

Name \_\_\_\_\_  
St.No. \_\_\_\_\_

Date(YY/MM/DD) \_\_\_\_/\_\_\_\_/\_\_\_\_  
Section \_\_\_\_\_ Group # \_\_\_\_\_

## UNIT 102-7: REFLECTION AND REFRACTION



“By three methods we may learn wisdom: First, by reflection, which is noblest; Second, by imitation, which is easiest; and third by experience, which is the bitterest.”

- Confucius

### OBJECTIVES

1. To study the law of reflection.
2. Use ray tracing to locate virtual images formed by mirrors.
3. Measure magnification and focal length of a cylindrical mirror.
4. Form an image using a concave mirror and measure its magnification.
5. Study Snell's Law.
6. Observe total internal reflection.

**OVERVIEW**

Many useful properties of light can be understood with a simple ray theory. In these experiments you will be observing light as it travels through air of uniform density. In this case light propagates in a straight line from its source. One can use a slit plate to select “rays” of light coming from a point source. These rays can be traced back to their origin where they cross at their source.

If light encounters a shiny surface it undergoes specular reflection. Rays reflect from mirrors according to the law of reflection: the angle of incidence equals the angle of reflection where the angle is measured from the normal to the reflecting surface. The rays reflected from a plane or convex mirror will not cross, but if one extends them back in a straight line to the other side of the mirror, these extensions will cross at a point called the virtual image of the source. The virtual image is at the position from where the light appears to come. In these experiments we emphasize point sources because any object can be considered as a collection of point sources. Therefore, the virtual image of any object can be understood as a collection of virtual images of point light sources.

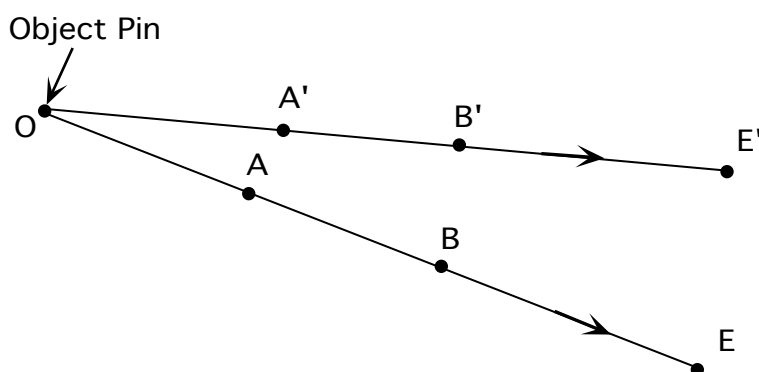
In this unit we will also be investigating how light behaves when it travels from one transparent medium into another. There are many examples of this phenomenon in real life such as light rays travelling from water to air when we see an object underwater from above. As you probably know, objects underwater appear to be at a depth that is different from their true depth. This occurs because the light rays from the object bend at the interface between the water and the air before they reach our eyes. This “bending” of light rays is known as refraction.

**SESSION ONE: RAY TRACING, REFLECTION AND CONCAVE MIRRORS**

This section allows you to investigate the properties of light by observation. The exercises below require you to stick pins in a board. The pins should always be carefully placed so that they are vertical.

For this activity you will need:

- push pins
- a piece of 8.5" x 11" foamboard
- a small plane mirror with magnet strip on back
- an Optics kit stand
- 2 sheets of plain 8.5" x 11" paper



**Figure 7.1:** Tracing rays.

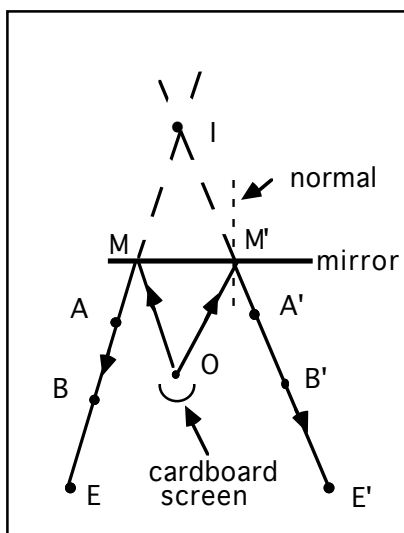
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**Activity 7-1: Tracing Light Rays on Paper**

(a) Lets first do some ray tracing. Tack a piece of paper on your board and place a pin on the paper. As you look at the pin, light rays are coming from the pin to your eye. If you place something between the pin and your eye, you will block the light from the first pin. You can trace a ray of light by putting pins along its path as shown in Figure 7.1. Call the pin that is the source of the ray the object pin O. If you look at the object pin with your eye at point E (on the surface of the board), then a pin placed at point A will block you view of the object pin. Likewise, a pin placed at point B will block your view of pin A. If you now draw a line through points A and B, you will have the path of the ray from the object pin and your eye. Now move your eye to point E', then locate points A' and B' that define the ray in that direction. By moving your eye all the way around the pin, you could trace a series of rays that come from the object pin. Because you can see the pin from all directions, that is evidence that rays are coming from the pin in all directions.

(b) *Sketch* below the pattern of rays you would get if you moved your eye 360° around the pin in steps of 30°. Put arrows on the rays for the direction of the rays (from the object pin to your eye). This pattern is very important to understand: an object sends rays out radially.

(b) Now tack a new piece of paper on your board and place a mirror and an object pin O on the paper as shown in Figure 7.2 below. Draw a line on the paper along the front of the mirror. Be sure to keep the mirror located on that line; if it moves during the time you are tracing rays, put it back and check your previous rays.



**Figure 7.2:** Tracing a reflection.

(c) Look at the reflection of the pin in the mirror from point E (E for eye!). Trace the rays that come to your eye by placing pins along the ray as follows: Place one pin (A) near the mirror so that it blocks the *image* of the pin (in the mirror). Then, without moving your eye, place the other pin (B) in front of pin A so that it blocks pin A (and the *image* of pin O). Pin B should be placed some distance from pin A so that you can draw an accurate line.

(d) Repeat for another observation point E'. Be sure to label the rays so you know from which pin they come.

(e) Remove the mirror and the pins and trace the rays to the mirror location and then extend the line behind the mirror location until the extrapolated rays meet. The point behind the mirror where the extrapolated rays meet is called the image point I. If you traced rays from the pin to your eye at many different positions, they would all appear to come from the image point I. Note that the rays that you see do not actually come from this image point, they only appear to come from the image point. Therefore, this is called a **virtual image**.

(f) Draw lines from the object pin (O) to M and M' (labelled in Figure 7.2). These lines represent the rays that actually go from O to M and M', the points where the rays you traced in (e) pass through the mirror line. Draw a line perpendicular to the mirror line at these two points. This line is called a normal line (meaning perpendicular; not that it is not abnormal!).

(g) Measure the angles the incoming rays along OM and OM' make with the normal lines using a protractor. Now measure the angles the outgoing rays along ME and M'E' make. Record the values below. Do you see any relationship between incoming angle and outgoing angle of reflection? If so, explain what it is.

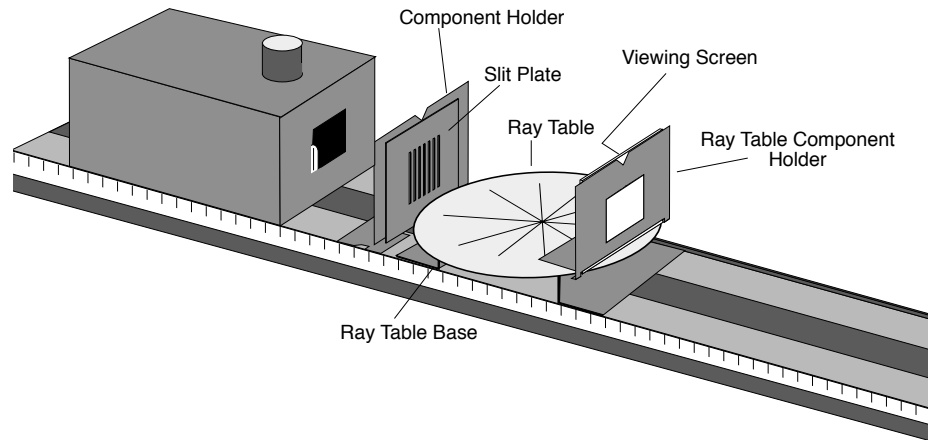
**(Note:** One lab partner should attach both sheets of paper from this activity to their Activity Guide when it is handed in.)

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For the following activities you will need:

- Optics Kit
- 11" x 17" piece of plain paper

The equipment we'll be using for the next few activities is shown in Figure 7.3. You may leave off the viewing screen at first. Plug in the light source and turn it on. The bulb has a linear filament running vertically.



**Figure 7.3:** Basic Ray Optics Set-up.

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**Activity 7-2: Preliminary Observations on Straight-Line Propagation**

(a) Observe the rays that emerge from the slit plate. Look at the rays on the ray table then lower your head and peer along a ray. Are you sure that the rays do not bend as they pass through the slits? Sketch the rays you see below.

(b) Vary the distance between the slit plate and the light source and note how the width, brightness and sharpness of the rays change. Observe how the distinctness and the direction of the rays change as you rotate the slit plate so that the slits are not parallel with the light bulb's filament. Summarize your findings below.

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**Activity 7-3: Locating the Filament**

(a) Fold a piece of 11x17 inch paper in half to make an 8.5x11 inch sheet. Tape the paper on the ray table with the fold facing the filament and directly above the ray table base. Turn on the light and trace four rays that cross the paper.

**Hint:** If the rays are wide, it may be better to trace the edge of the rays. You may mark two points of each ray before removing the paper. Choose points which are widely separated for greater accuracy.

(b) Remove the paper and unfold it. Use a clear plastic ruler to trace the rays back to the source. Mark every point where two rays cross. Find the average distance between the ray table edge to the filament by means of the ray-crossing points you located.

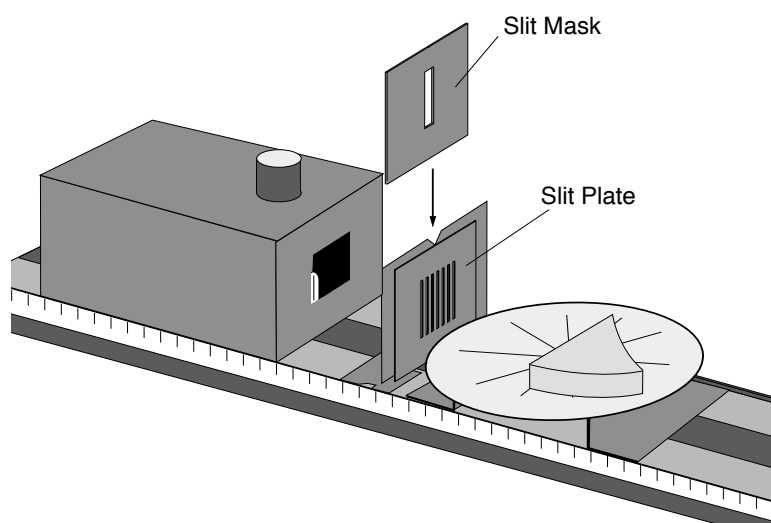
**Hint:** How many crossing points should there be? If two points coincide, include that distance twice in the average. As you measure more and more points, your accuracy increases even though the points may get more scattered.

(c) Measure the distance between the light filament and ray table edge using the optics bench scale. Compare this distance with your ray tracing result. (**Note:** One lab partner should attach the sheet of paper to their Activity Guide when it is handed in.)

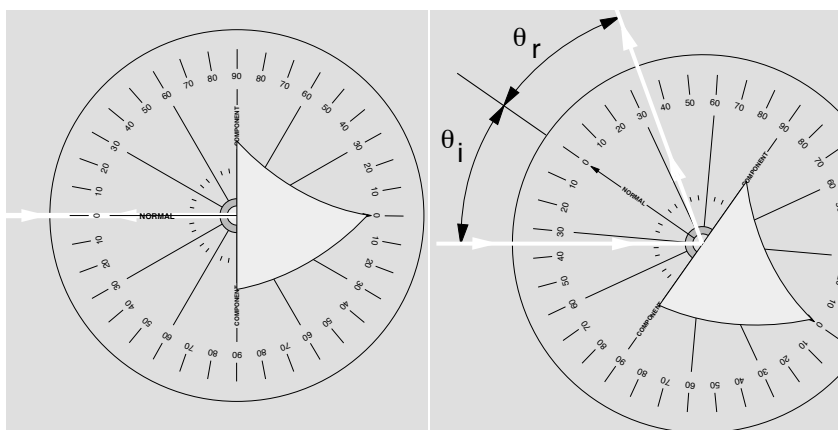
### The Law of Reflection

The Law of Reflection says that the angle of incidence of a light ray equals the angle of reflection where the angle is measured from the normal to the reflecting surface.

To study this law we will set up the equipment as shown in Figures 7.4 and 7.5 below. Adjust the components so that a single ray of light is aligned with the bold arrow labelled “Normal” on the ray table degree scale. Carefully align the flat reflecting surface of the ray optics mirror with the bold line labelled “Component”. With the mirror properly aligned the bold arrow on the ray table is normal (at right angles) to the plane of the reflecting surface. Turn on the light and make sure that you can see the incident ray and reflected ray on the ray table as you rotate it.



**Figure 7.4:** Set-up for measuring the law of reflection.



**Figure 7.5:** Alignment of the Ray Mirror for normal incidence and for incidence at an arbitrary angle.



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**Activity 7-4: Measuring the Law of Reflection**

(a) Choose five different angles ranging from  $0^\circ$  through  $90^\circ$ . Rotate the ray table to each of these incidence angles ( $\theta_i$ ) and measure the corresponding angle of reflection ( $\theta_r$ ). Record your results in the table below.

$\theta_i$	$\theta_r$

(b) Are your results consistent with the law of reflection?

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**The Focal Length of a Concave Mirror**

The image formed by a plane mirror is always virtual. A concave mirror can form either a real image or a virtual image. A real image occurs if the rays come from a distant source. If the source is closer than one focal length from the mirror, then a virtual image is formed. If the source is exactly at the mirror's focal point, the rays emerge parallel from the mirror. This is the principle used in flashlights, headlights and spotlights to produce a parallel beam of light.

Ideally, concave mirrors have a paraboloidal shape. Spherical shapes are cheaper to manufacture than paraboloids and most inexpensive concave mirrors are spherical. For most applications the loss in quality is insignificant, particularly where the mirror's f-number (focal length/diameter) is large. In the following exercise you will use the cylindrical ray optics mirror to visualize its image-forming properties and find the mirror's focal length by producing a parallel beam of rays.

For the following activities you will need:

- Optics Kit

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**Activity 7-5: Introduction to Concave Mirrors**

(a) Place the slit plate about 7 cm from the light source and place the parallel ray lens on the other side of the same stand. Use the ray table surface with a centimetre grid and turn it so that the grid is aligned with the optical bench axis. Place the ray optics mirror on the ray table, turn on the light and observe the rays reflected from the concave surface. When the mirror is at the far end of the table you should see the reflected rays converging at the position of the real image. Sketch what you see in the space below.

(b) Turn the mirror so that the image position is off the optical axis of the bench. What happens to the convergence of the rays? Draw a quick sketch below. This effect is known as spherical aberration when it occurs in spherical mirrors.

(c) Now remove the parallel wave lens and put the slit plate on the front of the light source. Also slide up the ray table so its edge touches the source. Slide the mirror closer to the light source until the reflected rays diverge. The rays don't actually cross now, but their projections on the dark side of the mirror will cross at the position of the virtual image. Move the mirror back until the emerging rays are parallel. Measure the distance between the light source and the mirror. Record this value. This distance is known as the focal length ( $f$ ).

**SESSION TWO: MORE CONCAVE MIRRORS AND REFRACTION****Forming an Image with a Concave Mirror**

The law of reflection implies that the virtual image formed by a plane mirror will be at the same distance from the mirror as the object, but on the other side. If we form a virtual image using a concave mirror, then the law of reflection tells us that the object-image distance is given by the following formula:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} = \frac{2}{r}$$

where  $d_o$  is the object-mirror distance,  $d_i$  is the image-mirror distance,  $r$  is the mirror's radius of curvature and  $f$  is its focal length. The magnification of the mirror is given by

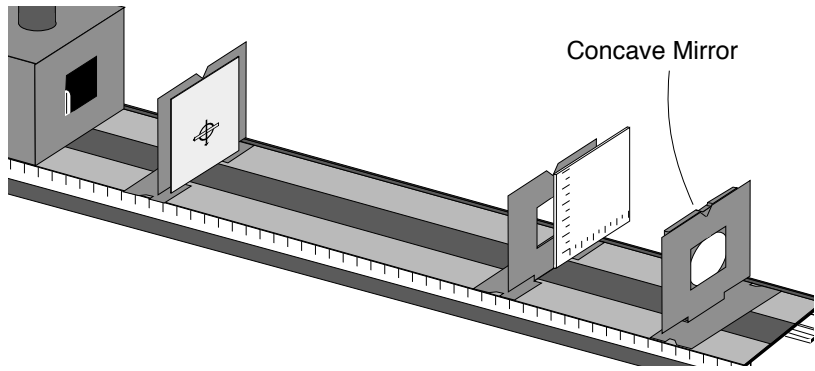
$$m = \frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

where  $h_i$  and  $h_o$  are the image and object heights respectively.

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** Activity 7-6: Forming an Image with a Concave Mirror**

(a) Set up the equipment as shown in Figure 7.6 with the concave side of the mirror facing the light source. The viewing screen should cover only half of the hole in the component holder so that light from the filament reaches the mirror. Estimate the focal length of the mirror by positioning the mirror on the optical bench as far from the crossed arrow target as possible. Vary the position of the viewing screen to find where the image of the target is focussed. Record this approximate value of the focal length and have another group member repeat the measurement independently. How do your two values compare?



**Figure 7.6:** Set-up to observe the image from a concave mirror

(b) Choose five distances between 50.0 cm and 5.0 cm. These are object-mirror distances  $d_o$  for which you will measure the image-mirror distances  $d_i$  and the image heights  $h_i$ . Record  $d_o$ ,  $d_i$ ,  $h_o$  and  $h_i$  with units in the table below. **Note:**  $h_o$  will be the same for all of your trials.

$d_o$	$d_i$	$h_o$	$h_i$	f(calc)

(c) Calculate  $f$  from  $d_o$  and  $d_i$  in each instance and record these values with units! in the table. Show at least one calculation of  $f$  in the space below.

(d) How do your five values of  $f$  agree with each other?

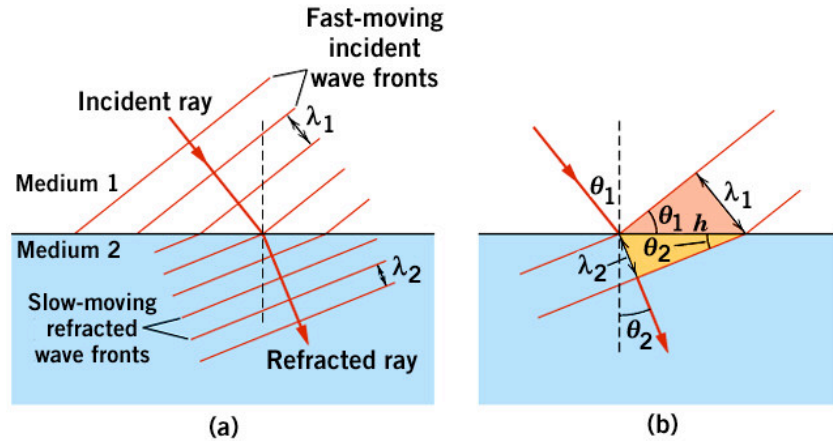
(e) For each of the five distances measured above, find the magnification derived from  $h_i/h_o$  and that calculated from  $-d_i/d_o$ . Show at least one sample calculation of each in the space below.

$m1 = h_i/h_o$	$m2 = -d_i/d_o$

(f) How do your two magnifications agree in each trial?

### Refraction

Refraction is the bending of light when it travels from one transparent medium into another. It only occurs when the speed of light in the two media is different. Because different portions of the wave front of a light ray reach the boundary between the two media at different times a change in direction of the light ray results as shown in Figure 7.7 below.



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**Figure 7.7:** Refraction of a light ray.

The amount of bending that occurs is dependent upon the speed of light in the two media. One can define a quantity called the index of refraction  $n$  as the ratio between the speed of light in a vacuum  $c$  and the speed of light in the medium  $v$  :

$$n = \frac{c}{v}$$

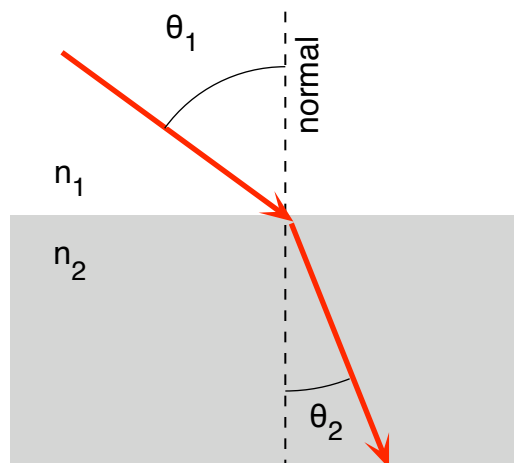
This yields a unit-less constant that is greater than 1. For example the index of refraction for water is equal to 1.333.

### Snell's Law

We call the angle an incoming light ray makes with the normal to the boundary between two media the angle of incidence. If the angle of incidence is not at right angles to the boundary (i.e. equal to zero) then the direction changes according to Snell's law:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

the constants  $n_1$  and  $n_2$  are the indices of refraction of the two media. The angles  $\theta_1$  and  $\theta_2$  are the angles the light ray makes with the normal to the boundary between the two media as shown in Figure 7.8 below. In this case  $\theta_1$  is the angle of incidence and  $\theta_2$  is the angle of refraction.

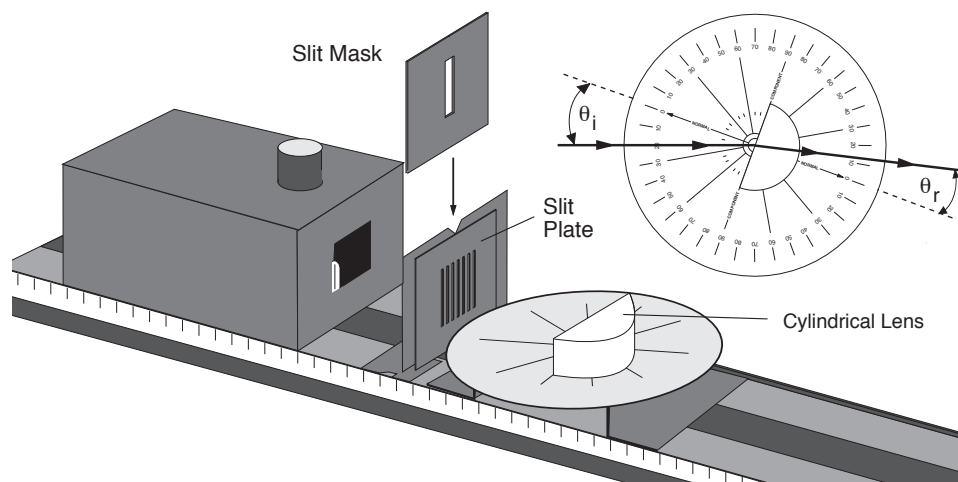


**Figure 7.8:** Angles and indices of refraction.

We are going to begin looking at refraction by studying Snell's Law.

For the following activities you will need:

- Optics Kit



**Figure 7.9:** Set up for measuring Snell's Law.

#### Activity 7-7: Snell's Law

(a) Mount the light source on the optical bench. Place the slit plate and slit mask on opposite sides of a component holder so that the centring notch points to the slit that is not covered by the slit mask. Put the ray table on its base, degree side up, and align all the components against the alignment rail as in Fig. 7.9. Turn on the light source and turn the filament knob and adjust the slit plate until one single ray coincides with the NORMAL line on the ray table. Place the cylindrical lens on the COMPONENT line of the ray table so that the ray hits the flat side of the lens. Choose five angles ranging from  $0^\circ$  to  $90^\circ$  and measure the angle of refraction for each angle of incidence chosen. In this case refraction occurs when the



rays travel from air into the plastic of the lens. You should make two measurements for each angle: one clockwise from the normal  $\theta_{rc}$ , the other counter-clockwise  $\theta_{rcc}$ . Using an average of these two values will compensate for slight misalignment of the lens on the table. Record your values in the table below.

$\theta_i$	$\theta_{rc}$	$\theta_{rcc}$	$\theta_r(\text{avg})$

(b) Create a graph in Excel of  $\sin \theta_r$  vs  $\sin \theta_i$ . Submit your graph to WebCT. Is your curve linear? (It should be.) Record the slope of the line in the space below. What does the slope of this graph mean? What does the intercept mean?

(c) Put the cylindrical lens on the other side of the COMPONENT line so that the ray hits the curved side. Measure the *same angles* you used in (a) to check the reversibility of Snell's Law. (You will need to think about what your incident angles should be in this case.) Record your results and conclusions below. In this set-up, the rays only undergo refraction when they travel from the plastic of the lens to the air at the flat side. Why is that?

### Total Internal Reflection

When light rays hit the surface between media of different refractive indices, there is always a reflected ray. There may or may not be a refracted ray going into the other medium. When the index of refraction of the medium from whence the light ray comes is larger than the index on the other side then there is an angle of incidence above which no ray is transmitted through the surface. The critical angle is the angle of incidence for which the refracted ray's angle is exactly  $90^\circ$ . Light incident above the critical angle is totally reflected. This is called total internal reflection. This is illustrated in Figure 7.10 below.

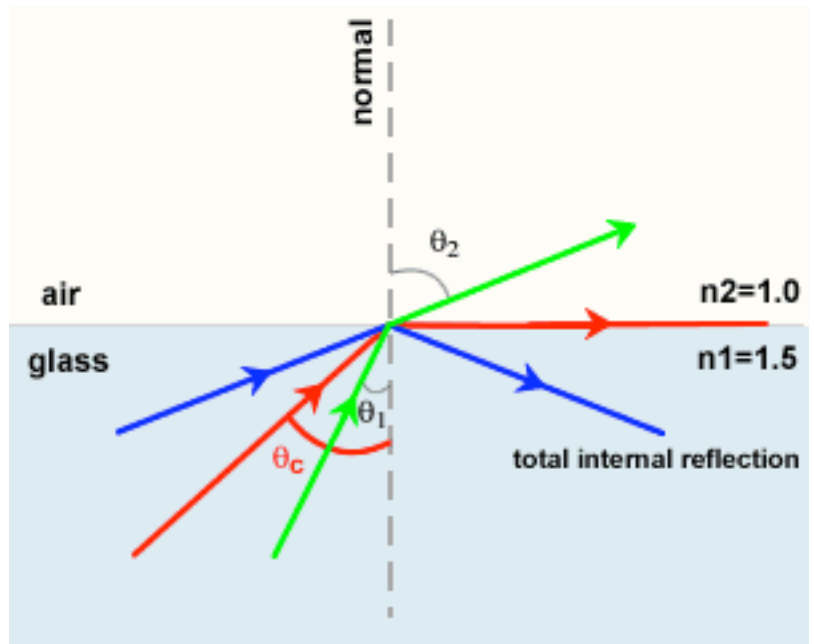


Figure 7.10: Total internal reflection.

### Activity 7-8: Measuring the Critical Angle

(a) Put the Parallel Ray Lens in place and insert the Slit Mask over the Slit Plate so that only one central ray is transmitted. With the Cylindrical Lens on the Ray Table, rotate the table until the critical angle is reached. Measure and record this angle below. You may wish to use one of the coloured filters because the critical angle will depend on which colour you look at. Record which filter you use.

(b) The critical angle occurs when  $\theta_2 = 90^\circ$ . Using Snell's Law show below that:

$$\sin \theta_c = \frac{n_2}{n_1}$$

(c) Use your measured value for the critical angle to determine the index of refraction of the plastic the lens is made from. Show this calculation below. Assume  $n = 1.000$  for air.