Refraction, Reversibility, Dispersion and Total Internal Reflection

Overview: This lab has three parts. The first part focuses on the way that the velocity of light changes as light passes into a different medium. You will determine the index of refraction of the Cylindrical Lens. You will also check to see if Snell's Law holds when light passes from acrylic into air, as well as when light passes from air into acrylic. In Part II, dispersion is investigated. Dispersion is the property of most media that allows waves of different wavelengths to travel at different speeds. Because of dispersion, the index of refraction of a particular material has slightly different values for longer and shorter wavelength waves. You will determine the index of refraction of the Cylindrical Lens for red and blue light. Part III introduces total internal reflection. When light is passing from an optically dense medium into a medium that is optically less dense, there are angles of incidence that result in no light being refracted into the second medium; this condition is called total internal reflection. For any pair of media, there is a critical angle of incidence that results in total internal reflection. You will determine the critical angle for acrylic in air.

Part I: Refraction of Light and the Reversibility of Snell's Law

Purpose: To study the refraction of light at the boundary between transparent media. To determine the index of refraction of the Cylindrical Lens. To test the reversibility of Snell's Law.

Equipment: Optics Bench, Light Source, Ray Table and Base, Component Holder, Slit Plate, Slit Mask, Cylindrical Lens.

Introduction: Refraction is the abrupt change in light's **velocity** when it passes across a boundary between two transparent media, such as between air and acrylic. We use the word velocity because not only does the *speed* of the wave change, but the *direction* that the wave is traveling changes as well. The Law of Refraction, also known as Snell's Law, gives us the relationship between the angle of incidence (for the incident ray) and the angle of refraction (for the refracted ray) as these quantities depend on the speed of light in the two media: $n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad Eq.1$

The quantities n_1 and n_2 are the **index of refraction of medium 1** and the **index of refraction of medium 2**, respectively. For any transparent medium, the index of refraction is defined as $n = \dfrac{speed\ of\ light\ in\ vacuum}{speed\ of\ light\ in\ medium} = \dfrac{c}{v}$. So we see that n is a unitless number greater than or equal to one. The angles θ_1 and θ_2 are the angles that the incident ray of light and the refracted ray of light make with the *normal* to the boundary between the two media, respectively (see the inset in Figure 1). The subscripts one and two refer to the medium on either side of the boundary. In the first part of the experiment θ_1 is the incident angle, and the medium is air. Recall that the speed of light in air is very nearly equal to c, the speed of light in vacuum. So we see that the index of refraction for air is nearly one, and you will use $n_1 = 1$ when the incident ray is in air. In this experiment you will determine the index of refraction for the acrylic Cylindrical Lens. You will address the question of reversibility by testing whether Snell's Law holds regardless of whether the light passes from air to acrylic, or from acrylic to air.

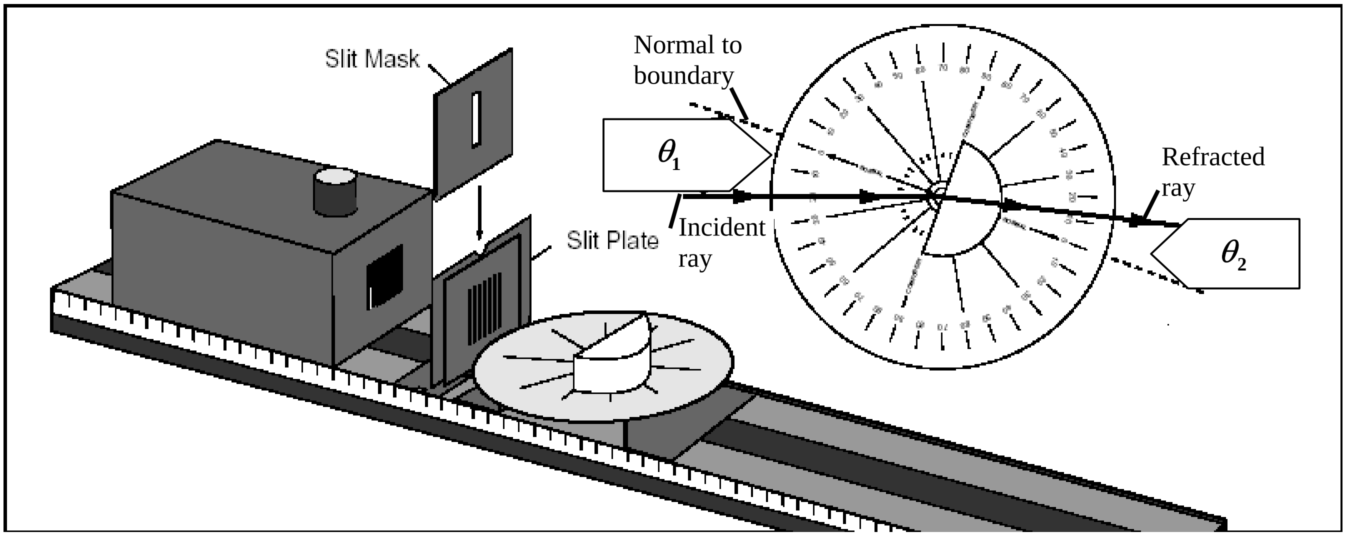

Figure 1 Experimental set-up for determining the index of refraction of acrylic, and the first part of testing for reversibility.

Procedure:

1. Set up the equipment as shown in Figure 1. Adjust the components so a single ray of light passes directly through the center of the Ray Table Degree Scale. Align the flat surface of the Cylindrical Lens with the line labeled "Component" on the Ray Table. With the lens properly aligned, the radial lines extending from the center of the Degree Scale will all be perpendicular to the circular surface of the lens and the incident ray will lie directly on the arrow labeled **NORMAL**. The angle of incidence is now $\mathbf{0°}$. Make a data table in your lab journal similar to Table 1. Record the resulting angle of refraction in your table in **two** columns: θ_2 under the heading "Light Ray Refracted into Acrylic" and θ_1' under the heading "Light Ray Refracted into Air". Without disturbing the alignment of the lens, rotate the Ray Table and set the angle of incidence to $\mathbf{10°}$. Record the angle of refraction in the two columns, as you did for $\mathbf{0°}$. Continue carefully rotating the Ray Table to each of the angles of incidence listed in Table 1, and recording the resulting angle of refraction in the two columns of your data table.

Light Ray Refracted into Acrylic				Light Ray Refracted into Air			
θ_1	$\sin\theta_1$	θ_2	$\sin\theta_2$	θ_1'	$\sin\theta_1'$	θ_2'	$\sin\theta_2'$
0°							
10°							
20°							
30°							
40°							
50°							
60°							
70°							
80°							

Table 1 Sample table of data and calculations.

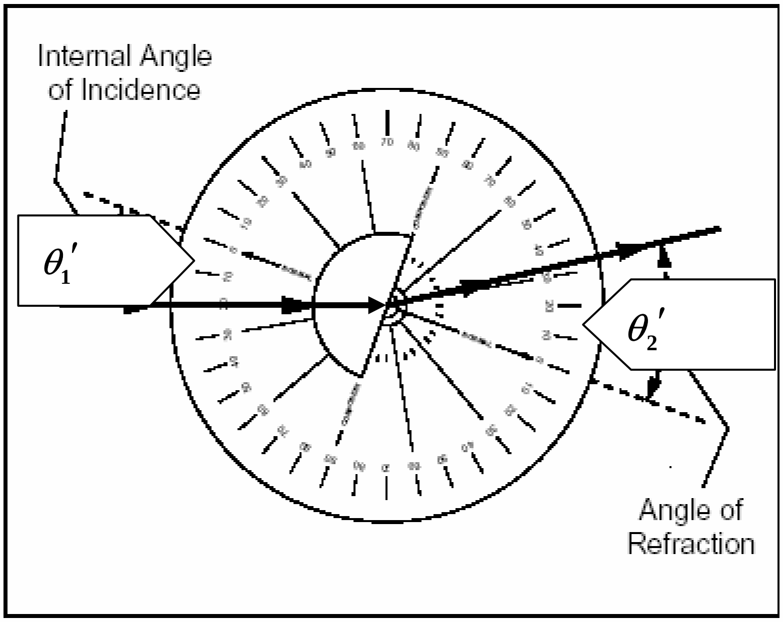

Figure 2 Experimental set up for testing reversibility.

2. Now let the incident ray strike the curved surface of the lens as in Figure 2. Just rotate the Ray Table 180°. The incident ray now reaches the flat surface of the lens after traveling through acrylic, and then it is refracted into air at the flat boundary. The internal angle of incidence, θ_1', for the flat surface of the Cylindrical Lens is shown in Figure 2. Set this angle of incidence to the values you have already listed in the table under the heading "Light Ray Refracted into Air" in the column labeled θ_1'. Record the corresponding angles of refraction, θ_2', for the ray transmitted into air.
3. Using your collected values for the angles of incidence, θ_1 and θ_1', and the collected values for the angles of refraction, θ_2 and θ_2', calculate the sines of the angles, and record in the appropriate columns in your table. Use three significant figures.
4. On the computer, open the desktop shortcut to **Physics Apps**. Find the icon for **Graphical Analysis**, and start this program. To determine the index of refraction of the acrylic, and demonstrate whether or not this law obeys reversibility, you will generate one graph that displays all the data you collected. For both of the experiments you did, you will treat the sine of the angle of incidence as the independent variable and the sine of the angle of refraction as the dependent variable. In the data table window, enter your values for $\mathbf{sin}\,\theta_1$ in the $\boldsymbol{x}$ column, and enter your values for $\mathbf{sin}\,\theta_2$ in the $\boldsymbol{y}$ column. You should also right-click on the headings of these columns to give them meaningful names. What are the units of these quantities? You should see a linear curve appear in the graph window. Turn off the "connect lines" feature.
5. Now, plot the data for the reversibility part of the experiment. On the menu bar, click on **Data** and select **New Data Set**. Again, enter the sine of the angle of incidence as the independent variable and the sine of the angle of refraction as the dependent variable, and give physically meaningful names to these variables, as you did for the first set of data. To plot the graph of these data, click on the $\boldsymbol{y-axis}$ (in the graph window), and in the dialog box that opens up, open **Data Set 2** and select your dependent variable, in this case, $\mathbf{sin}\,\theta_2'$. Again, get rid of the connect lines.
6. Fit your curves to a straight line. Referring to $\boldsymbol{Eq.1}$, what physical meaning does the slope of each line have? From the appropriate slope, determine the index of refraction of the Cylindrical Lens.
7. Is the Law of Refraction the same for light rays going in either direction between air and acrylic? How can you prove your answer? Be sure your graph has all labels, title, etc and print it for your lab journal.

Part II: Dispersion

Purpose: To observe dispersion and to determine the slightly different values of the index of refraction for long wavelength (red) light and for short wavelength (blue) light.

Equipment: Optics Bench, Light Source, Ray Table and Base, Component Holder, Slit Plate, Slit Mask, Cylindrical Lens, Ray Table Component Holder, Viewing Screen.

Introduction: For large angles of incidence, you will note Dispersion. Although we generally say that the velocity of a wave through a medium depends only on the characteristics of the medium, in fact, most media are dispersive. A dispersive medium allows waves with different wavelengths to travel at different velocities through the medium. Because the speed of light is slightly different for different colors of light, it follows that the index of refraction is slightly different for different colors of light. Dispersion (which occurs when light passes through water droplets in air) is responsible for rainbows. Dispersion is what separates the colors (each of which has its own wavelength) in white light, and spreads them out in a rainbow pattern when light passes through a prism.

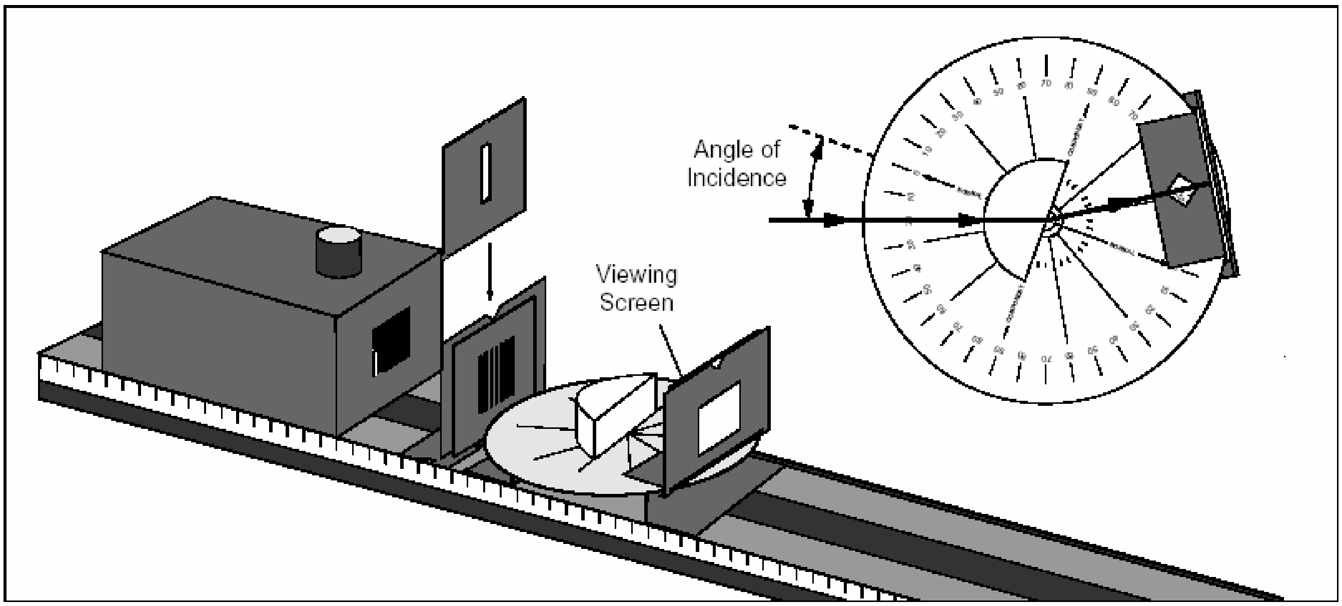

Figure 3 Experimental set-up for observing dispersion and total internal reflection.

Procedure:

1. Set up the equipment as shown in Figure 3, so a single light ray is incident on the curved surface of the Cylindrical Lens. Set the Ray Table so the angle of incidence of the ray striking the flat surface of the lens (from inside the lens) is zero-degrees. Adjust the Ray Table Component Holder so the refracted ray is visible on the Viewing Screen.
2. Slowly increase the angle of incidence. As you do, watch the refracted ray on the Viewing Screen. At what angle of refraction do you begin to notice color separation in the refracted ray?
3. At what angle of refraction is the color separation a maximum? What colors are present in the refracted ray? Write them in the order of minimum to maximum angle of refraction.
4. Calculate the index of refraction of acrylic for red and blue light using $\boldsymbol{Eq.1}$ and your measurements of the angles of refraction when the angle of incidence is $\mathbf{40°}$.

Part III: Total Internal Reflection

Purpose: To observe the behavior of refracted light that is traveling from a medium with a higher index of refraction into a medium whose index of refraction is lower. To observe total internal reflection, and measure the critical angle for the Cylindrical Lens in air.

Equipment: Optics Bench, Light Source, Ray Table and Base, Component Holder, Slit Plate, Slit Mask, Cylindrical Lens, Ray Table Component Holder, Viewing Screen.

Introduction: If we study Snell's Law, we will note that it is possible that the refracted ray can make an angle of $90°$ with the normal to the boundary. In this case, the refracted ray leaves the boundary *parallel to the boundary* and we say that the light has undergone total internal reflection. The incident angle that corresponds to this condition is called the critical angle, and you can determine it by solving the following equation: $\sin\theta_C = \frac{n_2 \sin 90°}{n_1} = \frac{n_2}{n_1}$ ***Eq*.2** . When the angle of incidence is increased beyond the critical angle, there is no transmitted (refracted) ray. All of the incident light is reflected back into the optically dense Cylindrical Lens.

Procedure:

1. Set up the equipment as shown in Figure 3, so a single light ray is incident on the curved surface of the Cylindrical Lens. Set the Ray Table so the angle of incidence of the ray striking the flat surface of the lens (from inside the lens) is zero-degrees. Rotate the Ray Table slowly and notice that not all of the light in the incident ray is refracted. Part of the light is also reflected. From which surface of the lens does the strongest reflection occur?
2. Is there a reflected ray for all angles of incidence? (Use the Viewing Screen to detect faint rays.) Are the angles for the reflected ray consistent with the Law of Reflection?
3. Is there a refracted ray for all angles of incidence?
4. How do the intensity of the reflected and refracted rays vary with the angle of incidence?
5. At what minimum angle of incidence does the refracted ray vanish?
6. Calculate the critical angle from ***Eq*. 2** , using your experimental value of the index of refraction of acrylic (from Part I) in the numerator. Compare your calculated value of the critical angle with the value measured in Step 5.