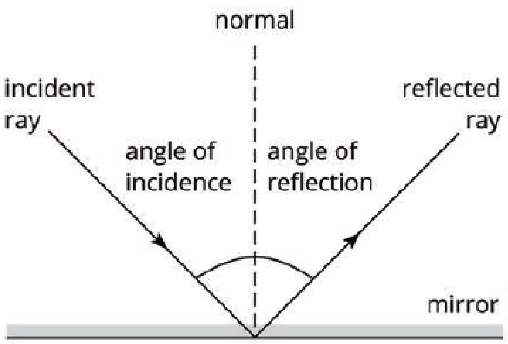
Light

Study Design

- investigate and analyse theoretically and practically the behaviour of waves including:
- refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$
- total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90^\circ)$
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another
- explain the formation of optical phenomena: rainbows; mirages
- investigate light transmission through optical fibres for communication

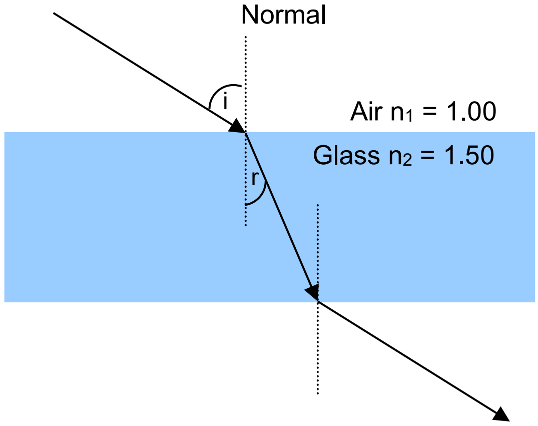


Reflection

- The **ray model of light** represents light as a very narrow beam, called a ray, which travels in a straight line in a uniform medium.
- **Regular reflection** is produced from smooth surfaces. **Diffuse reflection** is produced from rough surfaces.
- The **laws of reflection** state that when light is reflected:
  - the **angle of incidence** equals the **angle of reflection**
  - the incident ray, reflected ray and normal all lie in the same plane.
- **Luminous** objects emit light. **Non-luminous** objects reflect light from other sources.
- **Plane mirrors** are flat reflective surfaces.

Refraction of Light

A ray of light travels along a straight path within the same medium, e.g. air, water or glass. However, experiments show that when a ray of light enters one medium from another, the ray often changes direction at the point of incidence.

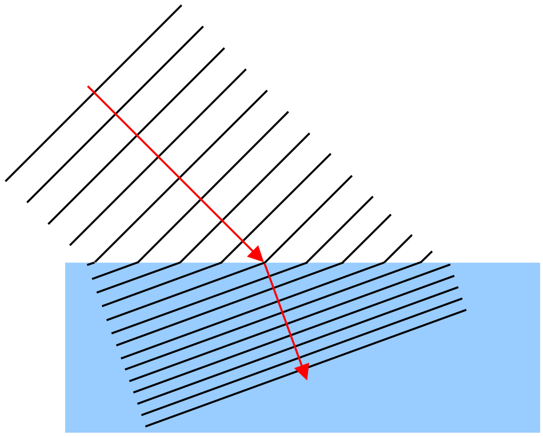


This change of direction is due to **refraction**. Refraction is the bending of the light path as it passes from one transparent material to another.

The angle between the incident ray and the normal to the boundary between the two media is called the angle of incidence. The angle between the refracted ray and the normal is called the angle of refraction. The change of direction depends on the angle of incidence and the media.

Why Light Refracts

Light travels at different speeds in different materials. In a vacuum, it travels at 3×10^8 m s^{-1}. In other transparent materials, such as glass and water, the speed is reduced. This reduction in speed causes the wavefront in the material to lag behind the wavefront outside the material. This causes the direction of the wavefront to change as shown in the diagram below.



The amount of refraction depends on the change of speed between the two materials. If there is not a change in speed, the wavefront will not change direction at all. If the change in speed is large, then a large amount of bending will occur.

Notice that the wavefronts have become closer together in the medium. This means that the wavelength of the light has been reduced. Because the speed of the wave has also been reduced the frequency of the wave will stay the same $f = \frac{v}{\lambda} = \text{constant}$

Refractive Index

Although it is the speed of light in a material that determines how much refraction occurs, speeds can be cumbersome numbers to deal with. Instead, we define another quantity called the refractive index (*n*), which is equal to the speed of light in a vacuum (*c*), divided by the speed of light in the material (*v*)

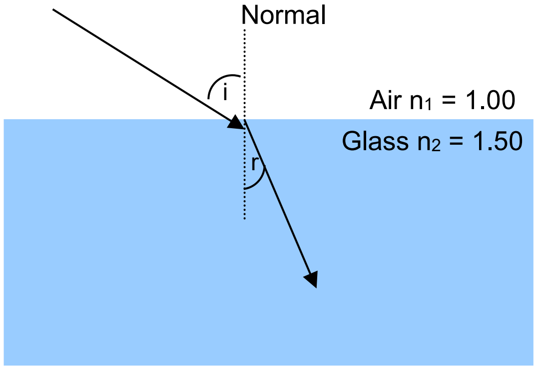
$$n = \frac{c}{v}$$

The table below shows the speed of light in different mediums and the refractive index in these materials, using a wavelength of 589 nm and a temperature of 20^0.

Medium	Speed of light (ms^{-1})	Absolute refractive index
Vacuum	3.0×10^8	1.00000
Air	3.0×10^8	1.000293
Water	2.25×10^8	1.333
Silica	2.0×10^8	1.458
Glycerine	2.0×10^8	1.473
Diamond	1.24×10^8	2.419

When light goes from a medium of low refractive index to one of high refractive index, the light ray will bend towards the normal. Conversely, when light goes from a medium of high refractive index to one of low refractive index, the light ray will bend away from the normal.

Snell's Law



The amount of refraction can be determined using Snell's Law.

$$\mathbf{n_1 \sin i = n_2 \sin r}$$

or

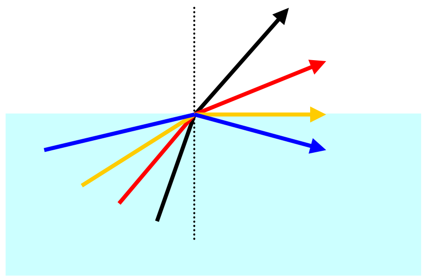
$$\frac{\sin i}{\sin r} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

or

$$\mathbf{n_1 v_1 = n_2 v_2}$$

Where v_1 = speed of light in medium 1,
v_2 = speed of light in medium 2,
n_1 = absolute refractive index of medium 1
n_2 = absolute refractive index of medium 2

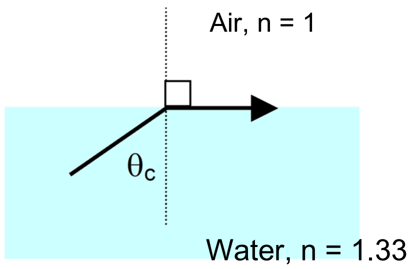
Total Internal Reflection



When light travels from a medium of high refractive index to a medium of low refractive index, it bends away from the normal, as shown in the diagram below. Eventually, and angle of incidence is reached such that the refracted ray skims along the surface of the medium (the orange line in the diagram). If the angles of incidence are greater that this angle, then the refracted ray will not leave the material. It will be *totally internally reflected*. In the diagram, the blue ray has been totally internally reflected.

The Critical Angle

The critical angle is the angle at which the refracted way will skim across the surface of the material (the orange ray above). For angles of incidence greater than this critical angle, the ray will be totally internally reflected. The critical angle can be calculated using *Snell's Law*.



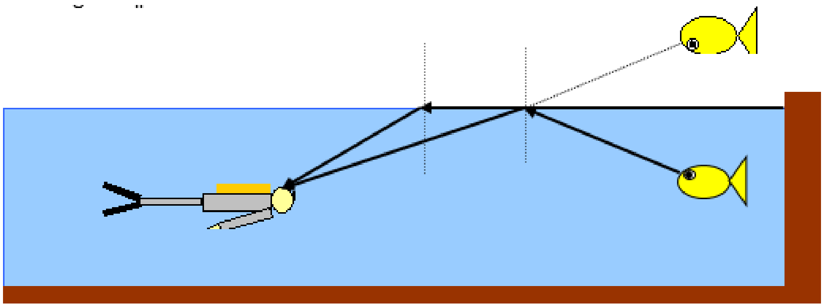
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$1.33 \sin\theta_c = 1 \sin 90$$

$$\sin\theta_c = \frac{1}{1.33}$$

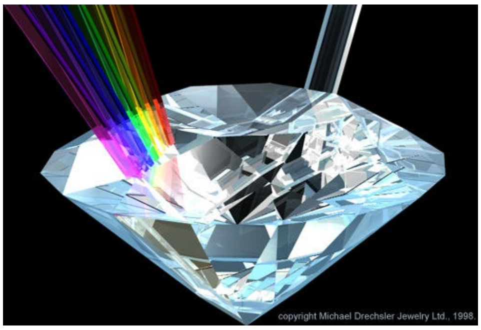
$$\theta_c = 48.8$$

Total Internal Reflection in Water



A person who is underwater and looking towards the sky will see a distorted view of the world. When the diver looks at an angle of 48.8° to the vertical (the critical angle), he sees the light from the bank. If he looks at an angle bigger than that, he will see the bottom of the pool reflected in the water's surface. Because of total internal reflection the diver sees an image of a fish in the sky as shown in the diagram.

Refraction in Diamonds

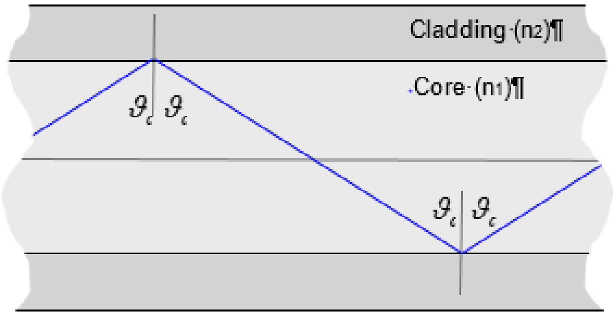


Jewellers cut gems, such as diamonds, to make them appear luminescent. They achieve this by making angles within the crystal that will totally internally reflect light. Hence any light that enters the diamond is totally internally reflected and comes back out again. This is how a diamond appears to sparkle even though no light can pass through the metal mount that holds the diamond in place. Diamonds are used because they have the highest refractive index of any material and thus they have the smallest critical angle.

Fibre Optic Cable

An optical fibre can be modelled as a pipe with like being shone down it. Total internal reflection can be used to transmit light signals down optical fibres.

If light travels along the fibre at an angle greater than the critical angle, it will totally internally reflect in the fibre and will bounce along the fibre. If the light comes in at too steep and angle, it will escape the fibre.



Optical Fibre Network

In an optical fibre network, and electronic signal, from a phone or a computer, is converted to a light signal. The light signal is transmitted along an optical fibre at the speed of light towards its destination. Once the signal has reached its destination, it is converted back to an electrical signal for use by an appliance.

Optical fibre networks have many advantages over the copper wire networks. The main advantage is the amount of data that can be sent down one fibre. Another advantage is that the fibre transmits an optical signal and therefore it will be unaffected by electrostatic interference, from things like thunderstorms and power lines.

Changing refractive index

The refractive index of a material is actually an average refractive index for that material. This is because the refractive index of a material depends on the wavelength of light travelling through the material. For example; the refractive index of silica ranges from 1.55 for light at a wavelength of 200nm, to 1.46 for light at 700nm. This is a large difference in speed and therefore a large difference in the angle of refraction. The effect that this has is to separate the colours of white light. This process is known as **dispersion**.