O2b: Refraction of Light

Introduction:

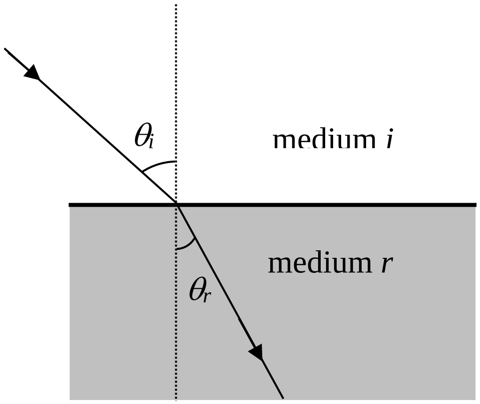


Figure 1

Light travels through the vacuum of empty space at the ultimate speed limit of the universe, c=3.00×10^8 m/s. The speed of light can change though, depending upon the media light travels through. Light slows down differently each time it passes through other media (such as water or glass).

This difference in speed as light transitions from one medium to another causes a "bending" of a ray of light entering the different medium, if the angle of incidence, θ_i, (the angle between the incident ray and normal to the boundary) is greater than 0°. This "bending" is known as refraction of light. The angle of refraction, θ_r (the angle between the refracted ray and normal to the boundary), depends on the angle of incidence and speed of light in both media. **Figure 1** illustrates a bending of a ray of light when it travels from medium *i* to medium *r* (when the speed of light in medium *r* is slower than the speed of light in medium *i*).

The index of refraction, *n*, is defined as the ratio of the light's speed in a vacuum, *c*, to the light's speed in the medium, *v*:

$$n \equiv \frac{c}{v} \qquad (1)$$

The relationship between angle of incidence and angle of refraction is usually expressed through the indices of refraction of both media, and is called Snell's law, in honor of a Dutch mathematician William Snellius, who formulated it in 1621 (though several others also discovered the law, including Rene Descartes in 1637):

$$n_i \sin\theta_i = n_r \sin\theta_r \qquad (2)$$

The purpose of this lab is to observe the refraction of light and to determine the index of refraction for a piece of clear glass.

Apparatus:

- Laser / Optical rail
- Component carriers
- Mounting hardware
- Angular translator
- Linear translator
- Polarizer
- Focusing lens
- Adjustable aperture
- Media (glass)
- Photometer
- Comp. w/ interface

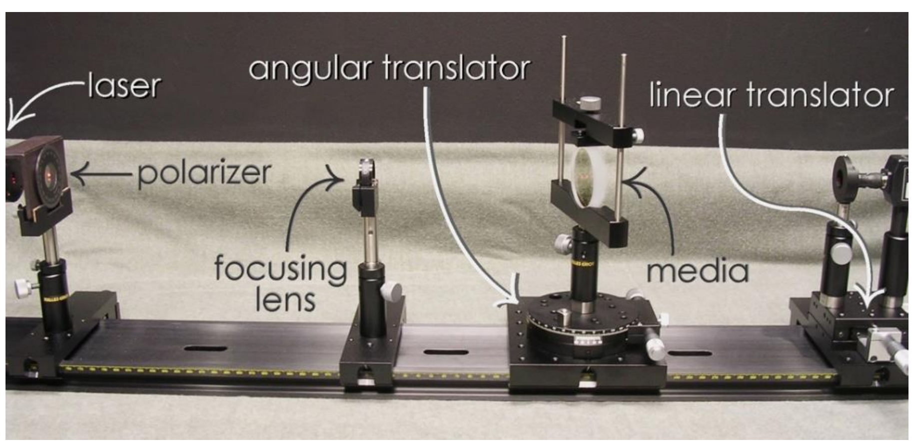


Figure 2

Theoretical Background:

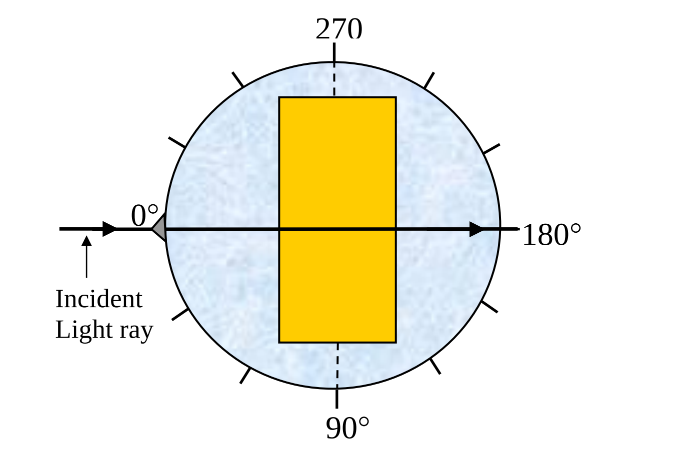


Figure 3

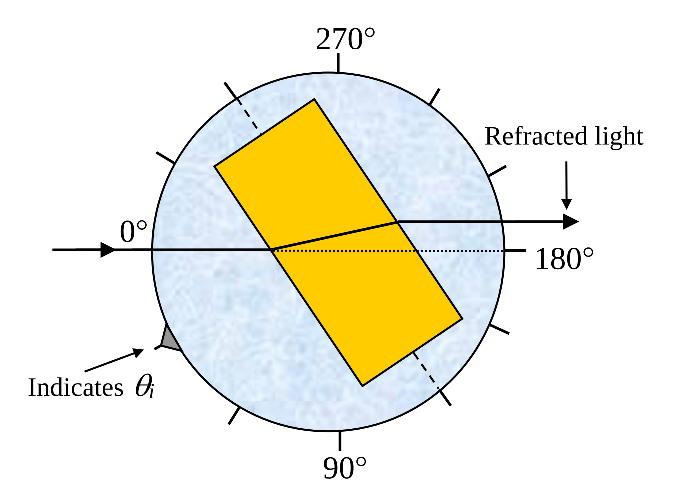


Figure 4

In this experiment you will estimate the index of refraction of a glass by simply shining a laser light through a large rectangular prism and making a drawing similar to that shown in **Figure 1**, and then make a precise determination of the index of refraction using the apparatus shown in **Figure 2**.

The "Media" in the apparatus is a precision cylindrical glass block usually referred to as an optical window. The block will first be positioned on an angular translator, perpendicular to the incoming ray of light, $\theta_i=0$, where no refraction of the light beam occurs, as shown in **Figure 3**. Then the angle of incidence will be changed using the angular translator, causing the laser light to be refracted within the material (see **Figure 4**).

The sensor of the photometer, which is measuring the intensity of the laser light, is set on the linear translator, at the opposite end of the optical rail. The linear translator allows to slowly move the sensor in order to align it with the refraction-shifted laser light, and thus determine the displacement *d* of the light ray corresponding to each angle of incidence. The displacements of the ray of light, along with the thickness of the material, *t*, can then be used to calculate the angle of refraction, θ_r, for each angle of incidence, θ_i.

Figure 5 shows a detailed path of the laser beam through the glass, including angles of incidence and refraction on the first air/glass interface, normal to the boundary, and displacement of the laser beam from its initial path, *d*. Analyzing this figure, it becomes possible to derive the equation necessary to find θ_r. Making use of the geometric fact that two intersecting lines form vertical angles which are congruent, it can be seen that $\theta_i = \theta_r + \theta_\beta$. Therefore,

$$\theta_\beta = \theta_i - \theta_r \qquad (3)$$

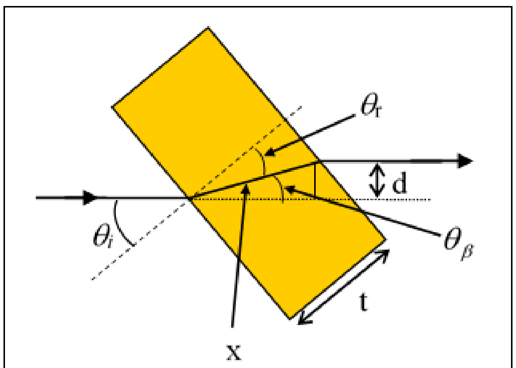


Figure 5

Also, apparent from closer consideration of **Figure 5**, is the fact that the dotted line through the glass block is of length ***t***, where ***t*** represents the thickness of the block. Additionally, it can be seen that the shifting of the laser light has created two right triangles. The first triangle has an angle of θ_r, an adjacent side with length ***t***, and a shared hypotenuse that has been labeled ***x***. The second triangle has an angle of θ_β , an opposite side of length ***d,*** where ***d*** is equal to the displacement of the laser light, and a shared hypotenuse ***x***.

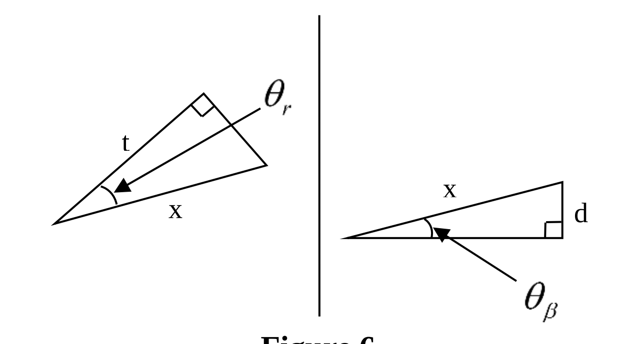


Figure 6

The layout of the two right triangles created by the laser light's displacement, as shown in **Figure 5,** can be seen much more clearly if one separates those two triangles out, as done in **Figure 6**.

From the provided picture and geometrical definitions, the following relationships may be stated:

$$\cos\theta_r = \frac{t}{x} \qquad \sin\theta_\beta = \frac{d}{x} \qquad (4)$$

Now, by solving both equations so that x is isolated, and then setting the two equations equal to each other, the following result may be obtained:

$$\frac{t}{\cos\theta_r} = \frac{d}{\sin\theta_\beta}. \qquad (5)$$

Substituting (3) into (4) yields:

$$\frac{t}{\cos\theta_r} = \frac{d}{\sin(\theta_i - \theta_r)} \qquad (6)$$

At this point, it becomes necessary to consider the following trigonometric identity**:** $\sin(\alpha - \beta) = \sin\alpha\cos\beta - \cos\alpha\sin\beta$. By applying this identity, (6) yields:

$$\frac{t}{\cos\theta_r} = \frac{d}{\sin\theta_i\cos\theta_r - \cos\theta_i\sin\theta_r} \qquad (7)$$

Now, by cross multiplying, one can obtain that:

$$\frac{\sin\theta_i\cos\theta_r - \cos\theta_i\sin\theta_r}{\cos\theta_r} = \frac{d}{t} \qquad (8)$$

And by then simplifying this equation, it becomes:

$$\sin\theta_i - \cos\theta_i\tan\theta_r = \frac{d}{t} \qquad (9)$$

From here, one simply has to subtract the $\frac{d}{t}$ over to one side, add the $\cos\theta_i\tan\theta_r$ to the other side, and divide out the $\cos\theta_i$ to isolate $\tan\theta_r$.

$$\frac{\sin\theta_i - \frac{d}{t}}{\cos\theta_i} = \tan\theta_r \qquad (10)$$

This, in turn, yields the needed equation to calculate the angle of refraction θ_r.

$$\theta_r = \tan^{-1}\left(\frac{\sin\theta_i - (d/t)}{\cos\theta_i}\right) \qquad (11)$$

After obtaining the angle of refraction, using it together with the angle of incidence and assuming that the index of refraction of air, $n_i \approx 1$, one can calculate the index of refraction of glass by using Snell's Law.

$$n = \frac{\sin(\theta_i)}{\sin(\theta_r)} \qquad (12)$$

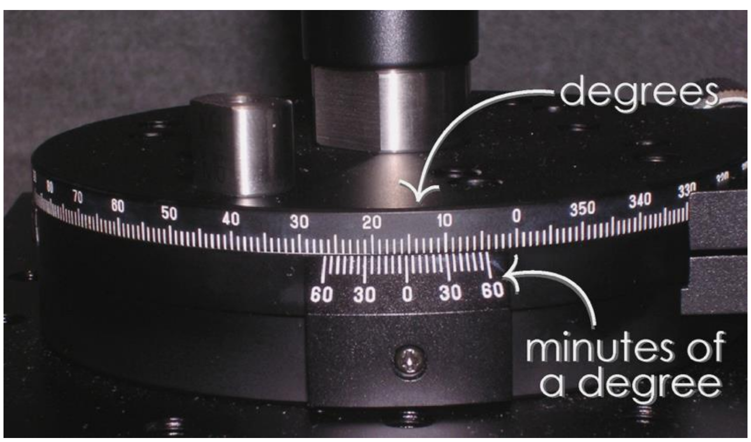
Procedure:

Part I: Observing the Refraction of Light and Estimating the Index of Refraction of Glass Using a Rectangular Prism.

1. Obtain a laser, a rectangular glass prism, a piece of paper, a ruler, and a protractor from a lab instructor.
2. Place the prism on the piece of paper and shine the laser beam through the prism, setting the angle of incidence between 20^o and 40^o. Observe the refraction of the laser light.
3. Use a pencil to mark a few points on the paper which will allow you to accurately draw the incident beam, the refracted beam, the boundary between the prism and air, and the normal to the boundary. ***Each student in a group must make his/her own drawing***.
4. Make an accurate drawing, label the angles, and use a protractor to measure the angles of incidence and refraction.
5. Use Snell's Law to estimate the index of refraction of the glass. Show all your calculations on your drawing.

Part II. Precise Measurement of Index of Refraction of Glass Using the Optical Bench and a Photodetector.

1) **Using a Vernier Scale Angular Translator and a Micrometer at the Linear Translator:**



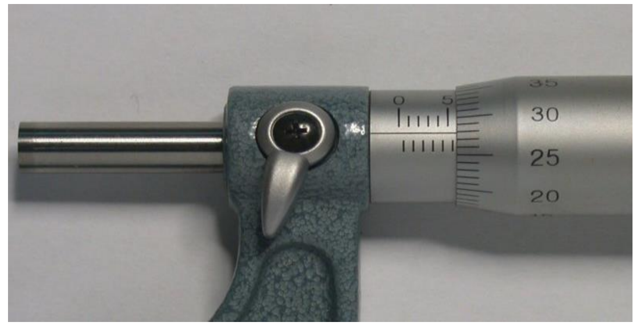
Angular Translator Scale

Figure 7

The glass ("media") is fastened on the angular translator, perpendicular to the incoming ray of light, at $\theta_i = 0$, so that no refraction of the light beam occurs.

The angular translator allows you to rotate the glass to different angles and thus change the angle of incidence, causing the light to be refracted within the material. The angular translator is equipped with a Vernier scale and a micrometer, allowing to measure angles to 1/60 degree - a minute of an arc. Minutes of a degree scale is located on the bottom half of the translator (see **Figure 7**). Reading minutes is similar to reading a Vernier caliper. So, if the zero line is between 15 & 16 degrees and the best alignment on the Vernier scale is 30 minutes (as pictured above) then the reading is 15 degrees and 30 minutes or 15.50 degrees.

A photometer, which is connected to the *Pasco Capstone* software on the computer, is mounted on a linear translator, and is set at the opposite end of the optical rail. The sensor measures the relative intensity of the light beam. This linear translator is constructed with a non-digital micrometer, which is used to measure the position of the laser light beam. The longitudinal line on the micrometer is graduated with 1 millimeter divisions and 0.5 millimeter subdivisions. The thimble has 50 graduations on it. Each graduation is 0.01 millimeter (one-hundredth of a millimeter). In order to read a metric micrometer, first count the number of millimeter divisions on the longitudinal line, and then add the total to the division on the thimble. For example, in the picture, 5.5 is read on the longitudinal line and 0.28 is read on the thimble. Adding these two together:



Micrometer

Figure 8

$$5.5 \text{ mm} + .28\text{mm} = 5.78 \text{ mm}$$

The reading on the micrometer is therefore 5.78mm.

2) Using the Software:

The Pasco Capstone software is necessary to read the relative light intensity of the refracted laser light ray. By adjusting the linear translator**,** the sensor of the photometer moves back and forth through the refracted light. When you login to the computer and load the appropriate software, the computer screen will display an arrow able to move in a circular arc, from 0 to 100. Start the collection and adjust the linear translator while watching the computer screen. Try to get the arrow to the point where it won't go any higher (maximum intensity).

The location where the maximum percentage reading is found represents the most intense point of light in the refracted laser beam. By reading this position, it is possible to determine the position of the refracted laser light as it exits the glass block. These positions are subsequently used to calculate the displacement of the light from its original position, ***d***.

1. Ask a lab instructor to check all components for correct initial positions and alignment along the optics rail.
2. Log on to the computer, then click on "Experiments – Galileo" icon, and chose "O2b – Refraction of Light" Pasco Capstone software for the experiment. **Do not attempt to make any adjustments to devices on the optical track before speaking with a lab instructor.**
3. Position the <u>angular</u> translator to read exactly zero degrees (to the minute of an arc). Ask a lab instructor for help if assistance is required.
4. Adjust the <u>linear</u> translator, which moves the photometer's sensor, to locate the position where the light intensity indicated on the computer is at maximum. Ask a lab instructor for help if assistance is required. Read and record this position as the zero degree position.
5. Adjust the angular translator to read exactly 20^o (to the minute of an arc).
6. Again adjust the linear translator to locate the position where the light intensity indicated on the computer is at maximum. Read and record this position as the 20^o position.
7. Calculate the displacement ***d*** for 20^o by subtracting the zero position from the located position.
8. Repeat steps 4 - 7 for 11 trials, varying the angle of incidence from 20^o to 65^o, in 5^o increments.

9. Calculate the angle of refraction for each angle of incidence using equation (11) provided in the theoretical background.
10. Calculate the index of refraction for each trial.
11. Calculate the mean and the standard deviation for your index of refraction data.
12. Make a graph of the sin(θ_i) as a function of sin(θ_r). Fit the graph with an appropriate function and determine the index of refraction of the glass using the parameters of the best fit provided by the computer. Your instructor might request you to attach a graph to your data, so, make sure to save the graph.

Experiment O2b: Refraction of Light

Student Name____

*Lab Partner Name*____

*Lab Partner Name*____

Physics Course____

Physics Professor______________________________________

Experiment Start Date__________________________________

Lab Assistant Name	*Date*	*Time In*	*Time Out*

Experiment Stamped Completed

Data Sheets: O2b: Refraction of Light

NAME: ______________________________ **DATE: __________________**

Material: ________________________________

Thickness of Material, *t*: ________________________________

Theoretical Index of Refraction, *n*: ________________________________

θ_i **angle of incidence**	**Maximum Intensity Position**	*d* **Displacement**	θ_r **angle of refraction**	**n index of refraction**
0°		**X**	**X**	**X**
20 °				
25 °				
30 °				
35 °				
40 °				
45 °				
50 °				
55 °				
60 °				
65 °				

Mean for index of refraction (*n*): ________________________________

Standard Deviation: ________________________________