REFRACTION

Purpose

a. To study the refraction of light from plane surfaces.

b. To determine the index of refraction for Acrylic and Water.

Theory

When a ray of light passes from one medium into another one of different optical density, it undergoes a change of velocity and a consequent change in direction. Figure 1 is an example of refraction. The incident ray makes an angle with the normal to the refracting surface called the *angle of incidence, **i***. The refracted ray makes an angle with the normal to the refracting surface called the *angle of refraction, **r***.

In Figure 1, if the incident medium is vacuum or free space, the speed of light is c. (The speed of light in air is very nearly equal to that in vacuum.) If the speed of light in the refracting medium *v* is ***less*** than the speed of light in the incident medium, the refracted ray bends towards the normal so that ***angle r is less than angle i***. (If the speed of light *v* in the incident medium is less than that of the speed of light in the refracting medium, the refracted ray would bend away from the normal. This can be seen in Figure 1 if the light path is reversed. The refracted ray now becomes the incident ray, and the incident ray is now the refracted ray, bending away from the normal.)

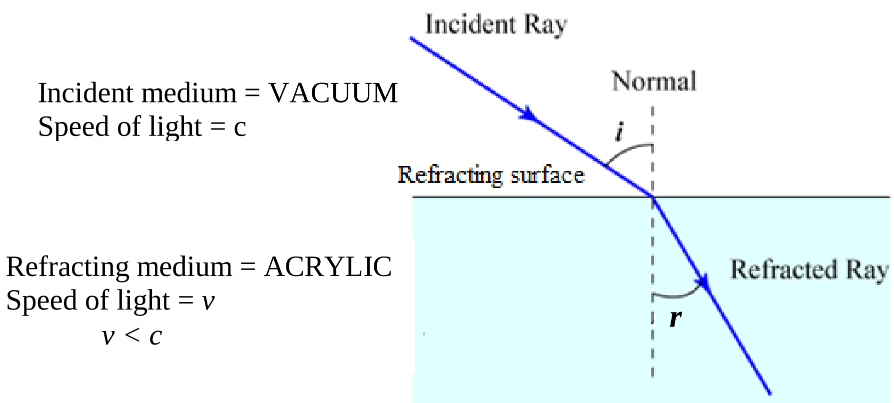


Fig. 1. The refraction of light as it passes from vacuum into Acrylic.

Snell's Law: If the incident medium is a vacuum (or air, approximately), the basic law of refraction is Snell's Law according to which

$$\frac{Sin\ i}{Sin\ r} = \frac{c}{v} \qquad (1)$$

The ratio *c/v* is called the *index of refraction, n,* of the refracting medium:

$$n = c / v \qquad (2)$$

Thus, Snell's Law may be written as

$$\frac{Sin\ i}{Sin\ r} = n \qquad (3)$$

It is therefore possible to characterize a medium via its index of refraction by measuring the angles of incidence ***i*** and the angle of refraction ***r***.

Finally, when light passes from one medium to the next, its frequency f does not change. The electrons in the refracting medium absorb energy from the light and undergo a vibrational motion with *the same frequency*. The motion of the electrons then causes reradiation of the energy *with the same frequency*. In any medium $v = \lambda f$. Since the speed of light in the refracting medium v is less than the speed of light c in vacuum, and its frequency f is unchanged, its wavelength λ is correspondingly reduced. Hence, the wavelength λ of light in a material is less than the wavelength λ_0 of the same light in vacuum by a factor of n:

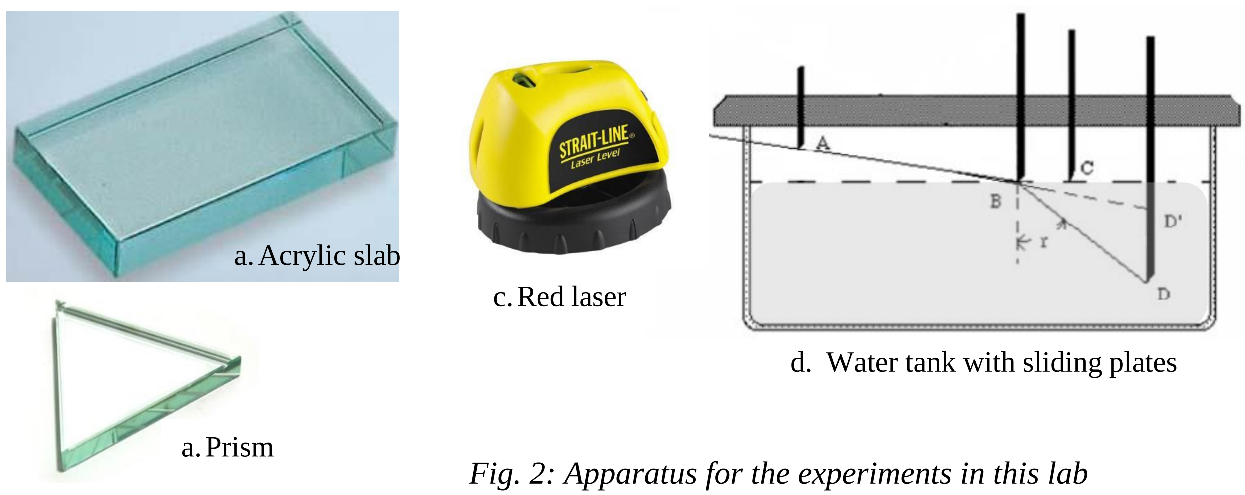
$$\lambda = \frac{\lambda_o}{n}. \tag{4}$$

Experiment: There are three parts to the experiment to study the refraction of light and determination of the index of refraction. In Part I we will use an acrylic slab, part II a prism, and part III a jar of water. You are provided with the following apparatus.

Apparatus

Rectangular Acrylic plate, Acrylic prism, protractor, ruler, Cork board, white paper, Red Laser.

Description of Apparatus



a. Acrylic slab

a. Prism

c. Red laser

d. Water tank with sliding plates

Fig. 2: Apparatus for the experiments in this lab

You will use an acrylic slab (Fig. 2a) and prism (Fig. 2b) to study the refraction of light from their surfaces to determine the index of refraction of the materials used to make the slab and prism by measuring the angles of incidence and refraction. The beam of a laser (Fig. 2c) is used to trace the direction of light.

You will also use a water jar to determine the index of refraction of water using an apparatus shown in Fig. 2d.

Procedure

Part I. Refraction by a rectangular Acrylic plate

1. Place a sheet of paper on the cork board, and on it the rectangular Acrylic plate. Carefully trace out the outline of the plate.
2. Place the laser on the bench table, not on the cork board. Shine the laser beam on the top vertical surface of the plate at some incident *angle* i_1. With your pencil, mark two points A and B along the incident beam, ***one near the plate*** and the other about 5 cm from it. See Figure 3. Do the same with the emergent beam, points C and D. Point C is ***near the plate***. See Figure 3.

**** Turn off the Laser when not in use ****

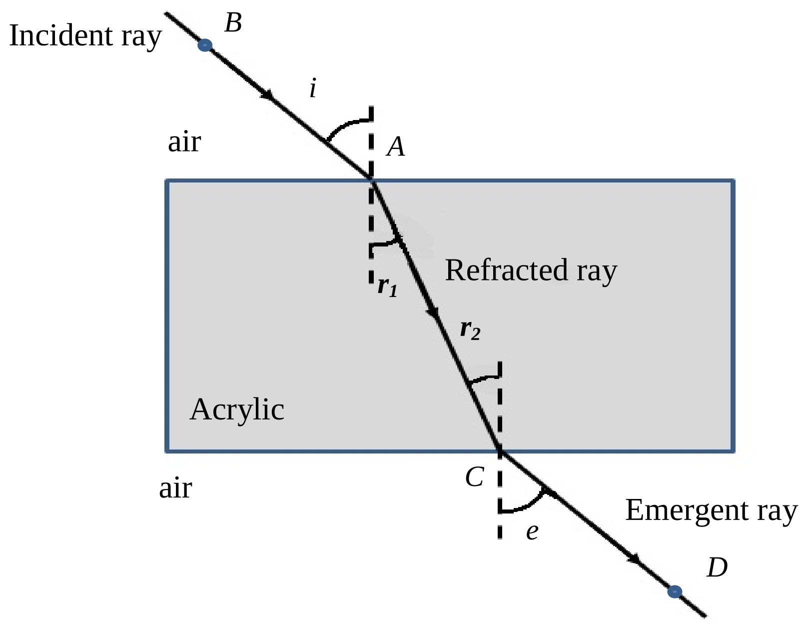


Fig. 3. Refraction by a rectangular Acrylic plate.

3. Now remove the plate from the paper. With the protractor, draw a perpendicular at points A and C. With the ruler, draw the incident, refracted and emergent beams. With the protractor, measure the angles i, r_1, r_2, e. Repeat the experiment for two other incident angles i. Then from Snell's Law, the index of refraction of the Lucite plate is

$$n = \frac{Sin\ i}{Sin\ r_1} = \frac{Sin\ e}{Sin\ r_2} \qquad (5)$$

Record the data in Table I.

Part II. Refraction by a prism

(a) Place the prism in the center of a sheet of paper on the cork board. Trace the outline of the prism. Mark off two points E and F on sides AB and AC of the prism that are ***equidistant*** from the vertex A. (See Figure 4.) With the laser on the bench table, shine the beam at the point E on side AB. Adjust the angle of incidence *i* of the beam such that the emergent ray emerges from point F on the side AC. Mark off two points J and K about 5 cm from points E and F along the incident and emergent beams, respectively.

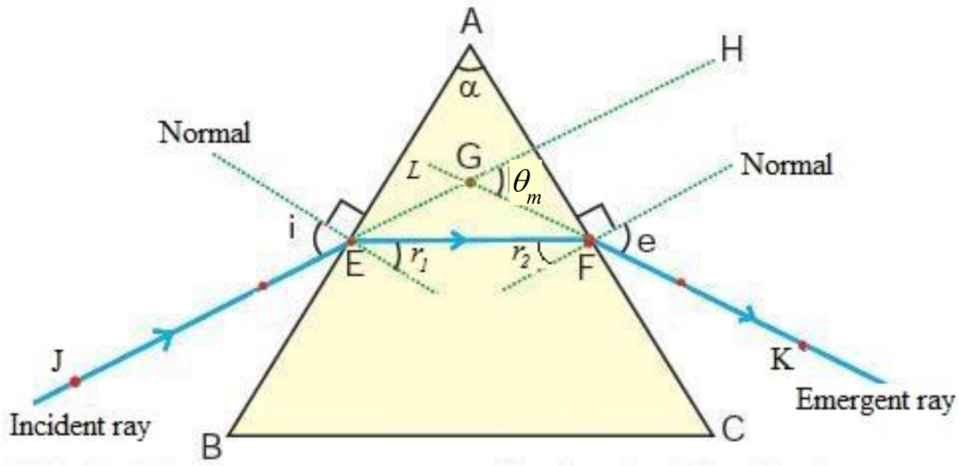


Fig. 4 Refraction by a Acrylic prism.

Now remove the prism from the paper. With the protractor, draw a perpendicular at points E and F. (See Figure 4.) With the ruler, draw the incident, refracted and emergent beams. Extend the incident beam JE to H. Extend the emergent beam FK backwards to L. With the protractor, measure the angles *i*, r_1, r_2, *e* the vertex angle α and the angle of minimum deviation θ_m. As shown below, the index of refraction *n* as obtained from Snell's Law can also be expressed in terms of the angle of minimum deviation θ_m and the vertex angle α as

$$n = \frac{Sin\ i}{Sin\ r_1} = \frac{Sin\ \dfrac{\theta_m + \alpha}{2}}{Sin\ \dfrac{\alpha}{2}} \qquad (6)$$

Proof of this equation is given in the appendix at the end of this lab manual.

Record the data in Table II.

(b) We next wish to show experimentally that θ_m is the angle of minimum deviation.

Again, on the paper, draw the outline of the prism, and mark off an arbitrary point E along the side AB. Then focus the laser beam on point E but with an incident angle *i* that is ***greater*** than that that employed in Part (a). Mark the point F on side AC from which the ray emerges. Mark off two points J and K about 5 cm from points E and F along the incident and emergent beams, respectively.

Remove the prism, and with the protractor, draw the normal at points E and F. With the ruler, draw the incident, refracted and emergent rays. Extend the incident ray JE to H. Extend the emergent beam FK backwards to L. Measure the angles i, r_1, r_2, e and the angle of deviation θ (angle FGH) (See Figure 4). Record the data, the value of the refractive index n, and the angle of deviation θ in Table III.

(c) Repeat Part II (b) for an angle of incidence that is ***less*** than that employed in Part (a).

Part III. Refraction by water

In this final component of the experiment, we will determine the index of refraction of water.

The apparatus used for this part of experiment is shown in Figure 5. It has a Metal Frame containing four brass sliders 1, 2, 3, 4, and a jar of water. See Figures 5 for the experimental setup.

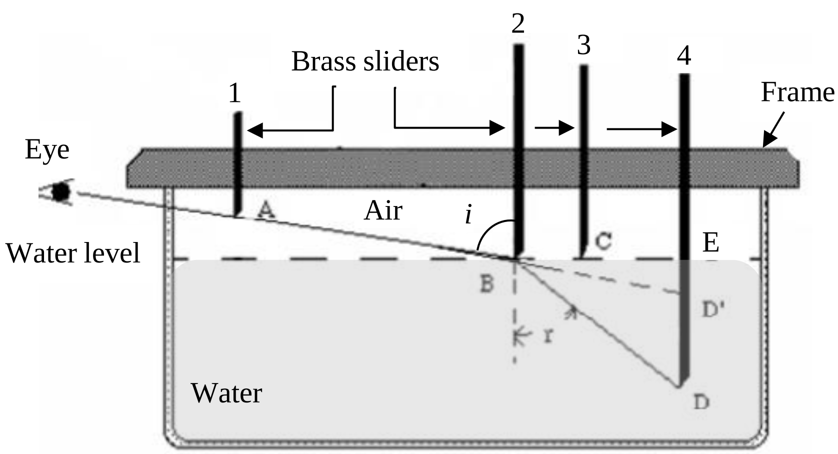


Fig. 5a Experimental setup for refraction by water.

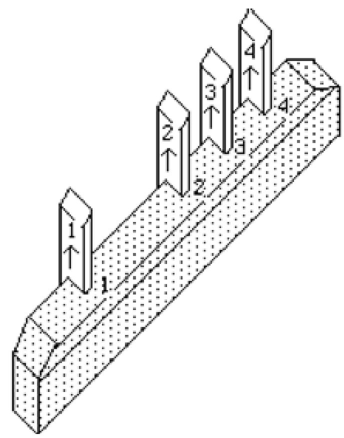


Fig. 5b Brass sliders in frame.

1. Set the sliders in the slots of the frame with the arrows pointing upwards, with the corresponding numbers as shown in Figure 5. Set the jar of water on a white sheet of paper. Mount the metal frame on the jar as shown in Figure 5a.

2. Push slider 4 as far down into the water as possible. Push sliders 2 and 3 as close to the surface of the water as possible without touching the water. Finally adjust slider 1 so that the point A appears to be in line with points B and D. See Figure 5a.

   To confirm your sighting, shine the laser beam along the line AB. You should see the beam reflected at D.

3. Remove the frame from the water and lay it on a sheet of paper without disturbing the sliders. Mark the positions of the points A, B, C, D on the paper. You must include this work in your report after further drawing and calculation.

Computation

1. Calculate the index of refraction of the plate from the data in Table 1 for angles of incidence, refraction, and emergence, and record in Table 1.
2. Calculate the index of refraction of the prism from the data in Table 2 for angles of incidence, refraction, and emergence, and record in Table 2. Also calculate the index of refraction from the angle of minimum deviation using Eq. 6.
3. Calculate the index of refraction of the prism from the data in Table 3 for angles of incidence, refraction, and emergent, and record in the Table 3. Determine the angle of deviation and compare this angle with the angle of minim deviation obtained in Part II (a).
4. For part III, once you have the marks of the sliders on the paper, draw the line BC (the water level). With the protractor erect a perpendicular to BC at B. Draw the lines DB and AB. Finally, measure the angles of incidence $\boldsymbol{i}$ and refraction $\boldsymbol{r}$ with the protractor. Determine the index of refraction of water via Snell's Law.
5. Extend the line of sight AB to D' on slider 4. The apparent position of the edge of the slider 4 is at D'. Measure the apparent depth ED' and the true depth ED. Then from triangle BED' (see Figure 5a)

   $$\frac{ED'}{BE} = \tan(90 - i)\,. \tag{7}$$

   From triangle BED (see Figure 5a)

   $$\frac{ED}{BE} = \tan(90 - r)\,. \tag{8}$$

   Then from Eqs. (7) and (8) we have

   $$\frac{ED'}{BE} = \frac{\tan(90 - i)}{\tan(90 - r)}\,. \tag{9}$$

   Determine the ratio ED'/ED from Eq. (9) and compare with the ratio of the measured distances ED' and ED.

Questions

1. In Part I, is the emergent ray parallel to the incident ray? What causes, other than experimental error, will make the emergent ray not parallel to the incident ray?
2. If you desire to shoot a fish whose image can be seen in clear water, should you aim above or below the fish? Explain by the aid of a diagram.

Data Sheet

Date experiment performed:

Name of the group members:

Table 1.

	Angles				Refractive Index n		
Trial	Incident i	Refracted r_1	Incident r_2	Emergent e	$\frac{Sin\ i}{Sin\ r_1}$	$\frac{Sin\ e}{Sin\ r_2}$	Average
1							
2							
3							

Table 2a

Vertex angle α =

Angle of minimum deviation θ_m =

Angles				Refractive Index n			
Incident i	Refracted r_1	Incident r_2	Emergent e	$\frac{Sin\ i}{Sin\ r_1}$	$\frac{Sin\ e}{Sin\ r_2}$	$\frac{\sin\left(\frac{\theta_m+\alpha}{2}\right)}{\sin\left(\frac{\alpha}{2}\right)}$	Average

Table 2b

Angles				Refractive Index, n		Angle of Deviation θ
Incident i	Refracted r_1	Incident r_2	Emergent e	$\frac{Sin\ i}{Sin\ r_1}$	$\frac{Sin\ e}{Sin\ r_2}$	

Table 3

Angles		Refractive Index of water, n
Incident i	Refracted r_1	$\frac{Sin\ i}{Sin\ r_1}$

Appendix: Proof: Derivation of Eq. 6 for an isosceles prism.

The minimum deviation in an isosceles prism occurs when there is symmetric refraction, i.e., Angle $\boldsymbol{i}$ = angle $\boldsymbol{e}$; angle r_1 = angle r_2; EF parallel to BC because $r_1 = r_2$.

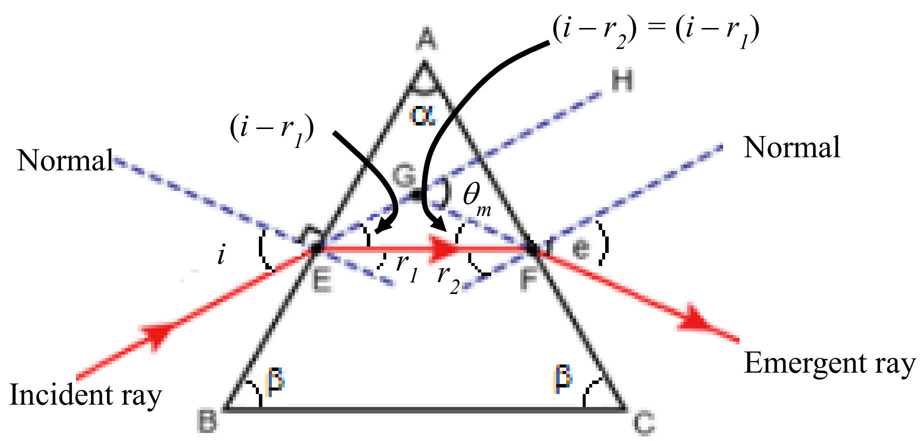


Fig. 6 Various angles in the refraction by a prism for minimum deviation θ_m.

From Fig. 6 and the properties of triangles,

$$\theta_m = 2(i - r_1)\,, \tag{10}$$

so that

$$i = \frac{\theta_m + 2r_1}{2}\,, \tag{11}$$

and

$$r_1 = 90 - \beta\,, \tag{12}$$

because EF is parallel to BC and angle AEF = β. A perpendicular bisector of BC passing through A bisects the angle of prism in half, thus

$$\frac{\alpha}{2} = 90 - \beta\,. \tag{13}$$

From Eqs. (12) and (13),

$$r_1 = \frac{\alpha}{2}\,. \tag{14}$$

On substituting Eq. (14) into Eq. (11), and then employing Eq. (11), Snell's law becomes

$$n = \frac{Sin\ i}{Sin\ r_1} = \frac{Sin\,\dfrac{\theta_m + \alpha}{2}}{Sin\,\dfrac{\alpha}{2}}$$ which is Eq. (6).