Lab 7

Reflection and Refraction at a Plane Surface

Experimental Objectives

- Experimentally verify the law of reflection from a plane surface by tracing the paths of the incident and the reflected light rays.
- Experimentally verify the law of refraction from a plane surface by tracing the paths of the incident and the refracted light rays to calculate n for the glass,
- Experimentally verify the law of refraction from a plane surface by predicting the path a ray of light will emerge from a prism for a given incident angle, and
- Experimentally determine the critical angle for a piece of glass.

Sir Isaac Newton developed a particle theory of light (essentially photons) in order to use geometry to explain two commonly observed optical properties of light: reflection and refraction. Those interested in optics in Newton's time had observed that whenever light is incident upon any surface, some of the light is reflected off from the surface and some of the light is transmitted through the surface. When the incident light approaches along a line normal to the surface, it continues along its straight-line path. However, when the incident light approaches at an angle as in Figure 7.0.1, then the light changes direction. The transmitted light is said to refract. The property that determines the amount of the refraction is called the *index of refraction* and is denoted by n. By convention, the angles for the incident, the reflected, and the refracted light are all measured from the line normal to the surface.

Since the reflected light never sees the material with a different index of refraction, the reflection follows the law of reflection, which states that the angle of the incident ray is equal to the angle of the reflected ray:

$$\theta_{\text{incident}} = \theta_{\text{reflected}}.$$

The transmitted light, on the other hand, enters the material, which has a different index of refraction and follows the law of refraction or Snell's Law, named for Willebrord Snell (1591-1626). This law is expressed in terms of the sine of the incident and refracted angles, θ_i and θ_r:

$$n_i \sin\theta_i = n_r \sin\theta_r$$

where n_i is the index of refraction for the incident medium, and n_r is the index of refraction for the refracted material.

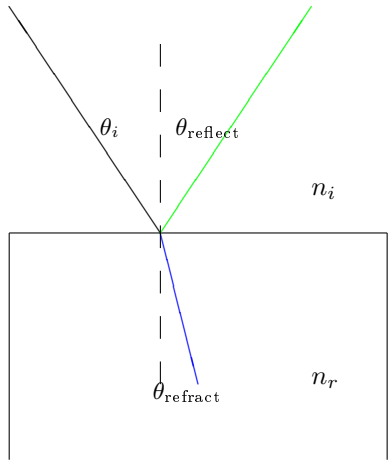

Figure 7.0.1: Some of the incident light from the upper left reflects to the upper right and the rest refracts into the material to the lower right.

The index of refraction determines the amount of refraction because it is a measure of the speed that light travels through the medium: $n = c/v$, where $c = 2.998 \times 10^8$ m/s is the speed of light in a vacuum and v is the speed light travels through the medium. The index of refraction for a vacuum is therefore identically 1. It happens that the index of refraction for air is close enough to 1 that we will not be able to measure a difference at our level of precision.

7.1 Pre-Lab Work

1. Since light travels faster in a vacuum than in any other material, $c > v$, determine if n has a maximum or a minimum value and what that might be.

2. Consider Snell's Law.

   (a) If it were possible to create two different materials with the same index of refraction, so that $n_i = n_r$, then comment on the relationship between the incident and refracted angles.

   (b) When light passes from a material with a small index of refraction to a material with a large index of refraction so that $n_i < n_r$, will θ_i larger than or smaller than θ_r? Draw an approximate diagram indicating if the light bends *towards* the normal, as in Figure 7.0.1 above, or if it bends *away from* the normal.

3. Critical Angle: It is possible, for the case where light is bent away from the normal (becomes more parallel to the surface), that it can be bent all the way over to actually being parallel to the surface. When this happens, the light is not transmitting into the new material and cannot be seen from the other side.

   (a) It is only possible to have a critical angle for either $n_i > n_r$ or $n_i < n_r$. For which of these cases is it possible?

   (b) Using Snell's Law above, derive an equation for the incident critical angle (the refracted angle is 90°), in terms of the two indices of refraction for the two media.

7.2 Procedure

7.2.1 Refraction at a plane surface

Place the square piece of glass on the cardboard that has been covered with a piece of paper. Orient the frosted sides of the glass towards the short sides of the paper. Draw the outline of the glass on the paper and

be careful to not move the glass. (You may want to use a pair of pins at the corners to fix the glass in place.)

Plug in and set up the PASCO light box to emit a single ray of light. Place the light box so that its single ray of light shines through the glass. Notice that the path the light follows through the glass is like the solid line in Figure 7.2.1 following points 1, 2, 3, and 4. Notice that the path the light follows above the glass is like the dashed line in Figure 7.2.1 following points 1, 2, 3′, and 4′.

To mark the incident path of the light, stick a pin in the paper at location 1, closest to the light box. You should see the shadow of the pin in the light beam. Place **pin 2** in the shadow of **pin 1**. You should also see the shadow of the pin in the exiting light beam. Place **pin 3** and **pin 4** so that each lines up with shadows of the previous pins.

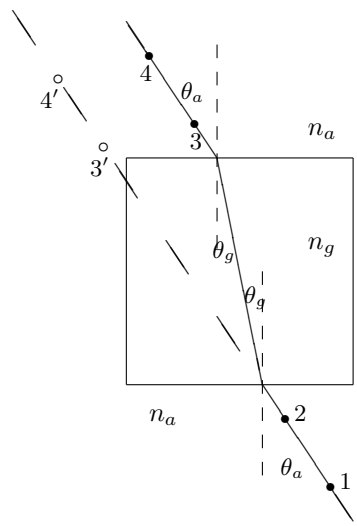

Figure 7.2.1: Square Glass Ray Diagram. The light travels from pin 1 past pin 2 through the glass to pins 3 and 4. At the first boundary, air is the incident material and glass is the refracting material. On the second, glass is the incident material and air is the refracting material.

Once you and all of your partners are satisfied with the location of the pins, verify that the glass has its outline drawn on the paper and remove the glass from the paper. You may also turn off the light box. Use a straight-edge to draw a straight line through each pair of pins up to the edge of the lens. Use a straight-edge to draw another line inside the glass connecting where the pin-lines meet the surface. Use the protractor to measure all incident and refracted angles. Look up the index of refraction of air and of glass and notice that they have a range of values. Select a reasonable value for n_{air} and use Snell's law to determine the index of refraction for the glass. This is your first verification of Snell's Law.

Notice that the angle decreases ($\theta_a > \theta_g$) when the light passes from small n (air) to large n (glass). This light is bent towards the normal. Similarly, when the light passes from large n (glass) to small n (air), the angle increases ($\theta_g < \theta_a$). This light is bent away from the normal.

7.2.2 Reflection at a single plane surface

Carefully replace the square piece of glass onto your diagram and turn the light box back on. Carefully re-align the light box to shine along the path that it previously followed. Now you should also notice that a portion of the beam reflects off of each interface. For the first boundary (after **pin 3**), place two pins along the beam that is reflected off of the glass. When you are satisfied that it is aligned as well as possible, turn off the light box and remove the glass. Measure the reflected angle and verify the law of reflection.

7.2.3 Predicting the Exiting Ray

Use the thin triangular prism in this part. Place the first two pins as indicated in Figure 7.2.2, which starts the drawing that you will need to complete. I have drawn the incident ray, the dashed normal line, and the refracted ray. You will need to figure out where the light hits the second boundary, draw a line normal to the second surface, and then use Snell's law to determine the direction that the light beam exits from the prism.

Step 1) Decide on a value for the incident angle. Assuming that the index of refraction of this glass is the same as what you calculated for the square glass, use Snell's law to determine the refracted angle.

Step 2) Notice that the light ray inside the prism forms a triangle with the apex of the prism. Since the angles of any triangle add to 180°, you can use the first refracted angle to determine the second incident angle. (Recall that a normal line makes a 90° with the surface.)

Step 3) Use Snell's Law to determine the exit angle.

Show your prediction to the instructor. Set up the triangular prism and the light box to verify your prediction. Your actual result will probably be noticeably different than your prediction. When you make your measurements your angles will not exactly match those you used in your prediction and the glass may have a different index of refraction. Use your measurements to determine the index of refraction for this piece of glass and verify that it is a reasonable value as your second verification of Snell's Law.

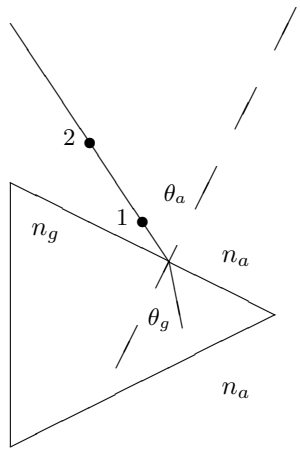

Figure 7.2.2: Triangular Glass Ray Diagram

7.2.4 The Critical Angle

Again consider the prism. Snell's Law makes an interesting prediction for large angle incident rays. This is the effect that allows optical fibers to carry signals without loss (unlike electrical cables which have resistance that degrades a signal). It is possible for light in a material with a high index of refraction that is incident upon a material with a low index of refraction to have total internal reflection — In our case, this means that the light does not refract out of the glass! To do this calculation you can repeat the steps of your previous calculation in the reverse order.

Step 3) Set your exit angle (the second refraction angle) to be 90°. Use Snell's Law to determine the second incident angle (inside the glass). This is the *critical angle*. Now we need to figure out how to set the equipment to produce this angle.

Step 2) Notice that the light ray inside the prism will again form a triangle with the apex of the prism. Since the angles of any triangle add to 180°, you can use the second incident angle to determine the first refracted angle. (Recall that a normal line makes a 90° with the surface.)

Step 1) Since you know the index of refraction of this glass, use Snell's Law and the first refracted angle to determine the first incident angle.

Set the light box off of the cardboard and paper so that you can rotate the cardboard to easily change the incident angle. Set the incident ray to be incident on one side at about ¼ of the way from the apex. If you set it right, then when you turn on the light you should see the light refracted off of the first surface, but then not exit the glass at the second surface. This may not actually be the case. Either way, slowly rotate the paper (and the prism) until you can see an exiting beam and then slowly rotate it again until the refracted ray is refracted by *just* 90°, the smallest angle that makes the light not exit the prism. The critical angle is now the incident angle at the second surface of the prism. Experimentally determine the critical angle for this piece

of glass. Compare the predicted value of the critical angle to the measured value of the critical angle as your third and final verification of Snell's Law.

7.3 Questions

1. Explain why a plane mirror reverse left and right. It will help to draw a ray diagram that replaces a the pins with a wider object that has a clear left side and right side.

2. What happens to the speed that light travels through a medium a greater index of refraction?

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