Reflection and Refraction of Light

Goals of this lab

- Study the reflection and refraction of light at plane surfaces.
- Find the critical angle

In this experiment you will move to several experimental stations. If you find a particular station is in use, go on to the next one.

Caution: You will use a low-power laser with risk of damage the retina of your eye. Never (ever!) try to look to look into the laser.

Overview

Visible light is a small portion of the spectrum of electromagnetic radiation, which extends from very long radio waves through very high energy X-rays and gamma rays. When the wavelength of the radiation is small compared to the dimensions of the objects with which they interact, the wave properties are difficult to observe and it is more convenient to use the *geometric optics* approximation in which one emphasizes the trajectories defining the direction of energy propagation. These trajectories, straight lines in uniform media, are the light rays of ordinary optics.

The velocity of light in a medium, denoted by the symbol *v*, is less than *c*, the velocity of light in vacuum. The ratio of the two velocities is the index of refraction of the medium.

$$n = \frac{c}{v} \qquad \text{or} \qquad v = \frac{c}{n} \qquad (1)$$

The law of reflection is illustrated in **Figure 1**. The two media in which light can propagate have different indices of refraction. The direction of the beams is shown by the arrow heads. When a light ray traveling in the medium with index of refraction n_1 strikes the boundary between that medium and another medium of index n_2, some of the light is reflected back into the first medium, and some transmitted. The angle θ_1 shows the direction of the incident ray, θ_2 the direction of the transmitted beam, and θ_3 the reflected ray.

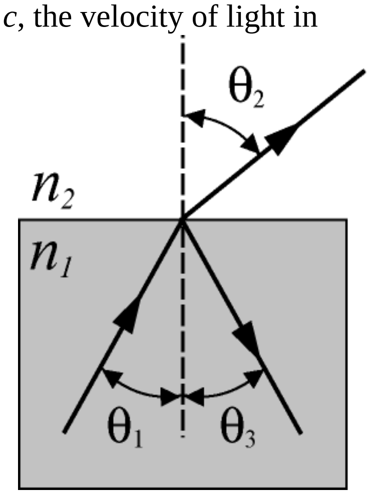

Figure 1: The Law of reflection And Refraction

The fraction of the light reflected and transmitted depends on the angle of incidence and the indices of the two materials. The directions of the reflected and original rays are related so that the angle of incidence equals the angle of reflection

Law of Reflection $\theta_3 = \theta_1$ (2)

Snell's Law is sometimes called the Law of Refraction and the transmitted ray is called the refracted ray. By Snell's Law the incident and transmitted rays are related by

Law of Refraction $n_2 \sin\theta_2 = n_1 \sin\theta_1$ (3)

For example, if $n_1 = 1, n_2 = 1.5$, and $\theta_1 = 30°$, then $\theta_2 = 19.5°$.

Prelab Question 1

A beam of light enters a parallel-sided transparent block, as shown in the figure.

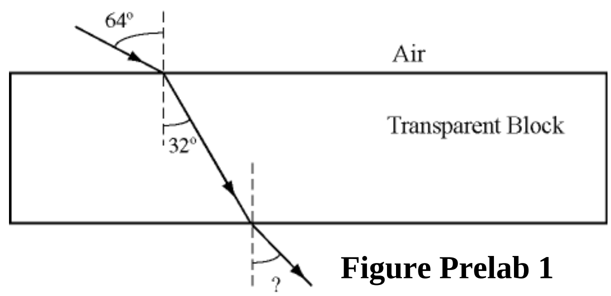

Figure Prelab 1

(a) What is the index of refraction of the transparent block?
(b) What is the speed of light in the transparent block?
(c) What is the angle at which the beam will re-enter the air from the bottom of the block? Support your answer with numbers or words.

A visible light beam is created by a cylindrical lens placed in front of the laser. The laser light striking the bench-top should form a line, making a "light ray" so we can trace the path of the light shown in Figure 2 below with arrows.

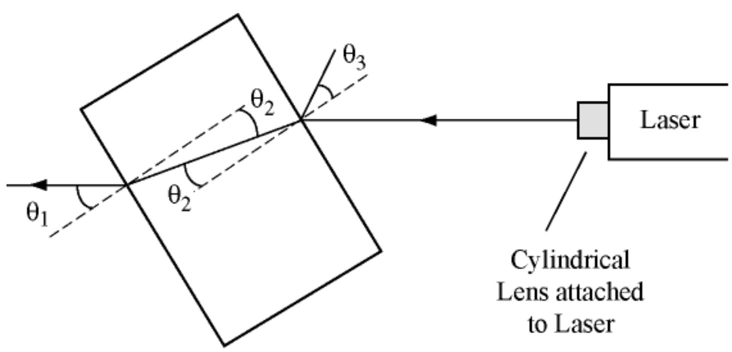

Figure 2: The arrangement of the plate, cylindrical lens and laser

Procedure

Station I: Measuring the index of refraction and critical angle by ray-tracing

1) Tape a piece of paper to the working surface to hold it in place. The lens may need to be adjusted to give a line image of the laser beam.

2) Place the plate so that the laser light strikes it at an acute angle.The incident, reflected, and refracted rays should be easily seen. Carefully trace the incident ray, refracted ray, reflected ray, and the incident and exiting sides of the plate. Repeat for other incident angles between 10^0 and 90^0.

3) Measure $\sin\theta_1$ and $\sin\theta_2$. Determine the index of refraction from the slope of the graph of $\sin\theta_1$ *vs.* $\sin\theta_2$. Estimate the error in the slope.

4) Compare θ_1 and θ_3 for your measurements.

5) Place the prism on the paper and trace the incident ray and the ray that leaves the prism. Construct the path inside the prism.

6) Measure the sines of the angles the rays make with the prism surface and compute the angles with respect to the normal.

7) Rotate the prism and observe the reflected ray. Describe what happens at near-grazing incidence.

8) Rotate the prism. Describe what happens at the critical angle. Measure the critical angle.

Questions:

1. Does taking more data for additional orientations of the prism (step 8) change your value for the index of refraction in any way?

2. Is the prism the same kind of material as the plate? Explain your answer.

3. Which method for measuring the index of refraction do you think is the most accurate and why?

Station II: Measuring the index of refraction by the apparent depth method.

An object on the bottom of a swimming pool or a clear lake appears to be closer to the surface than it actually is. This phenomenon may be understood by examining the light rays which pass from the object to the eye.

The perceived distance of the object is related to the angular divergence of the rays leaving the object. The rays from an object embedded in a medium with index of refraction *n* will be bent as they leave the medium and travel to the eye; accordingly, an observer will make an incorrect estimate of the distance of the object. The situation is illustrated in **Figure 4**.

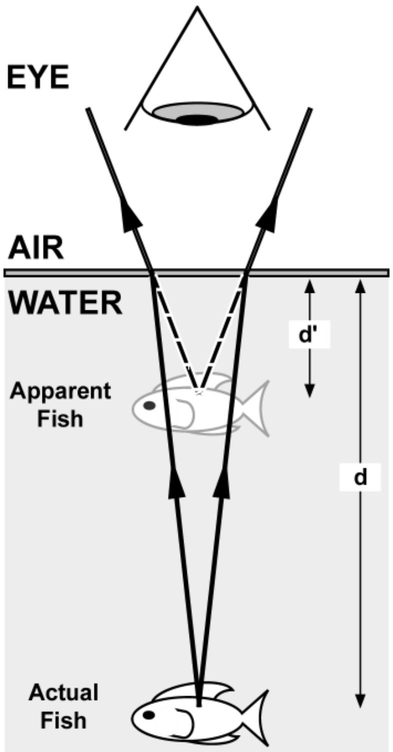

Figure 4: Apparent Depth

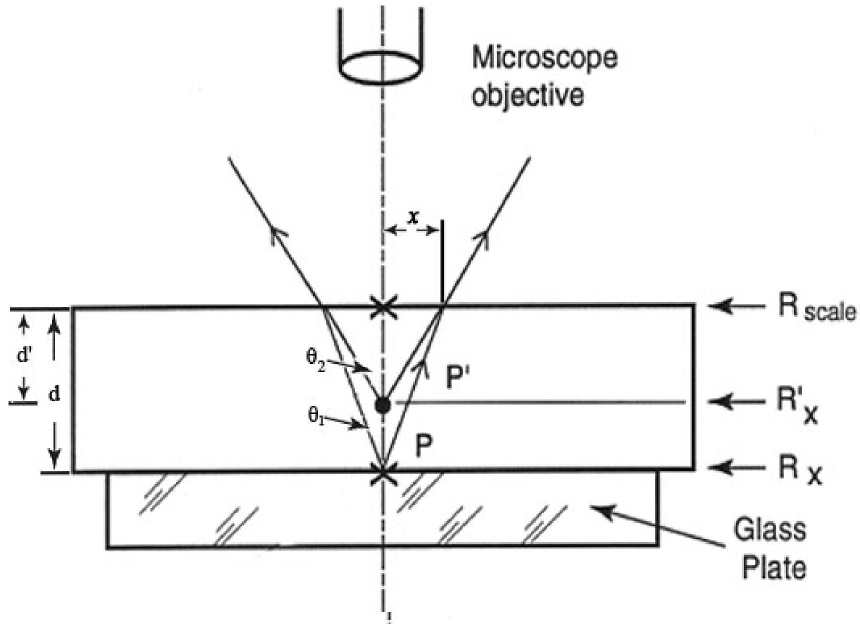

Figure 5: Apparent Depth with the microscope

In **Figure 5**, although the rays originate at *P*, they appear to come from point *P'* (which is closer to the surface) because the rays are bent away from the normal as they pass through the interface. All light rays making a small angle with the line of sight (these are the only rays that enter the eye) appear to come from the same point *P'*. Consider the particular ray which is incident on the interface at angle θ_1, is refracted to θ_2, and cuts the surface at a distance *x* from the line of sight.

The apparent depth is $d' = \dfrac{x}{\tan\theta_2}$ but the true depth is $d = \dfrac{x}{\tan\theta_1}$ and therefore the ratio of apparent to true depth is

$$\frac{d'}{d} = \frac{\tan\theta_1}{\tan\theta_2} \tag{4}$$

Snell's Law (3) relates the sines of the two angles

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} \qquad (5)$$

But, for small angles the sine and tangent are essentially equal. Therefore

$$\frac{d'}{d} = \frac{n_2}{n_1} \qquad (6)$$

is a very good approximation. Thus, all rays appear to emanate from the same point P'. In our case, medium 2 is air ($n_2 = 1$). Renaming $n_1 = n$, the apparent depth of the object is

$$\frac{d'}{d} = \frac{1}{n} \qquad (7)$$

Prelab Question 2

To make their lives more exciting, Mary Kate and Ashley decide to take a physics course. The next time they are at a pool party they notice the drain at the 10 foot deep end of the pool only appears 7 1/2 feet under water. They both quickly determine the correct index of refraction of water. What did they get, and how did they get it?
(a) Which point in **Figure 5** corresponds to the "apparent fish" in **Figure 4**?
(b) How would you find distance *d'*? How about *d*?

Procedure II

This station uses a depth-measuring microscope, which has a dial caliper attached to the focusing adjustment that allows you to measure the distance (from an arbitrary zero position) of the object focused in the microscope. The caliper can be read in inches or cm --- there is a button that selects the units.

The object whose real and apparent depth is to be measured is a cross mark on the top of a glass plate. Place the glass plate on the microscope stage with the marked side up. The mark will be observed through the plastic plate. Its apparent depth below the top of the plate will be measured.

You will need to take three readings:

- $R'_\times$ when the microscope is focused on the cross through the plastic plate
- R_{scale} when the microscope is focused on the scale on top of the plastic plate.
- $R_\times$ the true location of the cross mark

1) Look through the eyepiece and adjust the mirror to obtain the maximum possible illumination.

2) Place your plastic plate with the scale side up on top of the glass plate. Center the clear oval over the hole in the stage. Record values for $R_\times$, $R'_\times$, and R_{scale}.

3) Calculate *d* and *d'*. Find the index of refraction of the plastic plate. Use the dial caliper to verify your microscope measurement of the plate thickness. Include an estimate of your error.

Question:
How does the index of refraction you measured for water compare with the accepted value, 1.33?

Station III: Measuring the index of refraction by measuring the critical angle

Total internal reflection occurs when all the light incident on the interface between two media is reflected back into the original medium of propagation. As shown in **Figure 6**, this will occur when the angle of incidence exceeds the critical angle, θ_c.

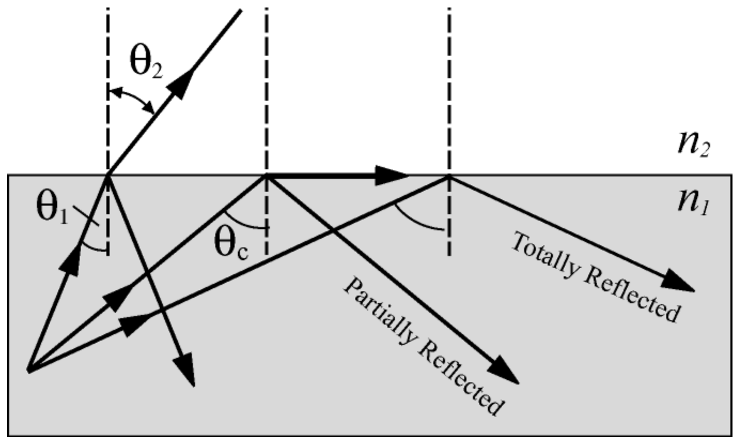

Figure 6: Reflection at less than, greater than, and at the critical angle. n_1 is the index of refraction of the shaded area

According to Snell's Law,

$$\sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

If $n_1 > n_2$, then $\sin\theta_2 > \sin\theta_1$ and it is possible mathematically that $\sin\theta_2$ could be greater than one. What this means is that in this circumstance there will, in fact, be no transmitted ray and the light will be totally reflected in medium 1.

The critical angle is the angle of incidence for which the angle of refraction θ_2 in Figure 6 is 90^0. Using Snell's Law, $\sin\theta_c = \frac{n_2}{n_1}$ since $\sin\theta_2 = 1$.

Total internal reflection is the basis of optical light guides, a sample of which should be available for your inspection.

In this experiment you will also use *Pfund's method* to measure the critical angle. Consider a point source of light focused on the painted side of a piece of transparent material of index n_1, which is submersed in a medium of smaller index n_2, as illustrated in **Figure 7**. The focused light acts as a point source.

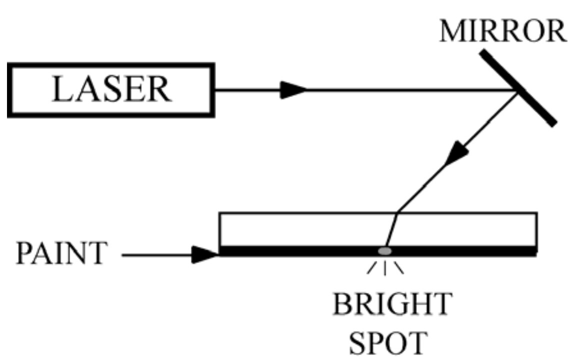

Figure 7: Laser set-up for Pfund's method

If the same material is covered with water as shown in Figure 8, the light from the point source on the bottom of the plate is either partially transmitted and partially reflected at the top surface of the plate or totally internally reflected (if the angle of incidence exceeds the critical angle). The region of the bottom surface illuminated by totally internally reflected rays will be brighter than the region illuminated by partially reflected rays. Accordingly, a circular region surrounding the point source will be a dark shadow of diameter d . The edge of the shadow is the locus of points on the lower surface that are struck by rays incident at the top face at the critical angle for total reflection. The second lighter shadow is formed by total internal reflection from the surface of the water.

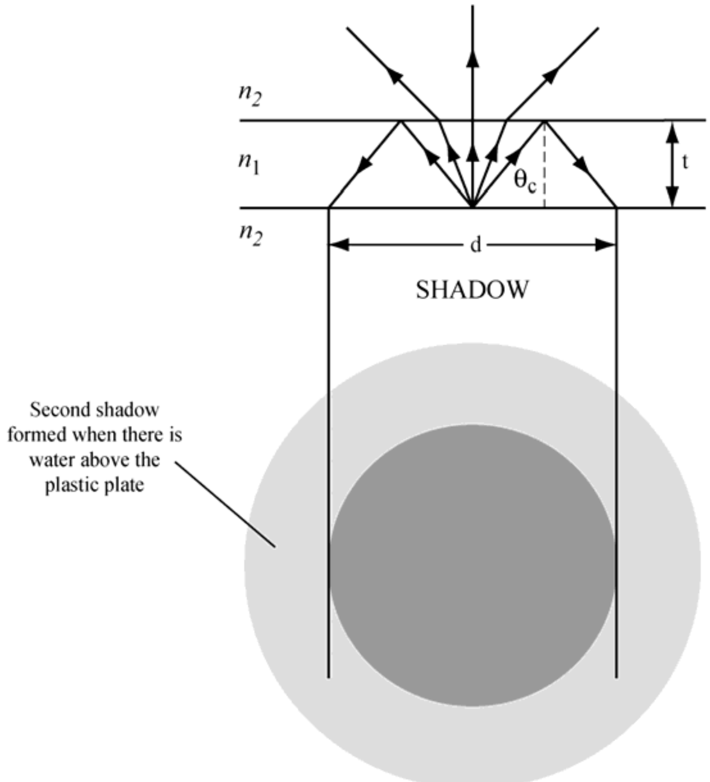

Figure 8: Total internal reflection shadow

Measurement of the shadow diameter provides a way to calculate $\frac{n_2}{n_1}$.

From the figure, $$\sin\theta_c = \frac{n_2}{n_1} = \frac{d/4}{\sqrt{t^2 + (d/4)^2}}$$

Solving for n_1 yields
$$n_1 = n_2\sqrt{16\left(\frac{t}{d}\right)^2 + 1} \qquad (4)$$

Prelab Question 3: Later in the day Mary Kate and Ashley become the heroes of the pool party when they go to the kiddie pool. They notice the light at the bottom of the 1 foot deep pool bounces off the surface from below and produces the expected ring of light on the bottom of the pool. However they are surprised to find the dark circle inside the ring of light has a diameter of 2.7 feet. Based on this fact, what can a well-prepared observer say about the index of refraction of the liquid in this pool?

Procedure III

1) Turn the laser on and place your plate on the lab bench. You should see a bright spot on the bottom of the plate. The circular shadow should be easily visible. (Do not move the laser.)

2) Measure the diameter of the shadow using the scale on the plate.

3) Calculate the index of refraction of the plate using Pfund's method.
4) Compare your values for the critical angle from the refraction method and Pfund's method.

5) Place the plate in the water tray and again measure the shadow diameter. The shadows may be distinguished by touching the surface of the water. Compute the index of refraction of water (n_2) using the known value for the index of the plastic plate (n_1). Compare with the accepted value.

Questions III

- Why do we use a tray with water and a station without water for the Pfund's method?

- How is the shadow formed by light focused on the bottom of the plate related to the critical angle?