Refraction

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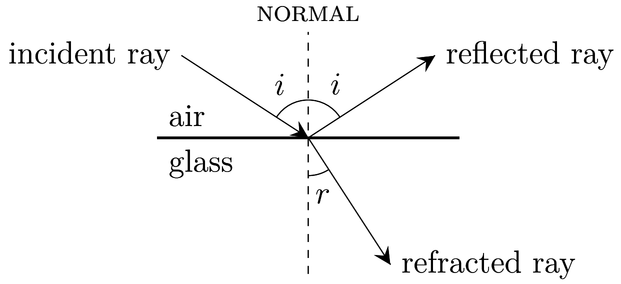
Refraction at a plane surface

All electromagnetic waves travel at a speed $c = 3 \times 10^8\ \mathrm{m\,s^{-1}}$ in a vacuum. However, when light enters a more *optically dense* medium such as water or glass, it travels more slowly. This leads to *refraction*, meaning bending of the light's path as it enters the medium.



When light slows down in moving from one medium to another, it bends towards the *normal*, an imaginary line at 90° to the interface[1]. This means that the angle of refraction r, measured between the refracted ray and the normal, is less than the angle of incidence i, measured between the incident ray and the normal. There is also usually some light reflected at the boundary between the two substances, and this follows the familiar law of reflexion, i.e. the angle of reflexion is equal to the angle of incidence i and is in the same plane.

Note that the frequency of the wave is unchanged as it refracts (this is a property of the source not the medium). Since the speed of the wave has changed, the wavelength must also change, because of the wave equation $v = f\lambda$. This can be seen most easily with shallow water waves, which slow down when they enter a shallower area, refracting and decreasing their wavelength.

[1] When light speeds up at the interface between two media, it bends away from the normal, as we shall see later.

Comments on page 1

Why is the speed of light 3x10^8 m/s?

What does it mean by "optically dense"?

What is optically dense?

What affects optical density? e.g. particles closer together or their clarity/clearness?

What slows down the light in different optical densities? Is it similar to particles losing energy through collisions or completely different?

What causes a material to be opaque, i.e. why can some materials refract light and others not?

I don't understand how it reflects and refracts...

Why does a mirror reflect all the incident light, rather than refract it?

Is the angle from the incident ray to the normal always equal to the angle from the reflected ray to the normal?

Refractive index

The *refractive index* of a medium is the ratio of the speed of light in a vacuum c to its speed in that particular medium c_s.

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

Since the refractive index is a ratio of speeds, it is a pure number having no dimensions. For example, the refractive index of water is 1.33, meaning that light travels 1.33 times faster in a vacuum than it does in water. Some refractive indexes of common substances are given below.

medium	refractive index
vacuum	1 (definition)
air	1.0003
water	1.33
crown glass	1.52
diamond	2.42

Snell's law

An accurate description of the geometry[2] of refraction can be given as follows:

1. The incident ray, refracted ray and the normal (drawn at the point of incidence) are all in the same plane.

2. For a given medium

$$\frac{\sin i}{\sin r} = \text{constant}.$$

   This is known as Snell's law[3], and the constant turns out to be the ratio of the refractive indices of the two media at the interface (and therefore the ratio of the speeds of light in the two media also).

A more general form of the refraction equation, for light passing from material 1, having refractive index n_1, into material 2 of refractive index n_2 is

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

[2]If you want to take care of the polarization and the reflected and transmitted intensities, too, you need the Fresnel equations (see a book such as Hecht's *Optics*).

[3]After Dutch astronomer Willebrord Snellius (1580–1626), though he was not the first to describe or use it.

How can you find the refractive index?

What determines this refractive index?

What does it mean by "1 (definition)"

What is crown glass? is it just glass?

What's geometry squared?

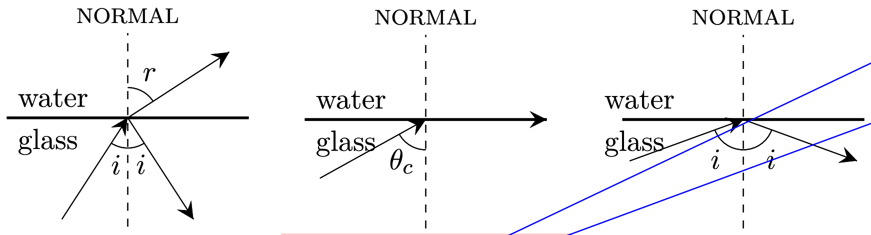
You could add triangles to show how this is derived.

Don't understand this equation.

Why is it named after him then? Who described it first?

Total Internal Reflexion

When light passes from a medium into one of lower of refractive index (meaning that it speeds up in the process) it will have an angle of refraction greater than the angle of incidence.



For small i, most light is refracted into the water at an angle $r > i$, but there is partial internal reflexion also.

A critical angle of incidence $i = \theta_c$ is reached and no light leaves the surface; the refracted ray travels along the boundary of the media, at 90° to the normal.

For $i > \theta_c$, total internal reflexion occurs. No light is emitted into the water.

e.g. For light travelling from glass ($n_1 = 1.52$) into air ($n_2 = 1$), we can find θ_c using Snell's law and the fact that θ_c is the angle of incidence for which the angle of refraction is 90°:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
$$\sin\theta_1 = \frac{n_2 \sin\theta_2}{n_1}$$
$$\sin\theta_c = \frac{1 \times \sin(90^\circ)}{1.52}$$
$$= 41.1^\circ.$$

Application: Fibre Optics

Light can be piped by total internal reflexion inside a glass (or plastic) tube which can guide it along a curve path. So long as each angle of incidence with the outisde of the tube is less than the critical angle for the material used, no light will escape from the tube. This has a wide variety of applications, from illuminating awkward spots for inspection, to medical examination of internal organs via endoscopy, to transmission of information in a fibre optic cable.

A typical optical fibre comprises a central core with a fairly high refractive index, surrounded by a cladding material of lower refractive index which will keep the light confined to the core by total internal reflexion.

Comments on page 3

I presume the critical angle is different for different surfaces?

I don't understand the r>i i=thetac i>thetac notation here.

How does information get converted into light and back again in fibre optic cables?

How do fibre optic cables send information?