Lab 16

Refraction and Lenses

Continuing Objectives

4. Be able to make careful measurements to ensure reproducible results.

5. Know how to keep a clear and organized record, including an introduction (with purpose of lab and appropriate laws or equations), apparatus sketch, table of raw data and calculated quantities, and a good conclusion or summary.

7. Know how to make comparisons: are two measured quantities equal? Is a measured quantity statistically equivalent to a theoretical value?

Introduction

When light interacts with matter it can be *absorbed*, *reflected*, and/or *transmitted*. What will happen depends both on the material and on the frequency of the light. For example, water is transparent for visible light. Microwave radiation, on the other hand, is strongly absorbed by water (this is the principle behind microwave ovens). Wood and paper, by contrast, absorb or reflect visible light, but allow radio waves to pass.

In this lab, you will explore *refraction*: the bending of light when it passes from one material into another. You'll also learn how the ideas of refraction connect to fiber optics and bending light along a curving path. Finally, you'll see how refraction allows a lens to bend and focus light and to form images, similar to how a camera or the lens in your eye forms images.

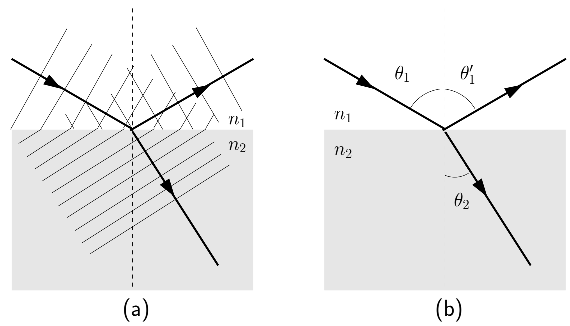


Figure 16.1: Two representations to describe the propagation of light across an interface: (a) propagating wavefronts; (b) rays. Note: all the angles in this lab are measured from the *normal*, i.e., from a line that is perpendicular to the plane of the interface.

Theory

Light travels through the vacuum of space at the speed $c = 3.0 \times 10^8$ m/s relative to any observer, but light slows down when it passes through matter. The speed at which light passes through a material is characterized by the *index of refraction* of the material, usually given the symbol n, which is defined as the ratio

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v}, \tag{16.1}$$

where v is the speed of light in the material (the *medium*). The index of refraction depends critically on the properties of the material (chemical composition, density, temperature, pressure), as well as the wavelength of the light passing through. Air has an index of refraction that is almost exactly one, i.e., light travels almost as fast in air as in a vacuum. For everything else, n is greater than 1, since light in a material can never propagate faster than light in vacuum.

When a beam of light hits the interface between two different materials, part of the light is reflected and part is transmitted into the second medium. Because of the difference in propagation speeds, the transmitted light bends with respect to the incident beam as shown in Figure 16.1. In Figure 16.1(a), the light is represented as a series of propagating wavefronts; in Figure 16.1(b), light is represented by a beam or *ray*, which indicates the direction of propagation. Rays are perpendicular to the wavefronts.

Straightforward geometrical arguments lead to the *Law of Reflection*, which states that the angle θ_1' of the reflected beam is the same as the incident angle θ_1. The transmitted beam is bent, relative to the incident beam. This is called *refraction*, and is described by *Snell's Law*, or the *Law of Refraction*:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \tag{16.2}$$

where θ_1 and θ_2 are the propagation angles (*relative to the normal, a line perpendicular to the interface*) for the light in media with indices of refraction n_1 and n_2, respectively. It is important to emphasize again that the angles here are measured with respect to the normal to the interface.

Part I: Refraction

The apparatus for this part of the lab, shown in Figure 16.2, is a small table consisting of a laser and a rotating platform with a protractor. The laser is aimed toward a semicircular object so that the beam strikes the center of the semi circle. As shown in Figure 16.2, light enters at the flat side of the semicircle (hemisphere.) The laser beam may be bent at the flat side of the semicircle due to refraction. However, the beam is undeflected at the curved side, since the angle of incidence is always 0° at this interface. Make sure you understand this point — it is a key geometrical feature in this experiment.

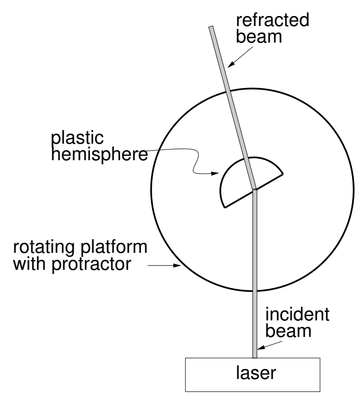


Figure 16.2: Part I set-up.

1. Place the solid plastic semicircular shape on the rotating platform. Orient the flat side of the piece of plastic along the 270°–90° line. Turn the laser on and make sure that the laser is aimed directly at the center of the semicircle. (If you have a "Laser Ray Box" at your desk, flip the switch towards the indicator for one beam only.) By rotating the stage, adjust the angle of incidence to be 0° (i.e., at the 180° mark). Measure the angle of refraction. Is this result consistent with Snell's Law?

2. Repeat Step 1 with angles of incidence of 20°, 40°, 60° and 80° and record your results in an Excel spreadsheet. For each, measure the angle of incidence and the angle of refraction. Be careful: with respect to which line are you measuring these angles? For each, use your measurements to determine the index of refraction for the plastic material. If you look carefully, you may also see the reflected beam. (Hint: look on the side of the laser facing the flat side

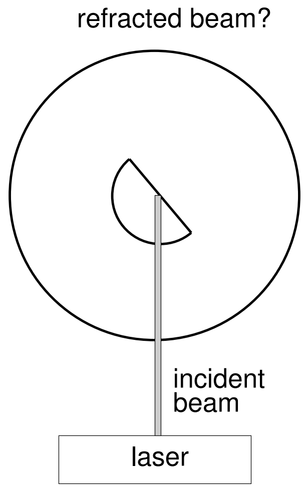
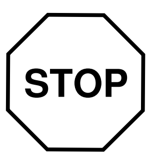


Figure 16.3: Experimental setup for step 4.

of the hemisphere. Remember that the reflected beam is on the same side of the interface as the incident beam.)

3. Calculate the average, standard deviation, and standard deviation of the mean of the results from step 2 to determine an **experimental** value (including uncertainty) for the index of refraction for this plastic. Compare your best result for the index of refraction of this plastic to the "accepted" value of 1.5. Is your result consistent with the accepted value?



Show your experimental result and comparison to your instructor or TA

4. Up until now, the beam has passed from a medium with low index of refraction (air) into a medium with higher index of refraction (plastic). Now, let's examine what happens if the beam of light passes from a medium with **higher** index of refraction to a medium with **lower** index.

   Orient the plastic hemisphere on the rotating stage so that the laser beam enters the semicircle **from the curved side** and exits out the flat side (see Figure 16.3). Orient the flat side of the hemisphere along the 90°–270° line. Consider the beam at the flat interface of the semicircle. Here, the incident beam is in plastic, while the refracted beam (on the other side of the interface) would be in air.

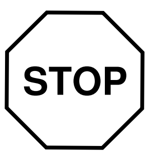
5. Now, look at the refracted beam as the angle of incidence is increased from 0° to 10° to 20° to ... Describe (and maybe draw sketches in your lab notebook)

what happens to the refracted beam as the angle of incidence is increased.

You should find that the refracted beam in air disappears entirely for larger angles of incidence. In other words, no light goes through the interface at all; instead, all of the light is reflected back into the plastic. This phenomenon is called *total internal reflection*.

6. The critical angle of incidence θ_c for total internal reflection can be found by assuming a refracted angle of 90° since the angle for the refracted beam can't be larger than 90°. Use this approach to calculate the critical angle of incidence for light passing from plastic into air. Then check your result experimentally: do you see a refracted beam for angles of incidence $\theta_1 < \theta_c$? How about if the incident angle $\theta_1 > \theta_c$?

7. Fiber optics depends critically on the principle of total internal reflection. Examine and play with the fiber optics demos. Does the light escape as it traverses the curved regions of the plastic? Why or why not? What happens if the fiber is bent very sharply? Write down a couple of sentences describing the principle behind the transmission of light in a fiber optic cable. Draw sketches to support your statements.



Show your sketches to your instructor or TA, and be ready to explain the criteria for total internal reflection to occur.

Part II: Lenses and images

We have seen now how light can be bent as it passes from one medium to another. This phenomenon can be used to focus light from distant sources and even produce images. This principle is used in lenses such as those one might find in glasses, your eyes, or telescopes. In this section, we will first investigate how a single lens may bend light from a laser source. We will then use an optical bench to explore the properties of a particular glass lens.

Remove the rotating protractor stage from the laser table assembly and place the clear plastic surface on the assembly (this gives you a smooth surface to draw on at the right height for the laser). Put a piece of paper on the drawing surface.

1. Place the flat lens (with curved surfaces on each side) on a piece of paper with the **center line of the lens perpendicular to the incident laser beam**. Trace the lens and the incident beam. On the other side of the lens, trace the exit beam. Move the paper and the lens sideways so that the laser beam enters the lens at another point (make sure the new incident beam is parallel to the

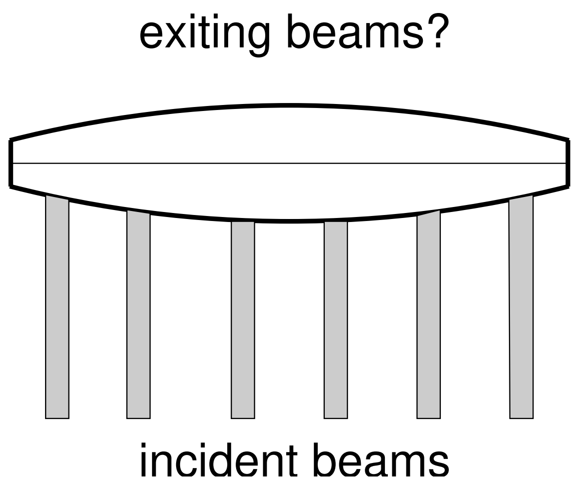


Figure 16.4: Refraction by a lens.

previous incident beam as shown in Figure 16.4). Trace the incident and exit beams. Do this procedure for six incident beams. Do all of the exit beams pass through the same point? This point, where *parallel incoming beams* converge on the other side of the lens, is called the *focal point*. (If you have a "Laser Ray Box" at your desk, switch the laser setting to emit three beams.) What would happen to the focal point if the lens were more curved? What would happen to the focal point if the lens were flatter?

The distance from the center of the lens to the focal point is called the focal length f of the lens.

2. Putting aside the platform and laser box setup, we will now use the optical bench for the rest of the lab.

   Set up the light source with the arrows, the lens, and the white screen on the optical bench as shown in Figure 16.5. Turn on the light source. Place the lens on the optical bench 40 cm away from the lighted arrow pattern. Move the screen until it displays a sharply focused image of the arrows. Measure and record the distance between the light source and the lens (the *object* distance, denoted d_o) and the distance between the lens and the focused image (the *image* distance, denoted d_i).

3. When an image is focused, the relationship between the focal length f, the image distance d_i, and the object distance d_o can be expressed via the thin lens equation:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}. \tag{16.3}$$

   Calculate the focal length of the lens given your measurements for d_o and d_i.

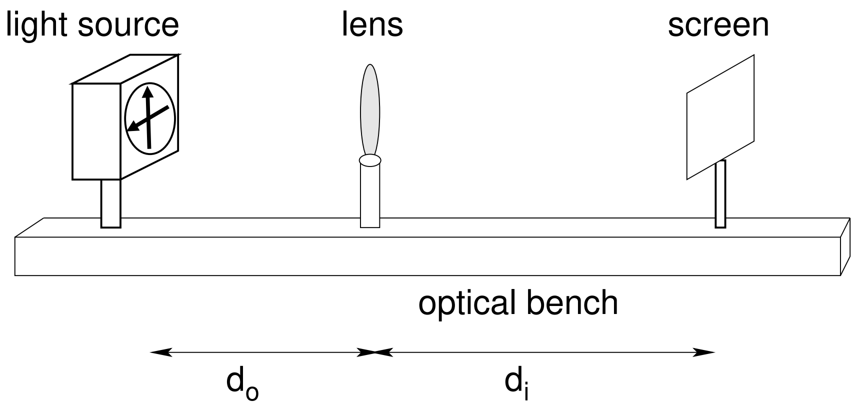
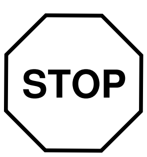


Figure 16.5: Experimental setup for image formation by a convex lens.

Then test the thin lens equation for two different image distances and recalculate the focal length. (Note: none of the image distances should be less than the focal length. What would happen to the object distance for $d_i < f$?) Are the calculated focal lengths consistent? What is the focal length of the lens (report the correct value with uncertainty)?

4. The *magnification*, m, is the ratio of the image size to the source size. Adjust d_o and d_i such that the source and the image are the same size, and record the values of d_o and d_i. Make a well-focused image that is approximately one-half the size of the source, and record d_o and d_i.

5. Try to deduce a simple equation relating m, d_o, and d_i. Then test this relationship by predicting how to make an image approximately twice the size of the source. Test your prediction and verify your equation for m.



Summarize your results from this series of investigations, including the focal length of the lens and your equation from #5 above. Discuss your results with your instructor or TA.

The human eye and cameras both use simple lenses to form images. In the eye, the lens is a fixed distance from the photosensitive surface in the back of the eye (called the retina) and focusing is accomplished automatically as the eye muscles change the focal length of the eye lens. In the camera, the lens has a fixed focal length (except for a zoom lens) and focusing is accomplished by moving the lens closer to or further from the film/electronic detector.

Part III: Demo – Telescopes

A *refracting* telescope is a combination of two-lenses that can be used to view distant objects. The idea is very simple: one lens, the "objective" lens, (in our case the red lens with $f_{\mathrm{obj}} = f_{\mathrm{red}} \approx 20\,\mathrm{cm}$) forms an image of the distant object. A second lens called the "eyepiece" (in our case the yellow lens with $f_{\mathrm{eye}} = f_{\mathrm{yellow}} \approx 5\,\mathrm{cm}$) is located one focal length behind the image formed by the objective lens. **Question:** can you explain why the distance between the two lenses should be the sum of the focal lengths of the two lenses if viewing an object that is **very** far away? (If your answer is "No, can't explain that," then you should discuss this with your instructor or a lab TA.) Hint: the thin lens equation should play a role in your discussion. What happens if d_o becomes very large?

A couple of two-lens telescopes will be set up in the back of the lab that you can play with. Look at a distant object – look through the window to something in a different building – through the telescope (a TA can help you if you have difficulties).

To see the image made by the objective lens for yourself, take an index card and hold it behind the objective lens. Move it between the objective and eyepiece lenses until a focused image appears on the card. This image forms exactly one focal length of the objective lens away from that lens. This is the new "source" that is then used by the eyepiece lens. Confirm that $f_{\mathrm{obj}} = f_{\mathrm{red}} \approx 20\,\mathrm{cm}$.

After you have done this exercise, look through the telescope at something close by (e.g., a nearby computer screen. What do you have to do to the distance between the lenses to focus on the nearby object?

FYI, a microscope is really the same thing as a telescope, except that the object is close by, rather than far away. The same principles come into effect in a microscope.