Apparatus for Teaching Physics

Snell's Law with Large Blocks

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The introductory physics lab curriculum usually has one experiment devoted to the study of the refraction of light. The most obvious way to study the refraction of light is to lay a transparent block down on the lab bench as in Fig. 1 and aim a laser beam horizontally at the block so that it refracts twice---inward upon entering the block and outward upon exiting. The vendors that provide us with lab equipment (Sargent-Welch, Pasco, Fischer Scientific, Frey Scientific to name a few) sell acrylic blocks for this very purpose, but these are not adequate or they are too expensive. If students are going to measure angles of incidence and refraction, the blocks should be larger than the typical student protractor which has a radius of three inches ($\approx 7\frac{1}{2}$ cm). These blocks are just not large enough. These blocks are generally not thick enough either so that the beam from a laser level passes over them and not through them. The blackboard optics kits, on the other hand, contain three blocks that are large enough---on the order of 10 to 20 cm. Unfortunately, these kits cost over $1000.

Fortunately, there is a small acrylic fabricator located in North Dakota that makes transparent blocks and does so inexpensively. Prairie Stamper[1] sells acrylic blocks for rubber stamping, but also does custom work. They cut a 1-inch thick sheet of Autofina Plexiglas® into 12 blocks for us and polished them for well under $20/block. We specified the five different shapes shown in Fig.2---three of them triangular and two of them rectangular. The precision of the cuts and the clarity was excellent. The blocks are appreciably larger than the typical student protractor. They are also thick enough so that the beam from a typical laser level will pass through them instead of over them. Our search revealed that many manufacturers will cut sheets of acrylic into blocks but they will not polish them. Also, they will steer you toward ½-in and ¾-in sheets which they keep in stock and away from 1-in sheets which they do not. Thirdly, they prefer large jobs.

As mentioned earlier, the most obvious way to study refraction is to place a transparent block onto the lab bench and direct a horizontal beam from a laser level so that it traverses the block. Fig.3 illustrates schematically the two refractions for a triangular block. The angles of incidence are ϕ_1 and ϕ_2' and the angles of refraction are ϕ_1' and ϕ_2. The refractive indices of the air and the block are *n* and *n'*, respectively. Snell's law yields

$$n \sin \phi_1 = n' \sin \phi_1'$$

$$n' \sin \phi_2' = n \sin \phi_2$$

where primed refers to the block and unprimed refers to air.

The students place the block on a sheet of 11x17 paper and orient the beam diagonally. The size of the paper and the diagonal orientation result in longer rays and longer rays result in smaller percent uncertainties in the measurement of angles. With triangular blocks be sure the students position the block so that the middle beam is longer than three inches. It is also important to pitch the incident surface enough so that the angles of incidence ϕ_1 and refraction ϕ_2 are both over 30° or so. The uncertainty $\delta n'$ drops appreciably with ϕ_1 because

$$\left(\frac{\partial n'}{\partial \phi_1}\right)_{\phi'_1} \propto \frac{1}{\tan \phi_1}$$

The same is true with ϕ_2. The uncertainty $\delta n'$ can be huge for small ϕ_1 and ϕ_2.

Once block, paper, and laser level are in place, students trace out the refracting edges of the block. Then they mark the paths of the incident beam for the first surface and refracted beam for the second surface by laying down a series of pencil ticks onto the paper just below the beam. The magnetic strip on a credit card provides an accurate vertical reference. See Fig.4. The middle beam is the refracted beam at the first surface and is also the incident beam at the second surface. Its path cannot be marked because the block is in the way. Once the paths of the first and third beams are marked, the block may be moved aside and the paths of the three beams traced as in Fig.5. Arrowheads are used to indicate the direction of the beam.

Next, students measure the angles of incidence ϕ_1 and ϕ_2' and the angles of refraction ϕ_1' and ϕ_2. They can be expected to measure angles to the nearest tenth of a degree---three significant digits. Strongly admonish students who are not showing the proper mindfulness. For $\phi_1 \approx 30^\circ$, an uncertainty of just 1° can result in percent uncertainties in n' of 3% to 5%. In this lab, experimental discrepancies are guaranteed to be low when students are attentive and conscientious. Finally, students will often try to draw normals---dashed lines perpendicular to the surface—before obtaining angles. This is unnecessary because the protractor may be positioned as in Fig.6. In fact, badly drawn normals are a common source of error.

Finally, the students use Snell's law to calculate the index of refraction of the block twice - once from ϕ_1 and ϕ_1' and once from ϕ_2' and ϕ_2. They use $n = 1.0003$ for the index of refraction of air. A physics student at Wheeling Jesuit University once measured the index of refraction n' of the blocks in an advanced lab course.[3] Using laser light traversing a block at minimum deviation and very long refracted rays, he determined that $n' = 1.490 \pm 0.002$ for Autofina Plexiglas®. Using this value, students can calculate experimental discrepancies for n'.

Summary

Although the vendors that provide us with lab equipment sell acrylic blocks for the purpose of studying refraction these are too small or too expensive. Blocks can be custom-made inexpensively so that they are larger than a protractor and thick enough so that the beam from a laser level passes through them.

References

1. Prairie Stamper, 207 Cimarron Drive, Roseglen, ND 58775; (701) 743-4500.
   http://www.prairiestamper.8m.com
   markrena@RTC.coop

2. Francis A. Jenkins and Harvey E. White, *Fundamentals of Optics* (McGraw-Hill Companies, Inc., 2001), p.30.

3. Adam R. DeMary (unpublished lab report, 2004).

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<snell.fig1.jpg>

Fig. 1. The beam from a laser level refracting twice---inward upon entering the block and outward upon exiting. (The path of the beam is made visible by chalk dust suspended in air. The picture was taken with very little light and later enhanced with Microsoft Photo Editor by greatly increasing brightness and contrast.)

<snell.fig2.jpg>

Fig. 2. The custom-made[1] acrylic blocks. Note that the blocks are appreciably larger than the typical student protractor. They are also thick enough so that the beam from a laser level passes through them.

<snell.fig3.tif>

Fig. 3. The three rays, the two normals, the angles of incidence ϕ_1 and ϕ_2' and the angles of refraction ϕ_1' and ϕ_2 for a triangular block (Jenkins and White[2]).

<snell.fig4.jpg>

Fig. 4. The path of the beam is marked using pencil ticks. The magnetic strip on a credit card provides an accurate vertical reference.

<snell.fig5.jpg>

Fig. 5. The paths of the three rays traverse the sheet of 11x17 paper diagonally. The middle ray is longer than three inches. It is the refracted beam at the first surface and is also the incident beam at the second surface.

<snell.fig6.jpg>

Fig. 6. The angle ϕ_1 is measured with a protractor positioned as shown. It is unnecessary to draw dashed lines normal to the surface.