Refraction of Light

The speed of light in a vacuum is

$$c = 3.00 \times 10^8 \ m/s$$

In air, the speed is only slightly less. In other transparent materials, such as glass and water, the speed is always less than that in a vacuum. The ratio of the speed of light in a vacuum to the speed v in a given material is called the **index of refraction**, n, of that material:

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

The index of refraction is never less than 1. Some common indices of refraction are listed below.

Medium	$n = c/v$
Vacuum	1.00
Air	1.00
Water	1.33
Ethyl Alcohol	1.36
Glass	
Fused Quartz	1.46
Crown Glass	1.52
Flint Glass	1.58
Lucite or Plexiglass	1.51
Sodium Chloride	1.53
Diamond	2.42

Example 1 Speed of light in a diamond.
Calculate the speed of light in a diamond ($n = 2.42$).

When light passes from one transparent medium into another with a different index of refraction, part of the incident light is reflected at the boundary. The remainder passes into the new medium. If the ray of light is incident at an angle (other than perpendicular), the ray changes direction, or **refracts**, as it enters the new medium.
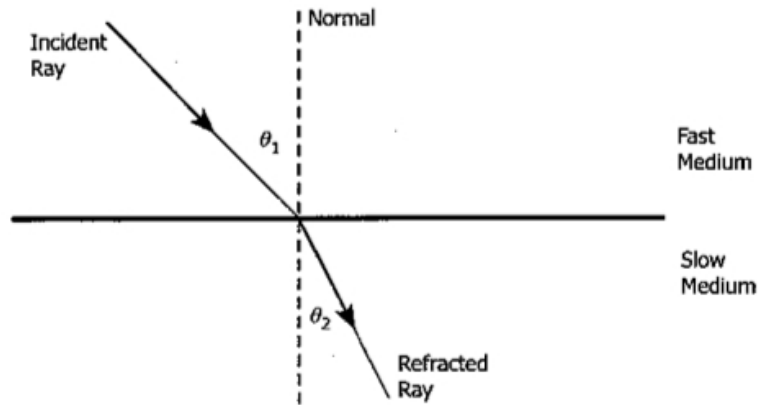
The angle of refraction depends on the speed of light in the two media and on the incident angle. A mathematical relationship between these quantities, known as **Snell's law**, states:

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

Snell's law is equivalent to the law of refraction developed earlier, but the concept of the index of refraction only applies to light, while the law applies to waves as well.

Example 2 Refraction through flat glass.
Light traveling in air strikes a flat piece of uniformly thick glass at an incident angle of $60°$. If the index of refraction of the glass is 1.50, (a) what is the angle of refraction in the glass and (b) what is the angle at which the ray emerges from the glass?

Total Internal Reflection

When light passes from one material into a second material with a smaller index of refraction (say, from water into air), the light bends away from the normal. At a particular incident angle, the angle of refraction will be $90°$, and the light will reflect instead of refracting. The incident angle at which this occurs is called the **critical angle**, θ_c, and is given by:

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

This phenomenon is known as **total internal reflection**.

Example 3 Water to air.
Determine the critical angle for a water-to-air interface. The index of air is 1.00 and that of water is 1.33.

Refraction Worksheet

1. Calculate the speed of light in each of the following mediums.

    a) Water ($2.25 \times 10^8 \ m/s$)
    b) Diamond ($1.24 \times 10^8 \ m/s$)
    c) Plexiglas ($1.99 \times 10^8 \ m/s$)

2. Calculate the index of refraction for a substance if the speed of light in that medium is

    a) $2.1 \times 10^8 \ m/s$ (1.43)
    b) $1.5 \times 10^8 \ m/s$ (2.00)

3. Calculate the angle of refraction for light as it passes from air to each of the mediums below. Assume that the angle of incidence is $25°$.

    a) Water ($18.5°$)
    b) Diamond ($10.1°$)
    c) Plexiglas ($16.3°$)

4. A ray of light is traveling in water when it strikes the boundary between water and a second medium at an incident angle of $20°$. If the angle of refraction in the second medium is $15°$,

    a) is the second medium more optically dense than the first medium, or less optically dense?
    b) find the index of refraction of the second medium. (1.76)
    c) find the speed of light in each medium. ($2.25 \times 10^8 \ m/s$, $1.71 \times 10^8 \ m/s$)

5. Repeat question 5, but assume the angle of refraction in the second medium is $25°$. (1.08, $2.79 \times 10^8 \ m/s$)

6. An aquarium filled with water has flat glass sides whose index of refraction is 1.52. A beam of light from outside the aquarium strikes the glass at a $43.5°$ angle to the perpendicular (see diagram below).
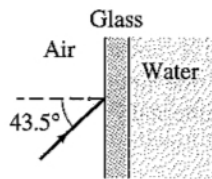
    a) What is the angle of this light ray when it enters the glass? ($26.9°$)
    b) What is the angle of this light ray when it enters the water? ($31.2°$)

7. What is the critical angle for the interface between water and Lucite? To be totally internally reflected, the light must start in which material? ($61.7°$)

8. The critical angle for a certain liquid-air surface is $47.7°$. What is the index of refraction of the liquid? (1.35)

9. A beam of light is emitted $8.0 \, cm$ beneath the surface of a liquid and strikes the surface $7.0 \, cm$ from the point directly above the source. If total internal reflection occurs, and the second medium is air, what is the index of refraction of the liquid? (1.52)