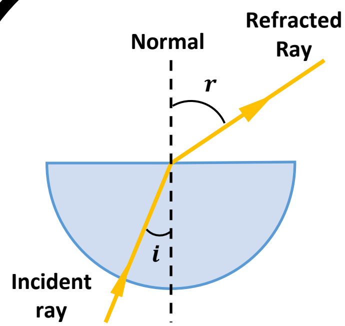
The result of this ratio will give us the refractive index, or n, of the glass.

Investigating the Refraction of Light by Glass

For a light ray that travels from the air to a transparent material, we get:

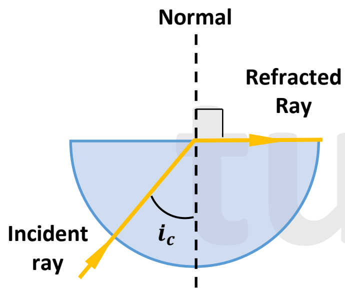
$$Refractive\ index\ of\ the\ subtance, n = \frac{\sin i}{\sin r}$$

Critical Angle and Total Internal Reflection (TIR)



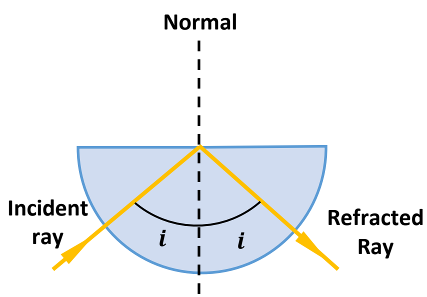
$i < critical\ angle$

When light rays pass through glass and into air, they refract away from the normal.



$i_c = critical\ angle$

If the angle of incidence is increased to a particular value known as the **critical angle**, the light ray refracts along the boundary.



$i > critical\ angle$

The light beam undergoes **total internal reflection (TIR)** at the boundary if the angle of incidence is increased beyond the critical angle, just as if the border were replaced by a plane mirror.

Critical Angle and Total Internal Reflection (TIR)

In general, total internal reflection is only possible if the following conditions are met:

- The angle of incidence is **greater** than the **critical angle**,
- The incident light ray travels from a higher refractive index to a lower refractive index (for example, glass $(n = 1.52)$ to air $(n = 1)$).

The light ray emerges along the boundary at the critical angle i_c, therefore the angle of refraction is $90°$. As a result, we can use Snell's law to calculate this critical angle, i_c:

$$n_1 sin i_c = n_2 sin r$$

Where:

n_1 is the refractive index of the incident substance (i.e. glass),

n_2 is refractive index of the other substance (i.e. air),

r is the angle of refraction.

Since $\sin 90 = 1$, then:

$$n_1 \sin i_c = n_2 \sin(90)$$
$$n_1 \sin i_c = n_2 (1)$$

Therefore:

$$\sin i_c = \frac{n_2}{n_1}$$

Remember air has a refractive index of 1, so we can substitute it into the equation above to get:

$$sin i_c = \frac{1}{n_1}$$

And we can re-arrange the equation to:

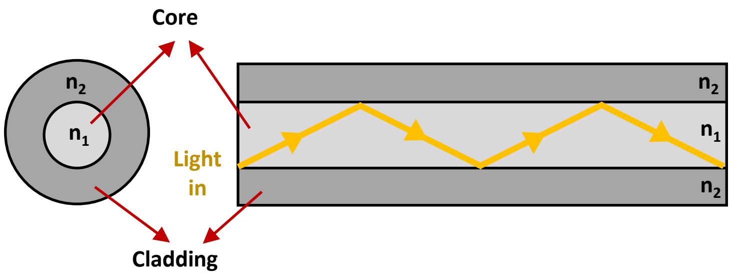
$$\boldsymbol{n = \frac{1}{\sin C}}$$

Where:

n = the refractive index of the incident substance

C = critical angle

Optical Fibres (AQA Only)



$$core\ refractive\ index\ (n_1) > cladding\ refractive\ index\ (n_2)$$

An optical fibre is a very thin flexible tube of glass or plastic fibre that uses total internal reflection to carry light signals around corners and across long distances.

Optical fibres come in different types, but you only need to be familiar with step-index optical fibres.

Step-index optical fibres are made up of a core that has a high refractive index that is surrounded by cladding with a lower refractive index.

The cladding also protects the fibre from scratches that could allow light to get out.

At one end of the fibre, light is shone in. The fibre is so narrow, that when light strikes the boundary between fibre and cladding it is always at an angle greater than the critical angle.

As a result, until the light reaches the other end, it is totally internally reflected from boundary to boundary.

Optical fibres may be used to carry light signals in communications, such as phones and cable television transmissions and signals.

Optical Fibres (AQA Only)

Using optical fibres to transfer information is preferable over using electricity flowing via copper wires because in optical fibres:

- Light has a higher frequency and therefore the signals can carry more information.
- Light does not heat the fibre, so little energy is wasted in the form of heat.
- Electrical interference is not present.

Endoscopes, cystoscopes, arthroscopes, communication, and other optical fibre applications have improved medical diagnostics, data transfer, and high-speed internet.

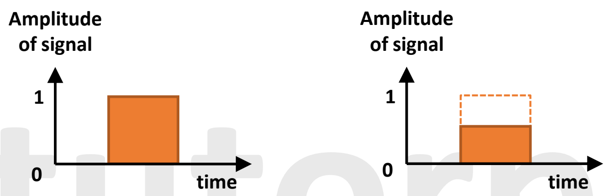
Optical Fibres (AQA Only)

Signal Degradation

Information is transmitted as light pulses through optical fibers, but degradation can occur due to absorption or dispersion, resulting in the loss of information.

Absorption

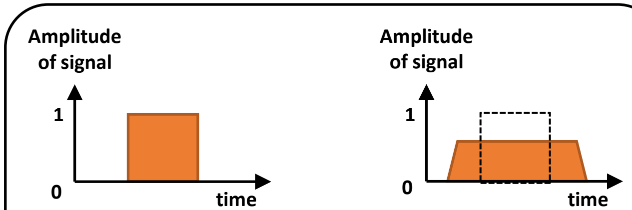
Absorption in optical fibres results in the loss of energy from the signal due to the fibre material absorbing some of the signal's energy, leading to a reduction in the signal's amplitude.



The impact of absorption on a digital signal.

Dispersion

Modal and material dispersion are two types of dispersion that can degrade an optical signal. Both types of dispersion causes Pulse broadening where the received signal is broader than the original signal. Broadened pulses can cause information loss through overlapping.

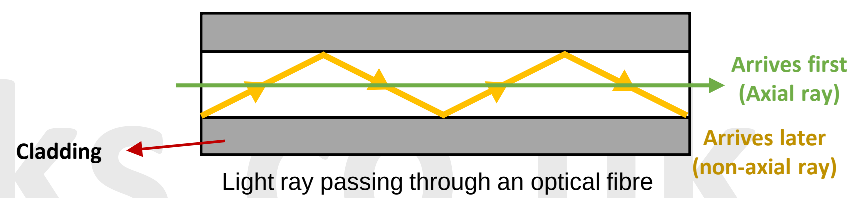


The impact of dispersion on a digital signal.

Optical Fibres (AQA Only)

Modal Dispersion is caused by light rays entering the optical fibre at different angles, taking different pathways down the fibre. As a result, rays travelling straight down the centre arrive faster than rays travelling via a longer reflected path. The use of a single-mode fibre can reduce modal dispersion by allowing light to travel through a very narrow path, reducing the difference in arrival times caused by different ray pathways.

An axial ray refers to a light ray that travels straight down the centre of an optical fibre, while non-axial rays are those that reflect off the sides of the fibre.



Light ray passing through an optical fibre

Material dispersion: is caused by the different amounts of refraction experienced by different wavelengths of light. Different wavelengths slow down by different amounts in a material. Since light is made up of many different wavelengths, some parts of the signal take longer to travel down the fibre than others. Material dispersion can be prevented by using monochromatic light.

Optical fibre repeaters can help prevent signal degradation caused by absorption and dispersion by periodically regenerating the signal.

Please see '4.2.2 Electromagnetic Waves worked examples' pack for exam style questions.

For more revision notes, tutorials and worked examples please visit www.tutorpacks.co.uk.