

## 1 Objective

- To explore the refraction of light.

## 2 Introduction

When a ray of light of some frequency travels from one medium into another it is refracted and can appear to bend at the interface between the materials. The way in which it bends depends on the refractive indices of the two media at that frequency and the angle of incidence of the ray. The “normal” refers to the normal line to the plane of the interface. Snell’s law relates the angle that the ray makes with the normal in one material, having refractive index  $n_1$ , to the angle it makes in the second material, having refractive index  $n_2$ .

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

The refractive index of a material at a particular frequency relates the speed of the light wave in the material,  $v$ , to the speed of the light wave in a vacuum,  $c$ :

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

Refractive indices are never less than 1.

When looking into a fish tank, the fish appear closer to the glass than they actually are. This is due to refraction as light bouncing off the fish leaves the water and moves into the air before reaching your eye. A boundary between two media is called a refracting surface, and it does not need to be flat. In the fish tank example, the distance from the fish to the tank surface is the object distance  $p$  and the distance from the surface to the image of the fish is the image distance  $q$ . For a real image, which is one that forms where light rays converge and could be projected on a screen,  $q$  is positive. For a virtual image, one that can be seen looking through the refracting surface, but does not appear on a screen,  $q$  is negative. (For the fish tank,  $q$  is negative, and its magnitude is less than  $p$ .) The relationship between the object and image distances is given by the refracting surface equation:

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R}$$

where  $n_1$  is the refractive index of the material the light comes from,  $n_2$  is the refractive index of the material the light travels into to, and  $R$  is the radius of curvature of the surface. ( $R \rightarrow \infty$  for a flat surface.) If light rays are parallel approaching a boundary, this is an infinite object distance,  $p \rightarrow \infty$ .

This lab will be done virtually using a *PhET* simulation created at the University of Colorado at Boulder. Click [here](#) to get started with the simulation.

## 3 Procedure

### 3.1 Snell’s Law

1. Open the Bending Light simulation and choose *Intro*.
2. Switch on the laser with the red button, and set the upper material to air ( $n_{\text{air}} = 1$ ) and the lower material to water.
3. Using the protractor measure and record the incident and refracted angles. Now calculate the refractive index of water. Does it agree with the refractive index for water displayed on the screen? Be sure to record your calculated value and the one on the screen.

4. Repeat the previous step with the lower material set to glass.
5. Now set the lower material to *Mystery A*. Determine the refractive index of this mystery material.
6. Determine the refractive index of the Mystery B material.

### 3.2 Total Internal Reflection

1. Still on the *Intro* screen, set the bottom material to water and the top material to Mystery A. Notice that for large angles of incidence there is no refracted ray. This is called total internal reflection. Move the laser source to decrease the incident angle until the refracted ray just appears, running nearly parallel to the interface between the two materials.
2. Consider Snell's law for this case. Why does the refracted ray vanish at this angle of incidence?
3. This angle of incidence is called the critical angle. For angles of incidence larger than the critical angle, total internal reflection occurs. For angles of incidence smaller than the critical angle, there is a refracted ray. Use Snell's law to find an expression relating the critical angle to the refractive index of the first (incident) medium  $n_1$  and the second medium  $n_2$ .
4. Does a critical angle exist when light goes from air into water? Why or why not? In what case will there be a critical angle?
5. Choose the *Prisms* screen.
6. Switch on the light and choose the red ray (leave the wavelength at 650 nm).
7. Pull a trapezoid or triangle prism into the "play area" and into the laser beam. Using the little tab in the corner of the prism rotate the prism around. You should notice that if the light moving through the prism strikes the edge of the prism making a glancing angle it is totally internally reflected.
8. Keep the environment set to *Air*, and using the protractor and selecting the *Normal* checkbox, find the critical angle for water, glass, Mystery A, and Mystery B. Use the critical angles and your formula to find another measurement of the refractive index for each of those materials. Put these results in a table (see Table 1).

material	$\theta_c$ (deg)	$n$
water		
glass		
Mystery A		
Mystery B		

Table 1: Example data table for section 3.2.

### 3.3 Refracting Surfaces

1. Still on the *Prisms* screen, pull out a half circle prism and put it with the curved side facing the light source, precisely on axis with the source so the ray of light is bisecting the half circle. To ensure that you have it exactly centered: check the *Normal* box to show the dashed normal incidence lines and make sure that the ray is going exactly along those lines at both the front and back on the half circle.
2. Now uncheck the *Normal* box and switch to the source producing 5 parallel rays. Notice that the half circle prism acts as a thick converging lens that focuses the rays to a point.

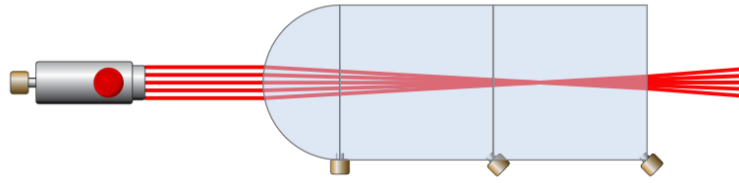


Figure 1: How to create a deep prism out of several separate prisms lined up in series.

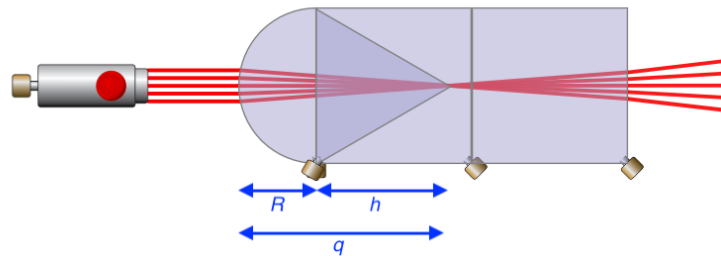


Figure 2: Example of how you could use the height of the triangle,  $h$ , to estimate the image distance  $q$  in terms of  $R$ . Your arrangement will look different.

3. Place square prisms directly behind the half circle, touching but not overlapping, to form a large prism. Continue placing squares until you see that the point where the rays are focused is inside the prism. (See Figure 1.)
4. Let the radius of the half circle be  $R$ . Using equation (2) find an expression for the image distance  $q$  in terms of the refractive index of the prism pieces  $n$  and  $R$ .
5. Taking the values of  $n$  for water and glass that were given on the *Intro* screen of the sim (recorded in steps 3.2.3&4) predict how far behind the front of the half circle the rays will be focused in terms of  $R$  for water and for glass.
6. Set the prisms to be *water* and see if your prediction is correct. Notice that the squares have side length  $2R$ , and you can use another half circle on top of a square to measure a distance of  $R$  since the thickness of the half circle is  $R$ . Draw a sketch or take a screenshot (and label it) to show how you measure  $q$  in terms of  $R$ .
7. Repeat the previous step with the prism set to *glass*.
8. Now predict the value of  $q$  (in terms of  $R$ ) for Mystery A, using your value of  $n$  for Mystery A from section 3.1.
9. Notice that the equilateral triangle prism has a side length  $2R$ . What is the height of the prism in terms of  $R$ ? Use the triangle (placed entirely on top of your existing half-circle-and-squares prism) to check if your prediction is at least roughly correct. Once again, sketch your arrangement or include a labelled screenshot. (See Figure 2)

### 3.4 Light as a Wave

1. Open the *More Tools* screen.
2. Switch on the laser and set the upper material to air ( $n_{\text{air}} = 1$ ) and using the slider, set the lower material to have a refractive index of  $n = 1.60$  (max).
3. Pull out the blue tool labelled *Time* and put one sensor in the incident ray and one sensor in the refracted ray. This tool plots the electric field against time. Remember that frequency is the number of oscillations per second. How are the frequencies of the incident and refracted rays related?
4. In the top left hand corner of the screen chose the *Wave* option. Check that the wavelength is set to 650 nm. This is the wavelength in a vacuum (and very nearly the same in air). With a ruler held up to your screen, measure across 10 (or more) wavelengths, peak-to-peak, in the incident ray. Record that length. Now measure across 10 (or more) wavelengths in the refracted ray. Find the ratio of the refracted wavelength to the incident wavelength. Knowing the incident wavelength is 650 nm, calculate the wavelength of the light in the refracted ray.
5. From your results about frequency and wavelength, calculate the wave speed of this frequency of light in the lower medium ( $n = 1.60$ ) in terms of  $c$  the speed of light in a vacuum (and very nearly the same in air).
6. Use the *Speed* tool to check your answer. Record its value and compare to your calculated value.
7. Now select the *Ray* option in the top right corner. Vary the wavelength from the minimum available (380 nm) to the maximum (700 nm). Does the angle of refraction remain constant? If it is hard to tell, check the *Angles* box in the bottom left corner of the screen. Does the speed of the refracted ray remain the same across all frequencies?
8. Switch back to the *Prisms* screen. Select a white light source. Pull a triangle or trapezoid prism into the “play area” and let the white light pass through it. Can you separate out the different frequencies that make up white light? You may like to use several prisms in series, or move the light source to make the effect more dramatic. This is called dispersion. Based on your results for the previous step, why do you think dispersion happens?