Physics notes – Wave-like properties of light
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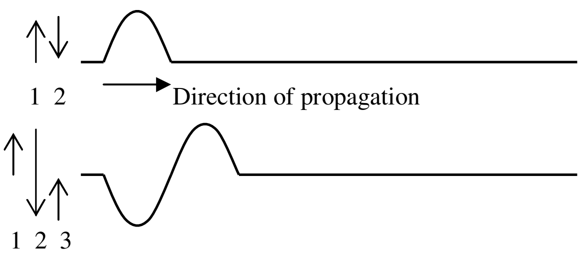
A good starting point to learn about the behaviour of waves is to study waves in a stretched spring or string.

A wave **pulse** is generated when a stretched spring is given a shake at one end. This wave pulse travels along the spring to the other end and turns back to travel in the opposite direction.

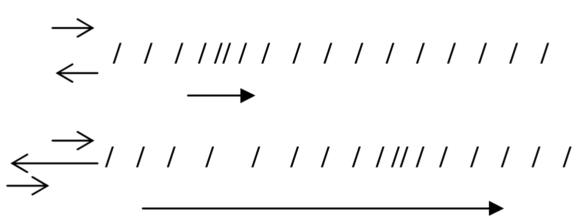


The spring is given a certain amount of energy during the shake. This amount of energy exists in the spring and is carried along the spring by the wave pulse.

The spring is the medium for the wave pulse (energy) to travel along. The particles of the medium are displaced while the pulse is passing and they returned to their original positions after the pulse is through. They do not travel with the pulse. The transfer of energy from one place to another does not involve the net transfer of any material of the medium.

When the spring is shaken perpendicular to the length of the spring, the motion of a particle in the spring and the motion of the pulse are perpendicular to each other. This type of waves is categorised as **transverse waves**.

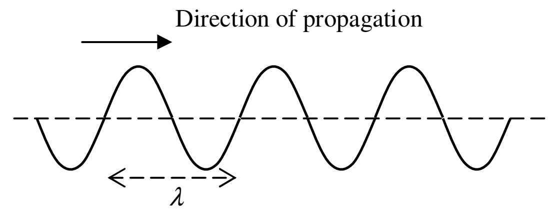
Wave pulses can also be generated by shaking a stretched spring along the direction of its length.



The motion of a particle in the wave is parallel to the motion of the pulse. This type of waves is categorised as **longitudinal waves**. Again the particles do not travel with the pulse. They are displaced when the pulse is passing through them.

Periodic waves

If the shaking of the spring is done repeatedly, a periodic travelling wave is formed in the medium (the spring).

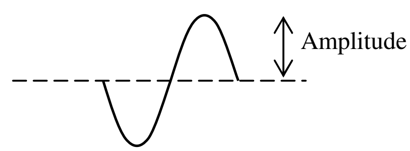


A 'full' shake produces a cycle of the periodic wave. The time interval for generating a cycle is the *period* T of the wave. The length of a cycle of the wave is called its *wavelength* λ. The number of cycles generated in a unit time (second) is the frequency f of the periodic wave.

Frequency and period of a wave are related according to

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

The highest point of a wave is the crest, and the lowest point the trough. Half way between the two is the equilibrium position where the spring is. The distance between a crest (or trough) and the equilibrium position is the amplitude of a wave.



A travelling wave moves a distance λ (the wavelength) during a time interval T (the period). Hence the speed of the wave v is given by

$$v = \frac{\lambda}{T} \quad \text{or} \quad v = f\lambda .$$

The first equation follows the general definition for speed.

$$Speed = \frac{dis\tan cetravelled}{timetaken}.$$

The second equation is called the **wave equation**.

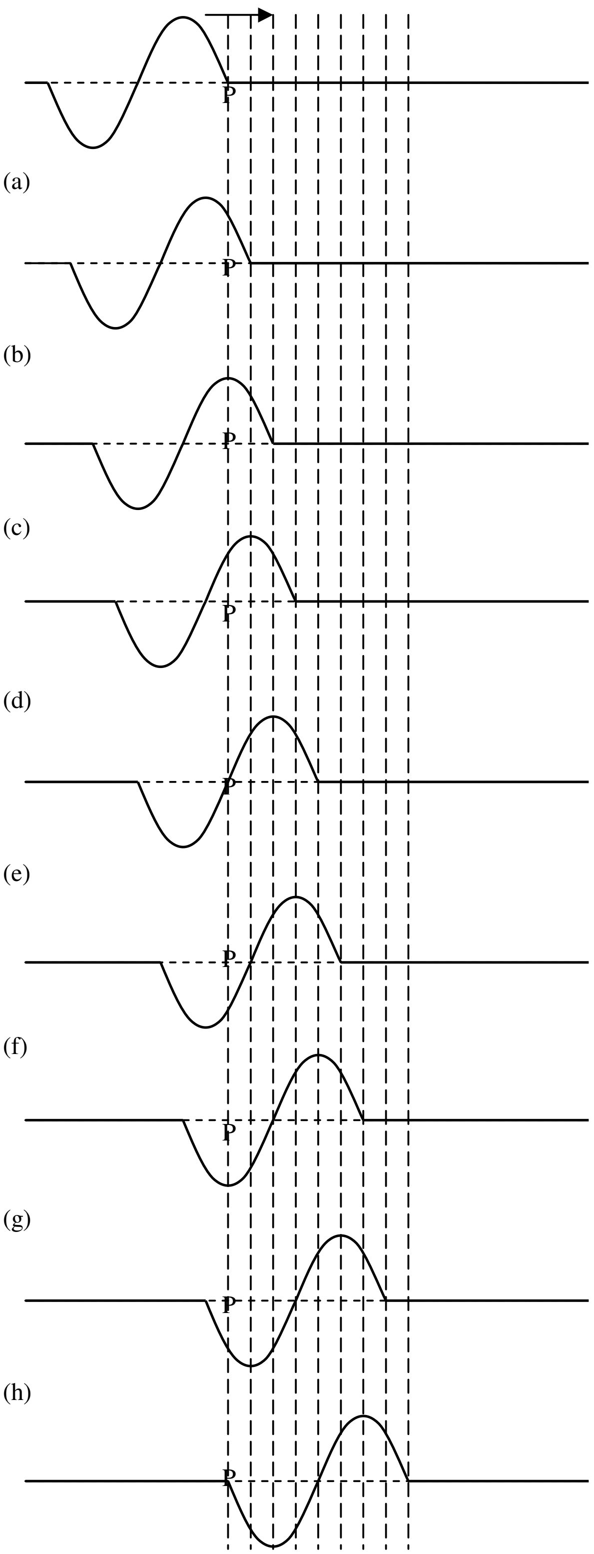
Example 1 A periodic wave is generated in a 5.00-m stretched spring by shaking one end 2 times in a second. The time taken to travel to the other end of the spring is 2.00 s. Find the speed and the wavelength of the wave.

$$\text{Speed} = \frac{dis\tan cetravelled}{timetaken} = \frac{5.00}{2.00} = 2.50\ \text{ms}^{-1}.$$

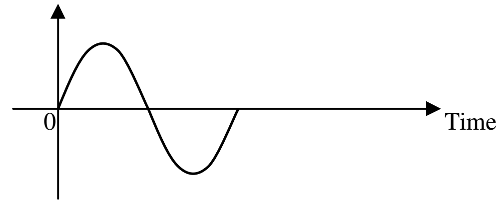
Frequency $f = 2\ \text{s}^{-1}$ (Hz).

$$v = f\lambda,\ \lambda = \frac{v}{f} = \frac{2.50}{2} = 1.25\ \text{m}.$$

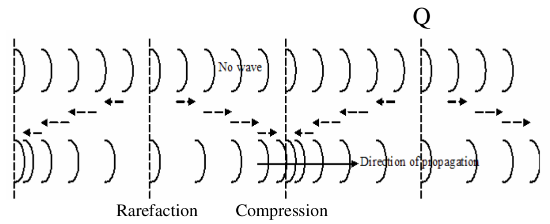
Example 2 Consider the following transverse wave pulse in a stretched rope travelling to the right. Draw the wave pulse at (a) $t=\frac{T}{8}$ (b) $t=\frac{T}{4}$ (c) $t=\frac{3T}{8}$ (d) $t=\frac{T}{2}$ (e) $t=\frac{5T}{8}$ (f) $t=\frac{3T}{4}$ (g) $t=\frac{7T}{8}$ (h) $t=T$. Draw a displacement-time graph for the particle at P.

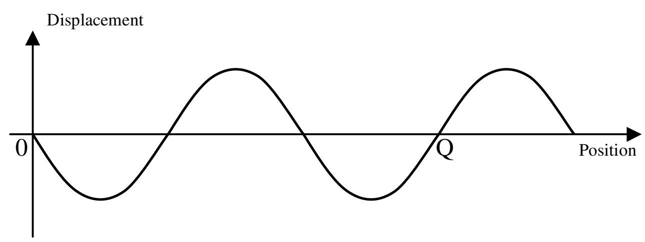


Displacement of particle at position P

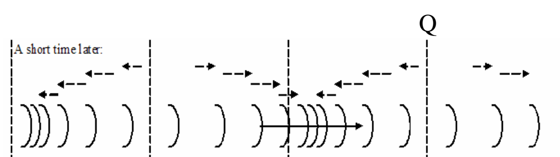


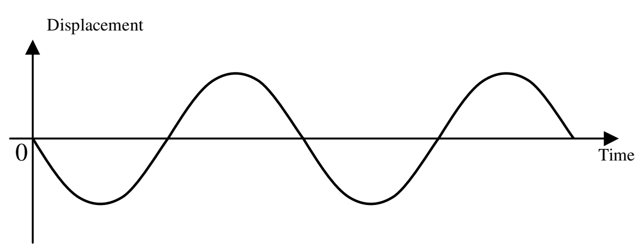
Example 3 Consider the following longitudinal wave pulse in a stretched spring travelling to the right. Draw a displacement-position graph of the wave at that particular moment (say $t=0$).





Example 4 Refer to example 3, draw a displacement-time graph for the particle at position Q.





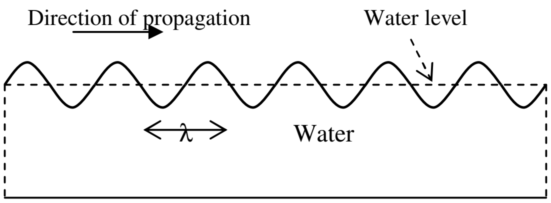
Phase

Two particles in a wave are in **phase** when they move in the **same direction** and at the **same speed**. The distance between two consecutive particles in phase equals the wavelength.

Two waves of the same frequency are in phase when they vibrate the same way at the same place and at the same time.

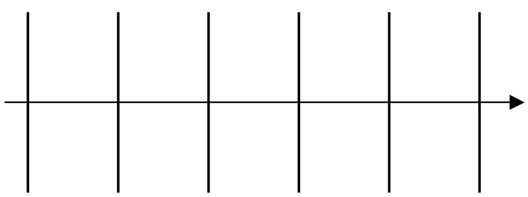
Examples of waves

Surface water waves



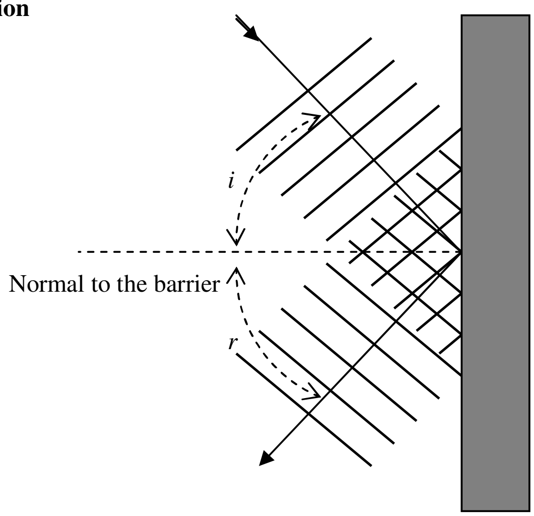
Surface water waves are transverse waves (as an approximation) because the motion of water particles is perpendicular to the direction of propagation of the waves. The highest points are called **crests** and the lowest points are **troughs**.

Aerial view of a surface water wave can be represented by a series of lines to stand for wave crests. An arrow perpendicular to the crests is used to indicate the direction of propagation.



Surface water wave is particularly useful to demonstrate visually some important behaviour of waves, e.g. reflection, refraction, diffraction and interference.

Reflection

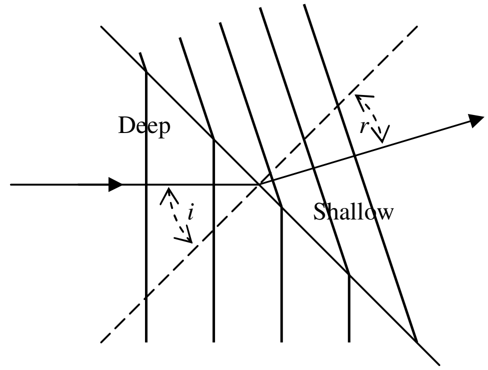


Wavelength, frequency and speed remain the same after reflection.

Angles of incidence and reflection are equal, $\angle i = \angle r$. This is known as the **law of reflection**.

Refraction

Wave changes its speed and direction when the depth of water changes.



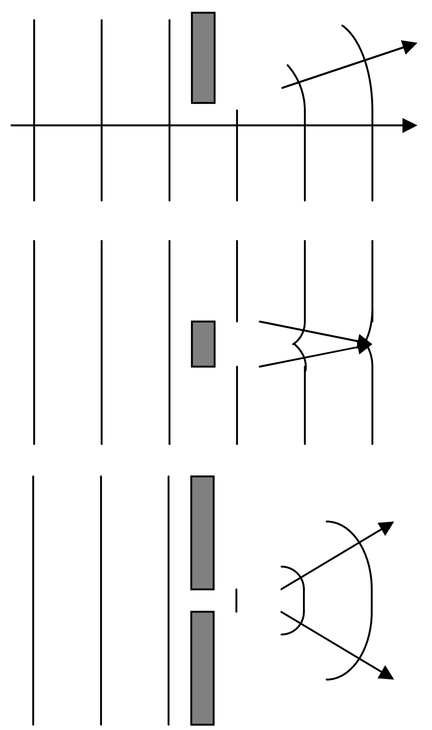
Frequency is the same in both regions.

$\lambda_d > \lambda_s$, $v_d > v_s$, $\angle i > \angle r$.

$\frac{v_d}{v_s} = \frac{f\lambda_d}{f\lambda_s} = \frac{\lambda_d}{\lambda_s}$.

Diffraction

Wave spreads out when it passes by an edge, an obstacle or through an opening.

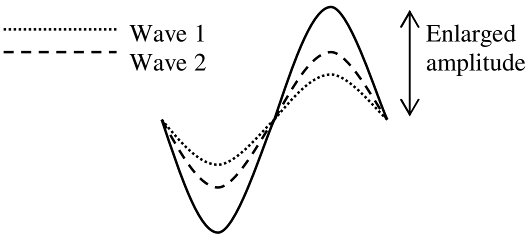


Wavelength, frequency and speed remain the same after diffraction.

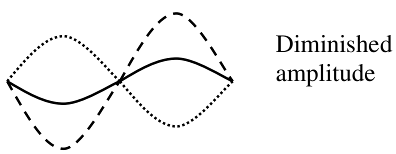
Spread due to diffraction $\propto \frac{\lambda}{w}$, where *w* is the width of the obstacle or opening.

Interference

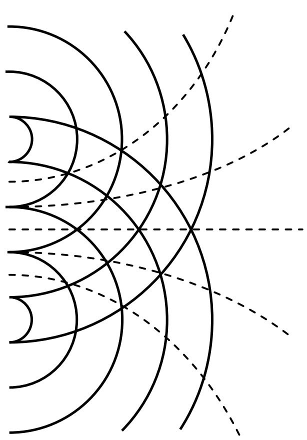
Two waves interfere when they cross or overlap each other. If they are in phase (crests meeting crests and troughs meeting trough), **constructive interference** is said to occur resulting in a wave with larger amplitude.



If they are half of a wavelength out of phase (crests meeting troughs), **destructive interference** occurs resulting in the destruction of both waves.



The diagram below is called an **interference pattern** of two circular waves generated by two sources producing the waves periodically and *in phase*.



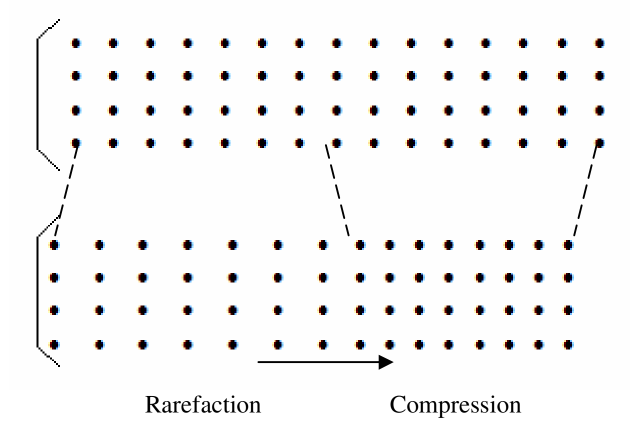
Wavelength, frequency and speed remain the same during and after interference.

Constructive interference occurs at places where a wave crest meets another crest, or a trough meets another trough. **Destructive interference** occurs at places where a crest and a trough meet.

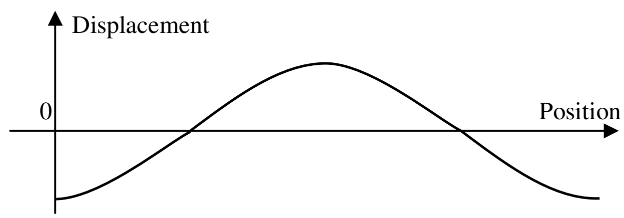
The regions marked with dotted curves are called **antinodal lines** where constructive interference takes place. The regions between two adjacent antinodal lines are called **nodal lines** where destructive interference occurs.

Sound waves in air

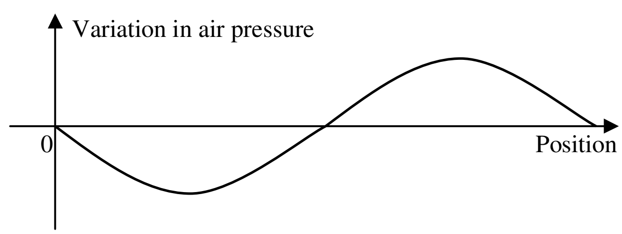
Each of following diagrams shows a simplified picture of the air molecules in front of a loudspeaker before and after it was turned on.



Sound waves in air are longitudinal because the particles oscillate parallel to the direction of propagation. A way to describe the above sound wave is in terms of the displacement of the particles at different positions from the loudspeaker.



Another way is in terms of the variation in air pressure at different positions.



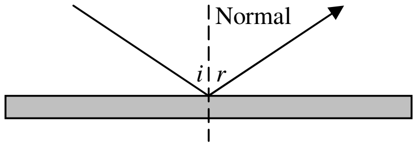
As a sound wave passes through air, a series of alternating high (compressions) and low (rarefactions) air pressure regions propagate forwards.

Sound has all the properties of a wave, namely reflection, refraction, diffraction and interference.

An example of refraction of sound is when it travels from a region into another region of different temperature. Sound travels faster in a warmer region (longer λ) than in a cooler region (shorter λ), and it bends towards the normal, i.e. $\angle i > \angle r$.

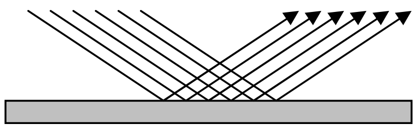
Wave-like properties of light

Reflection of a light ray

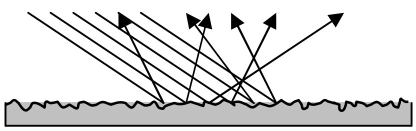


$\angle i = \angle r$

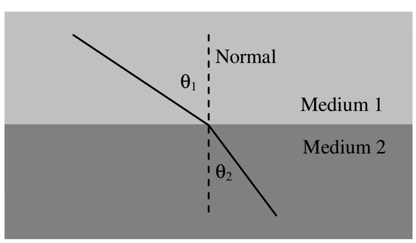
Specular reflection of a parallel beam of light



Diffuse reflection of a parallel beam of light



Refraction of a light ray



When a light ray enters a medium from a different medium at an angle to the normal, both direction and speed of the light ray change. This is called refraction of light.

If the light ray travels from medium 1 to medium 2, then $\angle i = \theta_1$ and $\angle r = \theta_2$, and the **relative refractive index** $r_{1to2} = \dfrac{\sin\theta_1}{\sin\theta_2}$. The relative refractive index can also be determined from the **absolute refractive indices** n_1 and n_2, $r_{1to2} = \dfrac{n_2}{n_1}$.

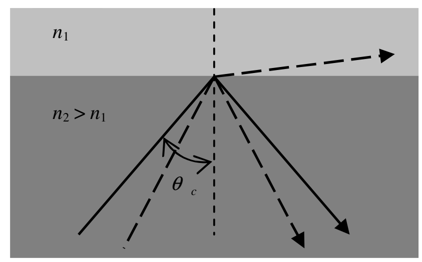
If the light ray travels from medium 2 to medium 1, then $\angle i = \theta_2$ and $\angle r = \theta_1$, and the **relative refractive index** $r_{2to1} = \dfrac{\sin\theta_2}{\sin\theta_1}$. Also, $r_{2to1} = \dfrac{n_1}{n_2} = \dfrac{1}{r_{1to2}}$.

Hence $n_1 \sin\theta_1 = n_2 \sin\theta_2$. This is known as **Snell's law**.

When a light ray enters an optically denser medium (i.e. medium of higher refractive index), its speed decreases, $v \propto \dfrac{1}{n}$ and $\dfrac{v_2}{v_1} = \dfrac{n_1}{n_2}$. In fact, $v = \dfrac{c}{n}$, where *c* is the speed of light in a vacuum ($c = 3.0\times10^8$ ms^{-1}).

When a light ray enters an optically denser medium, it always bends towards the normal, hence $\angle r < \angle i$.

When it enters a **less dense** medium, it bends away from the normal. This results in a phenomenon called **total internal reflection** if the angle of incidence $\angle i$ is sufficiently large for the two media under consideration. The minimum angle of incidence for total internal reflection to occur is called the **critical angle** θ_c for a particular colour (frequency) of light. A different critical angle results if a different combination of media is used.



When a ray (broken line) of light travels from n_2 into n_1 it splits into a refracted ray and a reflected ray at the interface. As the angle of incidence increases the refracted ray becomes dimmer and closer to the interface (angle of refraction approaches 90°), whilst the reflected ray becomes brighter.

When $\angle i = \theta_c$ (solid line), the refracted ray disappears completely and only the reflected ray remains, i.e. total internal reflection occurs.

The critical angle can be determined from Snell's law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$.

Let $\theta_1 = 90°$ and $\theta_2 = \theta_c$, then $\sin\theta_c = \dfrac{n_1}{n_2}$,

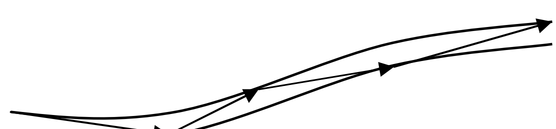
$$\therefore \theta_c = \sin^{-1}\left(\frac{n_1}{n_2}\right).$$

If medium 1 is a vacuum or air, $n_1 = 1$ or ≈ 1,

$$\therefore \theta_c = \sin^{-1}\left(\frac{1}{n_2}\right).$$

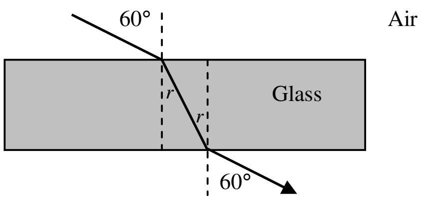
Total internal reflection is the principle behind fibre optics. Very thin (a few micrometres) glass and plastic fibres are bundled together to form a **light pipe** since light can be transmitted along it with almost no loss because of total internal reflection.

When light travels down a thin fibre, it makes only glancing collisions with the walls so that the angle of incidence is greater than the critical angle and no light can escape to the outside of the fibre.



Light travels inside a thin fibre

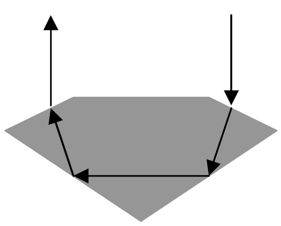
Example 1 Light hits a slab of glass ($n = 1.52$) at an angle of incidence of 60°. What is the angle of refraction? At what angle with the normal does it emerge from the glass?



Use Snell's law: $n_g \sin\theta_g = n_a \sin\theta_a$, $1.52\sin r = 1.00\sin 60°$, $r \approx 35°$.
Light ray emerges at 60° with the normal.

Example 2 Explain how a diamond achieves its brilliance. Explain how it loses its brilliance if its base is wet.

Diamond has an absolute refractive index of 2.42, which is much higher than other media, e.g. water ($n = 1.33$). Hence the critical angle for diamond-air $\theta_c = \sin^{-1}\left(\frac{1}{2.42}\right) \approx 24°$ is much smaller than that for other medium-air combinations. A smaller critical angle gives higher probability for total internal reflection of light entering the diamond from air. Thus the light retains almost all its intensity when it leaves the diamond at the uppermost surface of the diamond.



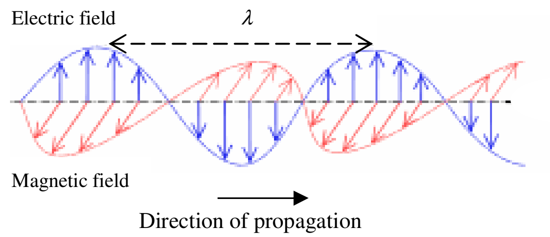
If the base of the diamond is wet, the critical angle for diamond-water is $\theta_c = \sin^{-1}\left(\frac{1.33}{2.42}\right) \approx 33°$ and it is greater than $\theta_c = 24°$ when the diamond is dry. This reduces the chance for total internal reflection and more light escapes through the base; hence the wet diamond is not as brilliant as before.

Light reflects, refracts, diffracts and interferes with each other; therefore a **wave model** is a suitable tool to describe light phenomena.

There is one important difference between light waves and the other waves mentioned previously. No medium is required for light to travel in. Light energy can be transferred from one position to another in a vacuum.

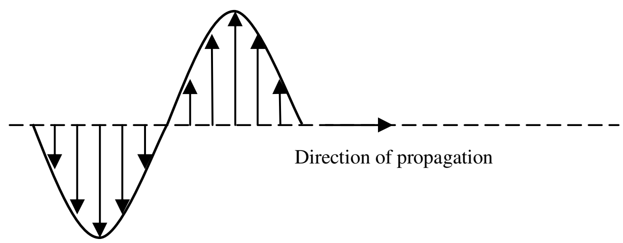
According to Maxwell light in space is an oscillating electric field 'combined' with an oscillating magnetic field. These two fields are related and they are perpendicular to each other. They are also perpendicular to the direction of propagation of the light wave; this means that light wave (an electromagnetic wave) is a *transverse* wave.

A pictorial representation of a light wave is shown below.
(Source: http://en.wikipedia.org/wiki/Electromagnetic wave)

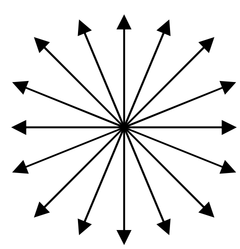


Polarisation of light

Light emitted by an excited atom is **polarised**, i.e. the oscillating electric field lies on the same plane along the direction of propagation. **Polarisation** of light is a good indicator that light as a wave is transverse.



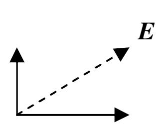
A light source (e.g. a fluorescent lamp) consists of many excited atoms emitting light independently. The light therefore consists of many independent waves that are randomly polarized about the direction of propagation. Such light is said to be **unpolarised**.



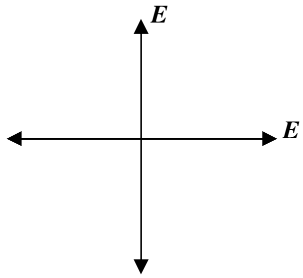
Electric field shown by the arrows

The diagram above shows an unpolarised light directed out of the page. It is made up of waves with randomly directed electric fields.

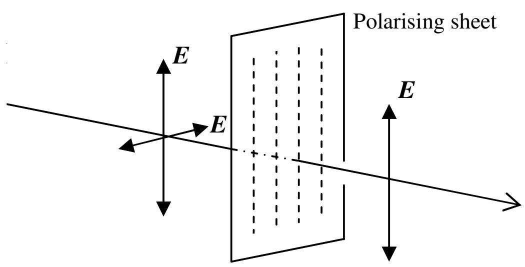
Each electric field can be resolved into two perpendicular components.



Therefore unpolarised light can be considered as two perpendicular oscillating electric fields of the same amplitude.



Unpolarised light can be made polarised by passing it through a polarising sheet (commercially known as a Polaroid sheet). A polarising sheet has a particular polarising direction on its plane that allows those components parallel to this direction and removes components perpendicular to it.



Theoretically the intensity of light is halved after passing through a polarising sheet. If a second sheet is placed in tandem with its polarising direction perpendicular to the first sheet, it is expected to block the rest from passing through.

Example 1   What do you think a third sheet will do to the light?

In fact, if you insert a third sheet between the two perpendicular sheets at about 45°, some light will pass through the three sheets. There is a quantum dynamic theory for this effect.

Visible light

Visible light is a particular region of the **spectrum of electromagnetic radiation**. Wavelength ranges from 4×10^{-7} m for violet light to 7×10^{-7} m for red light.

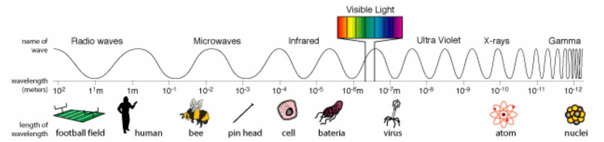
For light wave (electromagnetic wave), the wave equation is $c = f\lambda$.

Example 1   Calculate the corresponding frequencies for violet and red lights.

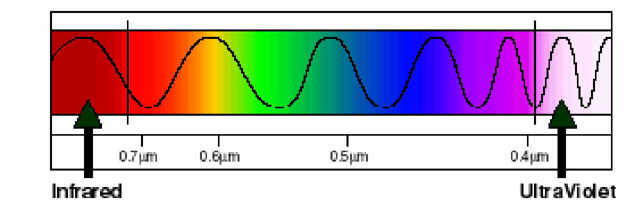
Violet light: $f = \frac{c}{\lambda} = \frac{3.0\times10^{8}}{4\times10^{-7}} \approx 8\times10^{14}$ Hz.

Red light: $f = \frac{c}{\lambda} = \frac{3.0\times10^{8}}{7\times10^{-7}} \approx 4\times10^{14}$ Hz.

The following diagrams are copied from http://science.hq.nasa.gov/kids/imagers/ems/waves3.html .

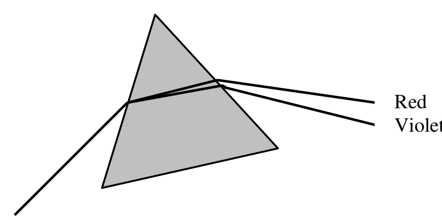


Electromagnetic spectrum



Colour components of white light

Light from the sun is called *white* light and found to compose of different colours (frequencies) of light. This can be demonstrated easily by passing a beam of sunlight through a triangular glass prism.



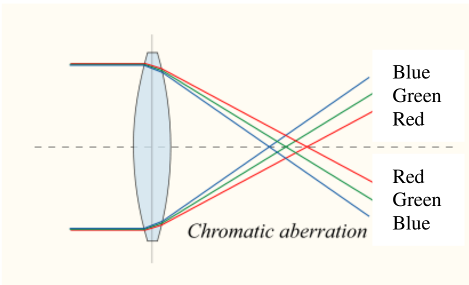
The prism separates the white light into a spectrum of colours on the screen. The spreading of white light into a full spectrum is called **dispersion**.

Dispersion occurs because the material of the prism refracts the different colour of lights to varying degrees. That is, the material has slightly different refractive indices for the different colours. Violet light (higher *n*) is bent the most and red (lower *n*) the least.

Colour	Absolute refractive index		
	Diamond	Crown glass	Water
Red	2.410	1.514	1.331
Yellow	2.418	1.517	1.333
Blue	2.450	1.528	1.340

Chromatic aberration

In optics, **chromatic aberration** is a term used to describe the effect of a lens failing to focus all colours to the same point. It occurs because lenses have a different refractive index for different frequencies of light. The refractive index increases with increasing frequency. Chromatic aberration appears as fringes of colour along boundaries that separate dark and bright parts of the image.



(Source: http://en.wikipedia.org/wiki/File:Lens6a.svg)

Speed of light in a medium

All light, irrespective of its colour, travels at the speed of light c **in a vacuum**, i.e. 3.00×10^{8} ms^{-1} (2.998×10^{8} ms^{-1} to be more precise). But once it enters a medium its speed depends on the refractive index of the medium for its colour, $v=\frac{c}{n}$.

Example 1 Compare the speeds of red and blue light in diamond.

Red light in diamond: $v=\frac{c}{n}=\frac{2.998\times10^{8}}{2.410}=1.244\times10^{8}$ ms^{-1}.

Blue light in diamond: $v=\frac{c}{n}=\frac{2.998\times10^{8}}{2.450}=1.224\times10^{8}$ ms^{-1}.

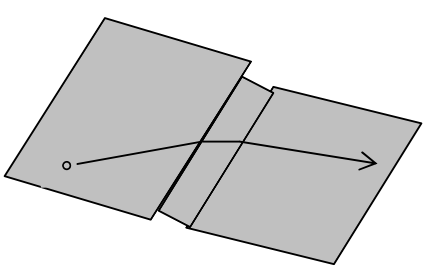
Red light travels faster in diamond than blue light.

A particle model of light

Light can be thought of as a stream of particles because it shows similar behaviours in *some* experiments.

Isaac Newton (~1665) made up a **particle model** of light to explain many of the known behaviours of light at that time. He was able to explain:

- Straight line propagation of light (Free particles move in a straight line)
- The intensity of light (Number of particles in the stream)
- Different colours (Different types of particles)
- Reflection of light from flat and curved surfaces (Particles hitting a solid surface follow the law of reflection, $\angle i=\angle r$)
- Refraction (change in direction) of light as it crosses the interface between two media.



The setup demonstrating the refraction of light consists of two horizontal levels connected with a sloping surface. A ball bearing rolls along the top level and down the slope to the lower level with a greater speed. A change in direction (towards the normal) is clearly observable. However, this demonstration fails to show that the speed of light decreases when it enters a denser medium (represented by the lower level).

He was unable to explain:

- Partial reflection and partial transmission of light at an interface
- The existence of Newton's rings and other related phenomena due to the interference of light.

Christiaan Huygens (~1678) considered light as a wave. Using a **wave model** he was able to explain all the known phenomena of light mentioned above as well as **interference** and **diffraction** of light.

