PHY 171

Lecture 7

(*January 25, 2012*)

Refraction of Light

The bending of light when it passes from one medium to another is called refraction.

We will discuss some aspects of refraction and its consequences below.

Speed of light in vacuum

Light travels fastest in vacuum, at a speed of $c = 3 \times 10^8$ m/s.

Index of refraction, *n*

The ratio of the speed of light in vacuum to its speed v in a given material is called the index of refraction n of that material:

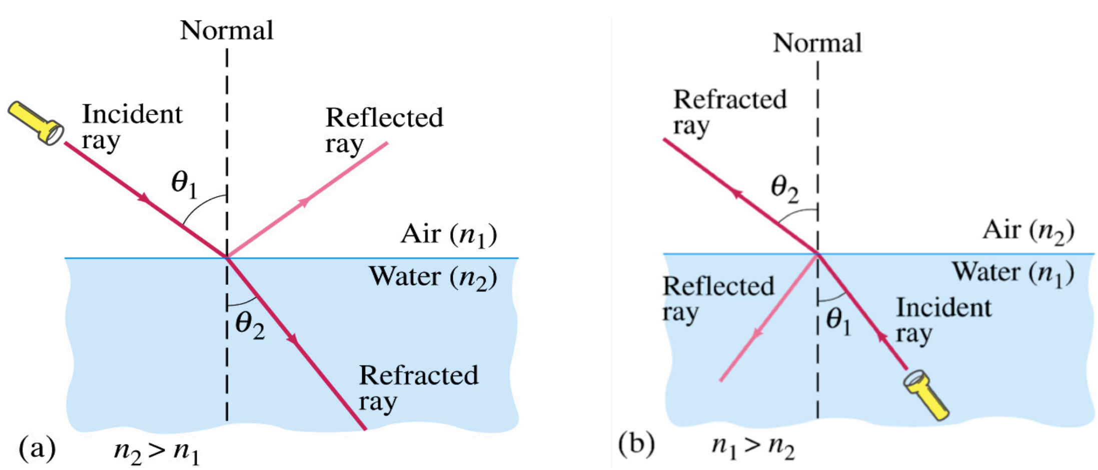
$$n = \frac{c}{v}$$

Since light travels fastest in vacuum, v is always less than c. So, the refractive index n of a medium will always be greater than 1.

Path of refracted light

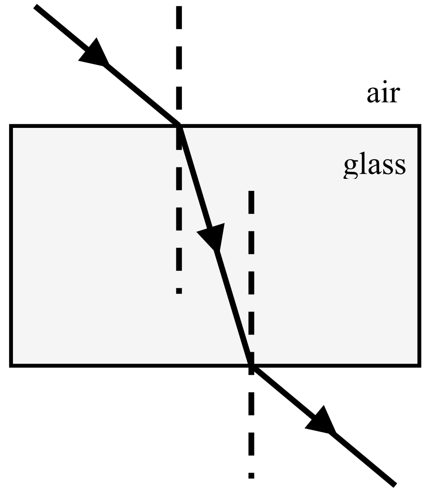
We looked at the following demonstrations in Blackboard optics:

- When a ray of light is incident perpendicular (at 90°) to a medium, it goes straight through without bending. Such a ray is called the *normal*. The normal is marked by a dashed line in both figures below.
- When a ray of light goes from a less dense medium (e.g., air) to a denser medium (e.g., water), it bends *toward the normal*. This is shown in Fig. (a) below.
- When a ray of light goes from a denser medium to a less dense medium, it bends *away from the normal*. This is shown in Fig. (b) below.



Refraction through a glass block

We demonstrated this with Blackboard Optics equipment. The ray of light bends toward the normal in going from air to glass (as expected, since glass is denser than air), then bend away from the normal in emerging from glass into air (again as expected, since air is less dense than glass).



Snell's Law

Consider a ray of light going from medium 1 (index of refraction n_1) to medium 2 (index of refraction n_2), so that

- the angle of incidence is θ_1
- the angle of refraction is θ_2

Then, the relations between these quantities are governed by Snell's law, which states that

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

Often in the problems we will be working, one of the two media will be air. *You should remember* that the index of refraction of air is, for all our purposes, equal to 1.

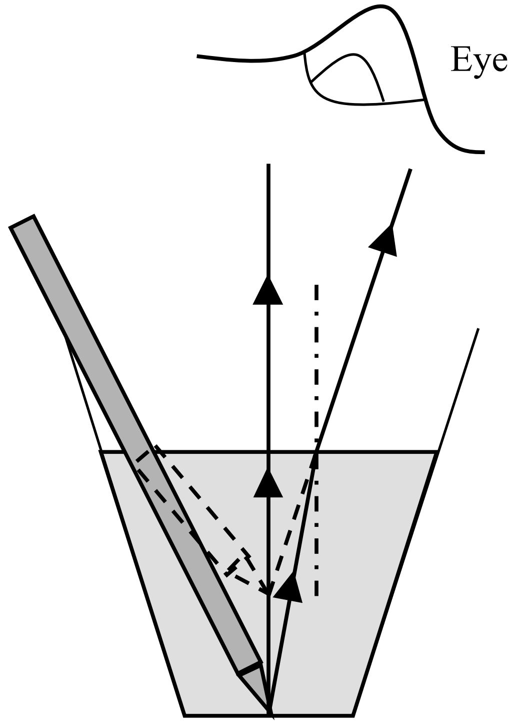
Consequences of refraction (Invisible tube demo)

We will study the following consequences/effects of the refraction of light.

- Apparent depth –
  - Bottom of a pool appears raised
  - Pencil dipped in water appears bent
- Total Internal Reflection – used in fiber optic cables
- (Chromatic) Dispersion
- Lenses

Apparent Depth

This is best explained by drawing a ray diagram.



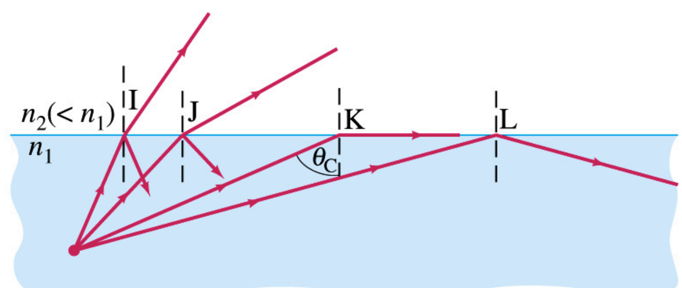
Recall from an earlier lecture that you need at least two rays coming from a source to locate the position of the image. In the present case, it is best to let one of the rays be at normal incidence from water to air. Then, you need let only the second ray refract (away from the normal) by following Snell's law (see figure on the right). The eye, positioned above the water surface, then follows these two rays back in a straight line, and where they meet is where you see the location of the bottom of the water pool, or the tip of the pencil.

As is clear from the figure, the tip of the pencil appears nearer, so the pencil appears bent under water. Likewise, you perceive the bottom to be nearer to you than where it is actually located.

Total Internal Reflection

Let us ask ourselves what happens to a ray going from a denser medium (e.g., water) to a less dense medium (e.g., air), as we increase the angle of incidence.

As we increase the angle of incidence, the angle of refraction also increases (recall Snell's law). In the figure on the right, this is clear in going from ray I to ray J.



So, as we keep increasing the angle of incidence, we will get a situation for which the angle of refraction is 90°, that is, the refracted ray moves along the interface between the two media (ray K in the figure).

If we increase the angle of incidence above this value, the ray will be reflected back completely into the denser medium; no part of the incident ray is refracted (ray L in the figure above). This phenomenon is known as *total internal reflection*.

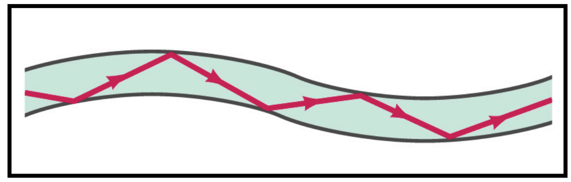
For a ray of light going from a denser medium to a less dense medium, the angle of incidence for which the angle of refraction is 90° is called the *critical angle* θ_C for the two media concerned. It can be calculated easily from Snell's law:

$$n_1 \sin\theta_C = n_2 \sin 90^\circ, \text{ which gives } \sin\theta_C = \frac{n_2}{n_1}$$

In particular, if the second medium is air ($n_2 = 1$), we get $$\sin\theta_C = \frac{1}{n_1}$$

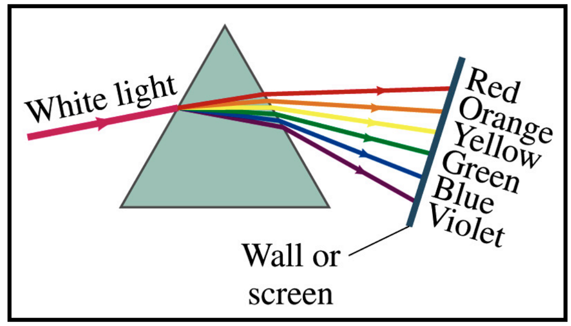
Application of Total Internal Reflection: Fiber Optics

Fiber optic cables are based on total internal reflection. Recall that 100% of the light is reflected in this process; even the best mirrors cannot achieve this.



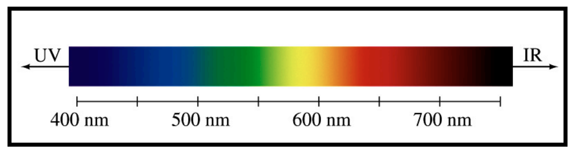
(Chromatic) Dispersion of Light

We demonstrated this process using Blackboard Optics equipment. When white light is passed through a prism, it breaks up into its constituent colors. We see a spectrum from red to violet on the other side.

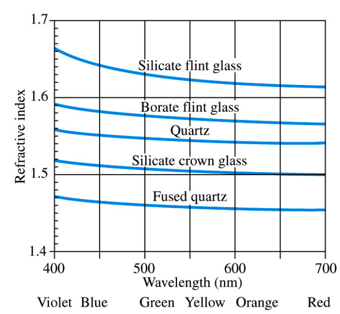


We concluded that this process occurs because the index of refraction (n) is different for different colors of light.

Note also that each color of light corresponds to a unique frequency, as shown in the spectrum of colors to the right (wavelengths are marked in the figure instead of frequency). The visible spectrum goes from approximately 400 nm (violet) to 750 nm (red).



As an example of the variation of index of refraction with color (frequency), see the graph on the right in which the index of refraction (called "refractive index" in the graph) is plotted against the wavelength of light (with prominent colors noted below the corresponding wavelengths). Notice that the index of refraction is higher for violet/blue than for red. In fact, this explains why violet bends more than red (see the figure showing white light dispersing after passing through a prism above).



We worked the following problem to calculate this explicitly:

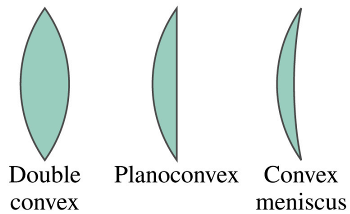
A ray of light is incident on a block of silicate flint glass at an angle of incidence equal to 40.0°. The index of refraction in silicate flint glass for red light is 1.62, whereas that for blue light is 1.66. Find the angle of refraction for red and blue light.

Using Snell's law, you found that the angle of refraction for the ray of red light is 23.4°, whereas for blue light it is 22.8°. This shows that the ray of blue light is closer to the normal, meaning that violet/blue bends more than red.

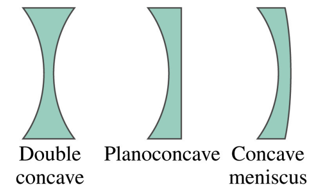
Lenses

A practical application of the phenomenon of refraction is in lenses. Ever since Galileo turned the first ones toward the heavens, lenses have proved an extremely effective tool in a variety of equipment. Since most of the treatment parallels that of spherical mirrors (except that now you have refraction to the other side), we will learn about lenses here very concisely. Also, you will learn more about them in lab.

Lenses can be of various kinds:



(a) Converging lenses



(b) Diverging lenses

However, we will use only double convex and double concave lenses in all our figures.

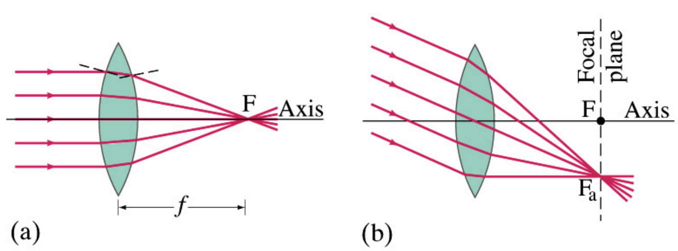
Thin Lenses

Another important assumption we will make is that the lenses are *thin*, meaning that instead of considering two refractions (one at each surface), we will draw our figures with one bending at the center line of the lens (i.e., at a straight line through the center and apex of the lens).

Converging and Diverging Lenses

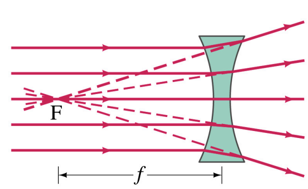
A convex lens is known as a *converging* lens, because it brings parallel rays to a focus.

> Note that this behavior is *opposite to that of a convex mirror* (from which the rays diverge upon reflection)



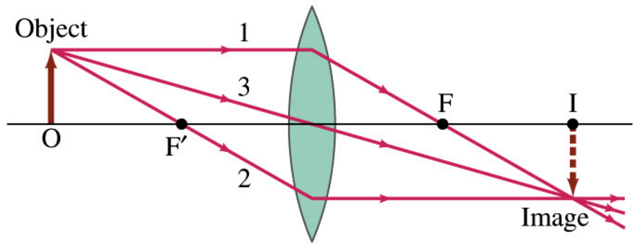
A concave lens is known as a diverging lens, because parallel rays appear to diverge from a focus after refraction.

> Note again that this behavior is *opposite to that of a concave mirror* (which brings the rays to a focus after reflection).



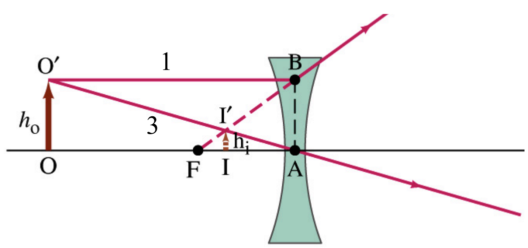
Locating Images for Convex Lenses - 3 rules

1. A ray parallel to the principal axis will pass through the focus after refraction through a convex lens. *This is shown by ray 1 in the figure below.*
2. A ray passing through the focus of a convex lens will become parallel to the principal axis after refraction. *This is shown by ray 2 in the figure below.*
3. A ray passing through the (geometric) center of the lens will pass through undeflected (i.e., without any bending). *This is shown by ray 3 in the figure below.*



Locating Images for Concave Lenses - 2 rules

1. A ray parallel to the principal axis will appear to diverge from the focus after refraction through a concave lens. *This is shown by ray 1 in the figure below.*
2. A ray passing through the (geometric) center of the lens will pass through undeflected (i.e., without any bending). *This is shown by ray 3 in the figure below.*



The Lens Equation for Convex and Concave Lenses

From geometry, we can easily show that

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$$

where d_o is the ***object distance*** (distance of the object from the lens, usually measured along the principal axis)

d_i is the ***image distance*** (distance of the image from the lens, usually measured along the principal axis)

and f is the ***focal length*** of the lens (distance from the focus to the geometric center of the lens)

This equation is applicable to both convex and concave lenses, provided the appropriate sign conventions are used — see below.

Magnification

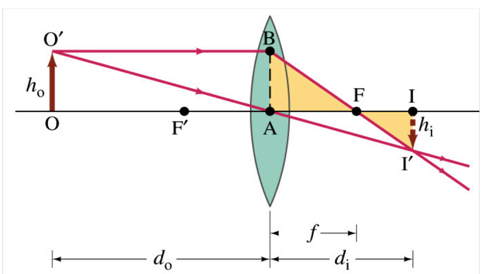
The magnification of the image is given by

$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

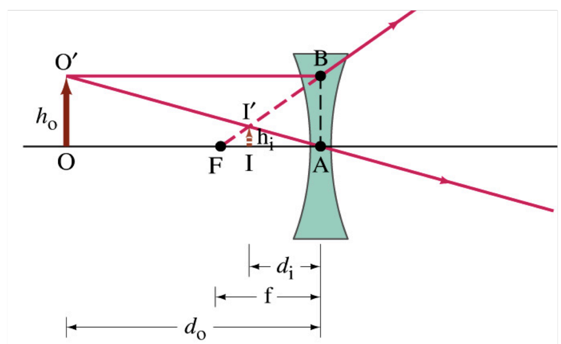
The minus sign above is inserted as part of the sign convention (given below).

Sign Convention

- The focal length *f* is positive for a convex (converging) lens, and negative for a concave (diverging) lens.
- The object distance (d_o) is positive if it is on the side of the lens from which the light is coming, otherwise it is negative (the latter situation usually occurs when you combine more than one lens in an imaging system).
- The image distance (d_i) is positive if it is on the opposite side of the lens from where the light is coming, negative if it is on the same side. Examples are given below.



$d_i = +$



$d_i = -$

- Consider object height as positive (always). Then, image height is positive if image is upright, negative if inverted relative to object.
  In the figure above, the image height is negative for the situation on the left, and positive for that on the right.

In a later meeting, you will be given a worksheet to locate the image in a convex lens for different positions of the object, and predict the characteristics of the image (just as you did for spherical mirrors).

You will also do labs on this topic.