Physics 102 Makeup Lab: Geometric Optics I: Snell's Law

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Theoretical Discussion

There are several different ways to answer the question "what is light?". On the one hand, it is known that light is a massless particle, which we call a photon. These photons can have any energy, but they all travel in vacuum at the same speed—2.99792458×10^8 m/s. This number is "exact"—has no uncertainty—because the standard meter is *defined* in terms of the speed of light. On the other hand, light can be successfully modeled as a wave—an electro-magnetic pulse—whose wavelength is inversely proportional to the energy of the wave.

In fact, both descriptions of light are correct; the question of whether a given description is useful depends upon the circumstances under which the light is observed. In particular, if the characteristic sizes of the objects with which the light interacts are large compared to the wavelength of the light, then the wave model is valid. The study of optical phenomena for which this condition is true is called "geometric optics". Since the wavelengths of visible light are roughly in the range from 400–600 nm, it is clear that the interactions of visible light with macroscopic objects like lenses and prisms can be understood using geometric optics.

The index of refraction: The index of refraction n of a material is a measure of the speed of light in that material. It is defined as the ratio of the speed of light in vacuum c to the speed of light in the medium v.

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

Because the index of refraction is a ratio of two speeds, it is dimensionless; i.e., it has no units. Naturally, the index of refraction of vacuum is one. The index of refraction of air, which depends weakly on the temperature and density of the air, is very nearly one as well, and we will use this approximation in our lab today.

When a light ray goes from one transparent medium to another, part of it will be *reflected*, which means that it will appear to "bounce" off of the interface back into the medium from which it originated. Another part of it will appear to enter the second medium. This beam is said to be *refracted*. In general, the direction of the refracted ray will be different than the direction of the incident ray. Incident, reflected, and refracted rays at the interface of two transparent media are shown in figure 1.

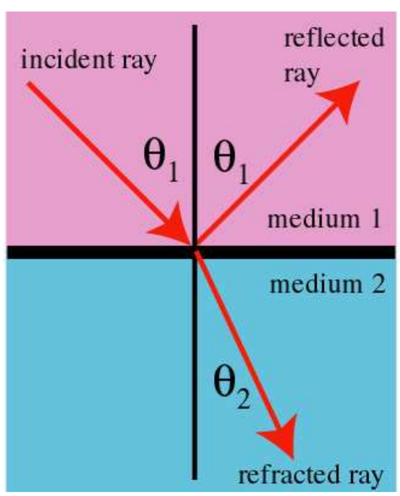

FIG. 1: Geometry of incident, reflected, and refracted rays in an optical medium

Two "laws" relate the various directions taken by the incident, reflected and refracted light rays. The first, that the angle of incidence is equal to the angle of reflection, is implicit in figure 1. The consequences of this law are apparent when you look into a mirror from the side: You do not see yourself. Instead, you see the light rays coming from objects whose angle of incidence with respect to the normal to the mirror's surface is equal to the angle your line of sight makes with the normal to the mirror's surface.

The second law is known as Snell's law. It relates the incidence and refraction angles, θ_1 and θ_2, respectively, to the indices of refraction of the two media. If n_1 and n_2 are the indices of refraction of media one and media two, then Snell's law states that

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

Procedure

There are many possible ways to measure the index of refraction of a transparent solid. Here is one method that will work with a transparent cube and a visible-spectrum laser. Your instructor may suggest a different method, or you may be asked to devise a method of your own.

1. Measure the length s of one side of the cube.
2. Place the cube on a sheet of paper and place another sheet of paper vertically behind the cube, as shown in figure 2A. It might be smart to mark the locations of the cube edges on the horizontal sheet.
3. Shine a laser through the cube. Use the largest possible angle of incidence that keeps the beam within the confines of the cube throughout its trajectory from the front to the back edge. Mark the points where the laser enters and leaves the cube. The purpose of the backing paper should now become clear; it helps you to locate the exit point.

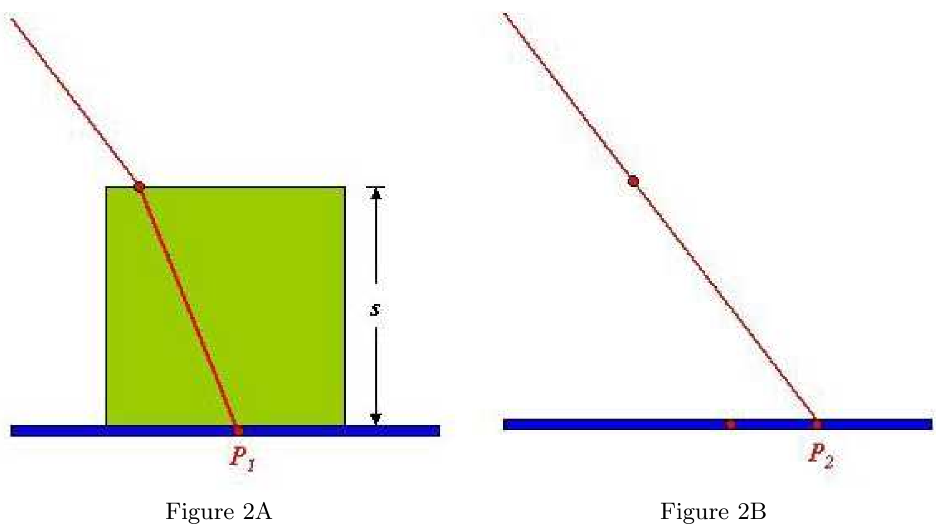

FIG. 2: Procedure for measuring incidence and refraction angles in a transparent cube

4. Gently slide the cube out of the path of the laser, being careful not to move the backing paper. Mark the point where the laser beam hits the paper, as shown in figure 2B.
5. If the beam had come in at zero angle of incidence, it would not be deflected, whether or not the cube was there. The distance between the undeflected beam and the exit point P_1 of the beam at non-zero incidence angle, with the cube in place, can be labeled l_1, as shown in figure 3A. Taking the arctangent of the ratio of l_1 to s gives the refraction angle θ_1; i.e.,

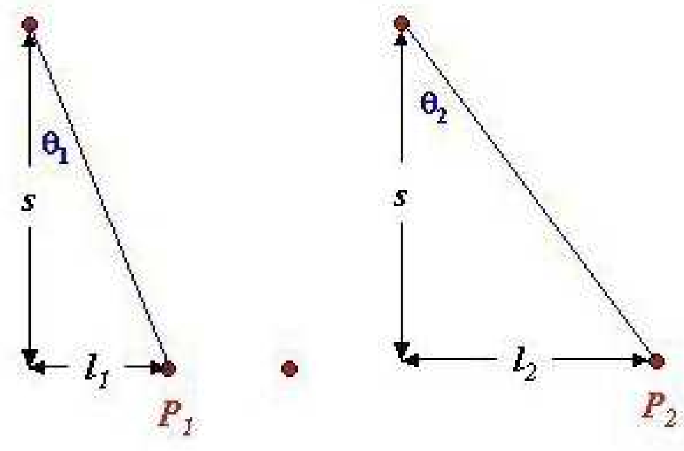

Figure 3A Figure 3B

FIG. 3: Analysis of measurements to determine the incidence and refraction angles of a transparent cube

$$\theta_1 = \tan^{-1}\left(\frac{l_1}{s}\right)$$

6. Likewise, the distance l_2 between the undeflected beam and the exit point P_2 of the beam at non-zero incidence angle without the cube in place—labeled l_2, in figure 3B—yields the angle of incidence θ_2 according to the equation

$$\theta_2 = \tan^{-1}\left(\frac{l_2}{s}\right)$$

7. Assuming that the index of refraction of air (the incident medium) is one, the index of refraction of the cube can easily be found from Snell's law. Note that θ_1 and θ_2 in the analysis may not be the same as the θ_1 and θ_2 of equation 1.