LABORATORY 10
GEOMETRICAL OPTICS I: REFLECTION AND REFRACTION

Objectives

- To be able to explain Law of Reflection

- To be able to explain the concept of refraction

- To be able to use Snell's Law

- To be able to determine by measurement or calculation the index of refraction

- To understand the relationship between the index of refraction and speed of light

- To be able to explain the concept of critical angle

- To be able to measure the critical angle

- To be able to calculate the critical angle

- To be able to explain the concept of dispersion

- To be able to explain the concept of a virtual image

Overview: In this lab, we will examine reflected and refracted light, verify Snell's Law, examine the critical angle experimentally and verify it mathematically, explore dispersion, measure the index of refraction and develop a model for understanding rainbows.

Equipment:
        1 Sheet 1 at the end of the lab
        1 mirror
        1 Pasco light source
        1 protractor

Investigation 1: Law of Reflection

Investigation 1.1 Take the pre-test for this lab.

Investigation 1.2 Angles of incidence and reflection

a. Place the mirror on the solid line on Sheet 1 from the last page of the lab. Use the light ray box with a single slit to send a ray of light on to the mirror. Determine the path of the light before it strikes the mirror and after reflection from the mirror.

Measure the angle of incidence, θ_i (the angle the incoming light ray makes with the line perpendicular to the surface of the mirror), and the angle of reflection, θ_r (the angle the reflected light ray makes with the line perpendicular to the surface of the mirror), for the angles in the table below.

Angle of Incidence (θi)	Angle of reflection (θr)
0	
20	
40	
60	
80	

b. How is the angle of incidence related to the angle of reflection for a mirror?

For a mirror, the angle of incidence is equal to the angle of reflection:

$$\theta_i = \theta_r$$

This is called the Law of Reflection.

Equipment:
    1 mirror
    1nail

Exploration 1: Images

When an object is placed in front of a mirror, light from each point on the object is reflected from the mirror and an image of the object is formed.

Exploration 1.1

Set up a mirror and a nail as in the diagram below.

a. Where is the image of the nail? Mark the image of the nail. How can you tell where the image is? Explain.

Discuss with the TA. Ask the TA how to use parallax to determine the location of the image of the nail.

b. Is there light coming from the image of the nail? Explain.

c. Consider a top view of the nail near the mirror, as in the picture below. Use the law of reflection to determine the direction of the reflected rays from the nail for 5 or 6 rays from the nail. Draw the rays in the diagram below.

Top view

When the reflected rays enter your eye, where do they appear to be coming from?

Why do you see an image of the nail at a point behind the mirror?

Is there light at the point of the image? Is there light coming from the image?

When an image can be seen, but no light is emanating from the image, it is called a virtual image.

It is useful to draw dotted lines backwards to the point of emanation of the rays, as in the picture below.
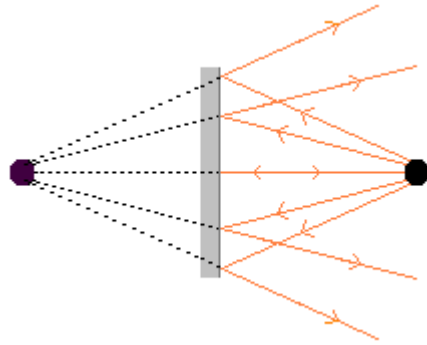
How does the object distance compare to the image distance for the nail in the picture above?

Equipment:
       1 Pasco Light source
       1 rectangular box
       1 solid, rectangular acrylic box
       water
       1 Sheet 2 at the end of the unit
       1 protracter

Investigation 2: Refraction and Snell's Law

Investigation 2.1. Place Sheet 2 from the end of the lab on the table, as in the picture below and place the clear, plastic rectangular box half filled with water on the sheet, as indicated. Place the light box so the light beam is at 35^0 from the line perpendicular to the front of the box.
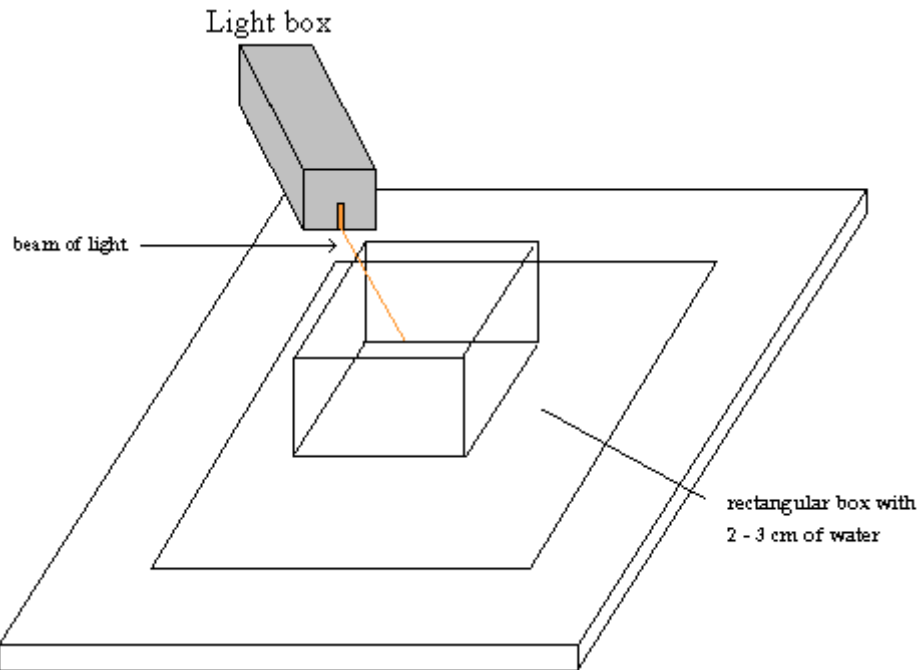
(adapted from *DOING Physics: Image Formation by Lenses*, Dewey I. Dykstra, Jr. and Wm. S. (Willy) Smith, Boise State University, 1995)

a. Trace the path of light entering and exiting the box. Observe the path of light through the water. Then remove the box and draw path of light through the water. Measure the angle that the path light through the water makes with the line perpendicular to the front surface of the box.

b. Replace the rectangular box with a solid, rectangular box made of acrylic and repeat part **a**. What is different between part **a** and part **b**?

c. What happens to the direction of the light when it goes from air to water? What happens to the direction of the light when it goes from water to air? What happens to the direction of the light when it goes from one medium to another?

d. For the rectangular box with water in it, repeat part **a** with the light entering the water at different angles. Use the angles in the table below. The angle the light makes with the line perpendicular with the front surface box before entering the water we will call θi. The angle the light makes with the line perpendicular with the front surface box after entering the water we will call θr. Fill out the table below.

Angle before entering water (θi)	Angle after entering water (θr)	sin θi	sin θr	sin θi/sin θr
0				
10				
30				
50				
70				

e. Repeat part **d** for the acrylic box.

Angle before entering acrylic (θi)	Angle after entering acrylic (θr)	sin θi	sin θr	sin θi/sin θr
0				
10				
30				
50				
70				

When the direction of light changes when the light passes from one medium to another, the "bending" of light is called refraction. If light travels from air into another medium, the ratio of the sin of the angle before entering the medium to the sin of the angle after entering the medium is called the index of refraction of that medium.

More generally, the speed of light is different in different materials. The index of refraction of a material is defined as the ratio of the speed of light in a vacuum to the speed of light in the material:

n = the speed of light in a vacuum / the speed of light in the material

The speed of light in air, is approximately equal to the speed of light in a vacuum, so the index of refraction of air, n_{air}, is approximately equal to one, and we will use $n_{air} = 1$.

When light passes from one material to another, the ratio $\frac{\sin\theta_i}{\sin\theta_r}$, is equal to the inverse ratio of their indices of refraction:

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_r}{n_i}$$

where θ_i is the angle of the incident light measured from a line perpendicular to the boundary and θ_r is the angle of the refracted light measured from a line perpendicular to the boundary, n_i is the index of refraction of the material in which the incident light is traveling and n_r is the index of refraction of the material in which the refracted light is traveling. This is called Snell's Law.

f. Use your experimental data to determine the index of refraction of water. Show your work in the space below.

g. Use your experimental data to determine the index of refraction of acrylic. Show your work in the space below.

Equipment:
      1 light pipe
      1 fiber optics cable
      1 laser

Exploration 2: Critical angle

Exploration 2.1

a. Consider light traveling from a medium of higher index of refraction into a medium of lower index of refraction. Consider, for example, light traveling from glass into air. If the angle of incidence, θ_i, is 53°, what is the angle of refraction, θ_r?

b. What happens to light that is traveling from glass into air at an angle of 53°? What is your idea? Explain.

c. Using a laser, observe how light travels through a light pipe when the light is incident on the side of the pipe at small angles and at large angles. For each case, is almost all of the light that enters the pipe leaving the pipe? Is light refracted at the sides of the pipe?

d. When light travels from a medium of higher index of refraction into a medium of lower index of refraction, there are angles at which all of the light is reflected, no light passes into the other medium. This is called total internal reflection. How could you mathematically determine the minimum angle at which all of the light is reflected? Explain.

When light travels from a medium of higher index of refraction into a medium of lower index of refraction, there is a minimum angle at which all of the light is reflected. This is called the critical angle, θ_c. The critical angle is the incident angle at which the refracted angle is 90°.

$$\sin \theta_c = \frac{n_r}{n_i}$$

e. A fiber optic cable works like a light pipe. Fiber optic cables are used to view objects in inaccessible locations. Physicians use fiber optic cables to examine internal organs of the body, using a device called an endoscope. In an endoscope, one bundle of optical fibers carries light into the body, and another bundle carries the reflected light back to the eye of the observer. It can also be used to perform surgery. Fiber optic cables are also used in telecommunications because they can carry a higher volume of information than copper wires. Observe light traveling through a fiber optics cable.

Equipment:
      1 light box
      1 prism
      1 set of slits covered with red, green and blue film

Exploration 3: Prisms

Exploration 3.1

a. Send a beam of white light from the light box into the prism. Describe what you see. If you have a possible explanation for what you see, write it here.

b. Turn the selector dial on the light source to the slits covered in red, green, and blue films, but **do not turn the light source on**. What do you think will happen if three beams of different colored light strike the prism? Write your answer in the space below and explain your reasoning.

c. Now do the experiment. Explain your observations using Snell's Law.

d. Is the index of refraction the same for different colors of light?

e. Is the speed of the light in the prism the same for different colors of light? Explain. Relate the speed in the prism to the index of refraction of the prism.

Discuss your answers with the TA.

This is called dispersion.

Equipment:
    1 light box
    1 prism

Investigation 3: Index of Refraction of the prism

Investigation 3.1 Measuring index of refraction

a. Take the prism and place it in the center of a clean sheet of paper. Trace the prism, then remove it. On one side of your drawing, use your protractor to draw a line of incident light striking the prism at an angle of 45°.

Put the prism back on the paper. Set the selector knob on your light source to the single slit and align the beam so that it is overlaid on your incident line.

You should see a rainbow on the other side of the prism. Mark the exit point of the red light. Also mark a point along the red refracted light far enough from the prism so that you can trace the path of the red light after it has left the prism. Since the light will tend to spread as it gets farther from the prism, put your mark in the middle of the red light. Do the same thing for the violet light.

b. What does the fact that the red and violet light entered the prism at the same point but exited at different points tell you about the speed of the red light in the prism compared to the speed of the violet light? What does this tell you about the indices of refraction for the red and violet lights? Discuss your answers to these questions with your TA and write them in the space below.

c. Now turn off your light source and remove your prism. Carefully draw lines from where the light entered the prism to the points where the red and violet light exited the prism. Use these lines and Snell's Law to determine the index of refraction. You have two incident and two refracted angles for both the red and violet lights, when the light enters the prism and when it leaves. Use both of these to calculate an average index of refraction for both red and violet light. Record your average values in the space below.

Equipment:
      1 Sheet 3 at the end of the lab
      1 Plexiglass cylinder

Application 1: Rainbows

By now you may have concluded that what we've been discussing has something to do with a rainbow. For this part of the lab, we will combine reflection, refraction, and dispersion to simulate what happens in droplets of water to cause a rainbow.

Application 1.1 Use Sheet 3 at the end of this lab for this part of the experiment. Sheet 3 has a line running along the left hand side of the page, a circle near the middle, and a line coming off the bottom right hand side of the circle. You will also need a Plexiglas cylinder to simulate a spherical raindrop.

a. Place the Plexiglas cylinder on the circle, and set the light source so that light from the single slit will follow the line touching the circle. You should see a rainbow pattern leaving the cylinder on the lower right. If you have trouble seeing it, bend your paper up along the line on the left side. This will cause the paper to form a screen, making the rainbow easier to see.

    Discuss in the space below what is happening to create the rainbow. What happens to the light when it enters the "raindrop"? Why does the light change direction?

b. Starting from the side of the rainbow closest to the incident ray, what is the order of the colors? Why do they have this order? Explain.

c. Mark the points on the "raindrop" where the red and violet light leave. Also mark the points on the line (or screen) where the red and violet light cross it. Remove the Plexiglas cylinder. Connect the exit points of the red and violet light with the points where they touch the "screen". Extend the line representing the incident light past the rain drop. Also extend the lines for the red and violet light past the raindrop so that they cross the incident line. Use your protractor to measure the angle between the incident line and the red and violet lines. Record these measurements in the space below.

In a rainbow, the red light has an angle of 42° with the incident ray, while the violet light has an angle of 40°. Do your measurements match these values? Why or why not?
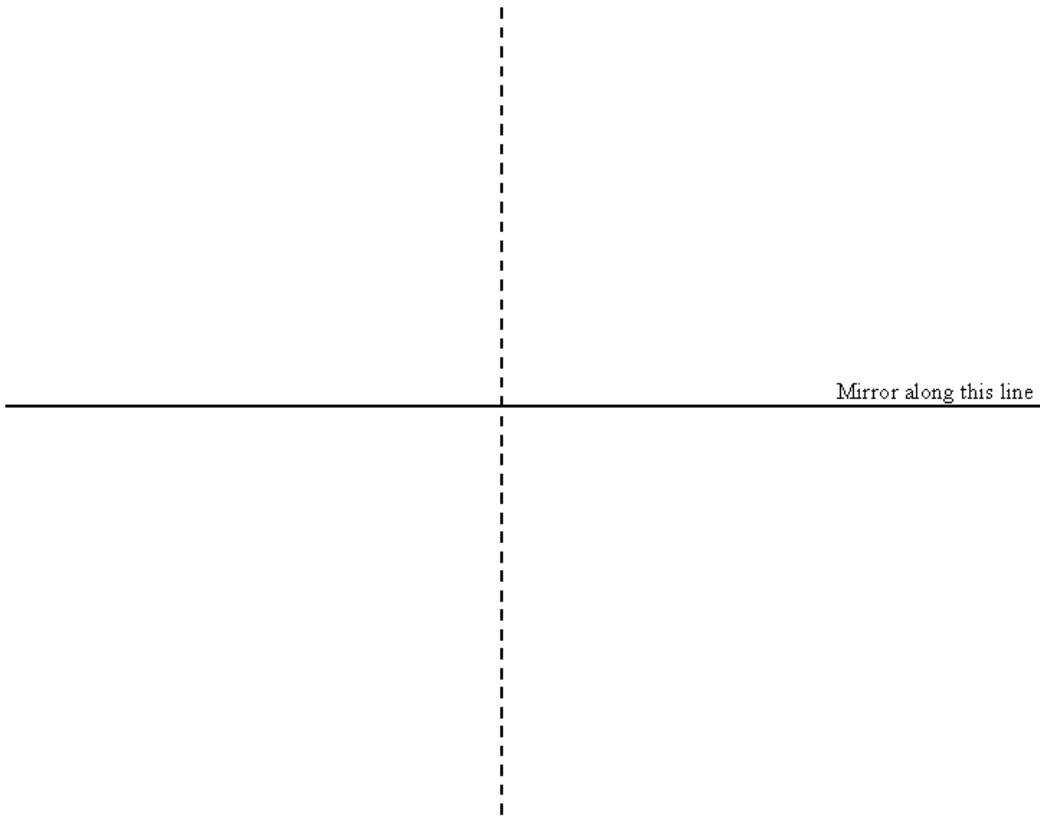
d. What do the different angles for the red and violet light tell you about where the light is coming from when you see a rainbow?
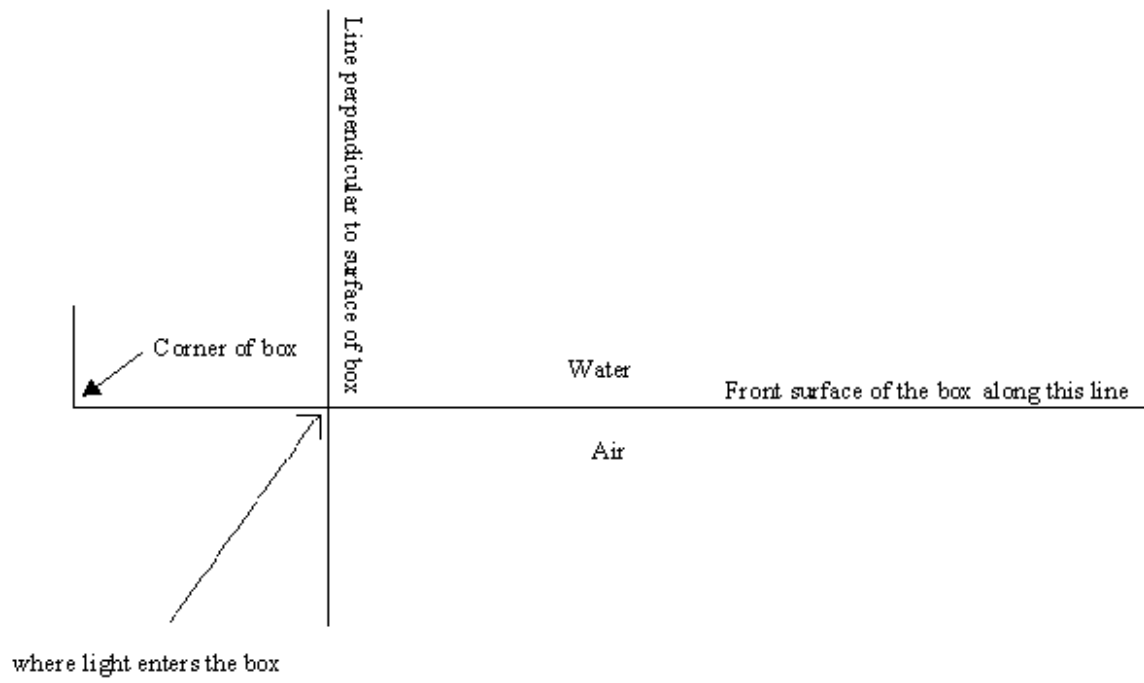
Discuss your answer with your TA.

e. What we have modeled here is called a primary rainbow, and is produced by one internal reflection. A secondary can sometimes be seen, in which the light undergoes two internal reflections. Based on what you've learned in this lab, what order should the colors have in a secondary rainbow compared to the colors in a primary rainbow?

Summary. Summarize what you have learned about refraction in this lab.

Sheet 1

Mirror along this line

Sheet 2

Line perpendicular to surface of box

Corner of box

Water

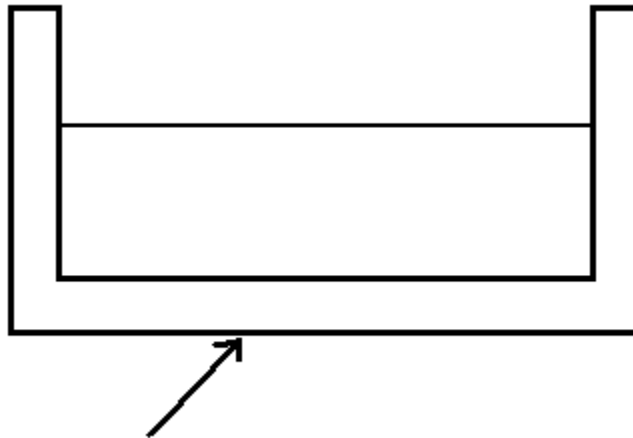Front surface of the box along this line

Air

where light enters the box

Sheet 3

Laboratory Homework 10
Geometrical Optics I

A layer of water is contained in a glass tank as shown. (The index of refraction of glass is greater than that of water.) A ray of light is incident at the bottom of the tank as shown.

a) Sketch the ray transmitted into the glass and then into the water and out of the water into the air.
b) Now assume that the water is removed from the tank. Sketch a ray incident, on the bottom of the tank as before, transmitted into the glass, and then into air instead of water. What differences are there between rays in parts (a) and (b)? Explain.