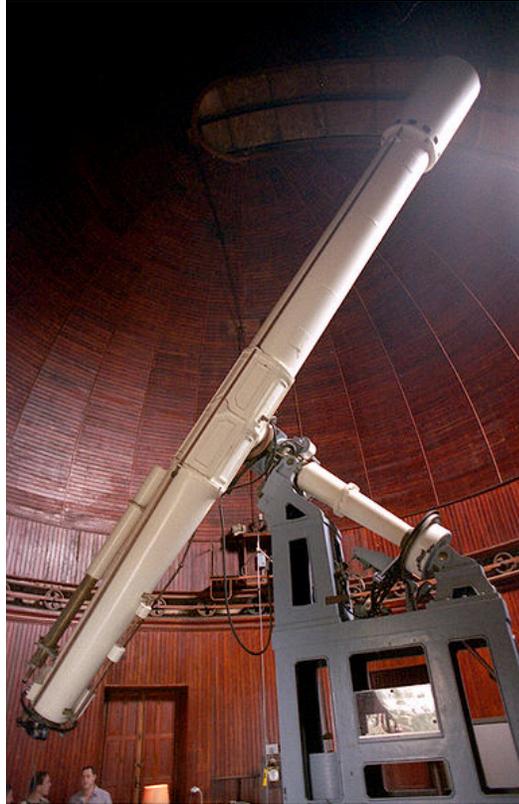


Name \_\_\_\_\_  
St.No. \_\_\_\_\_

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

## UNIT 30: REFRACTION AND LENSES



*Refracting telescope at Nice Observatory.  
(Wikimedia commons)*

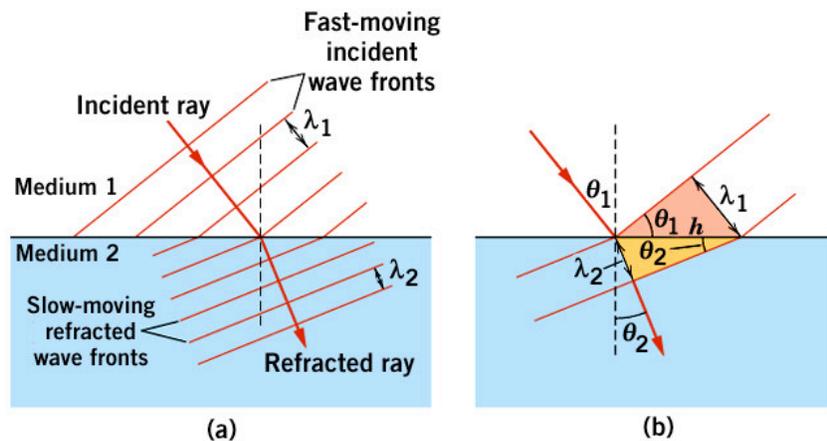
### OBJECTIVES

1. Study Snell's Law.
2. Observe total internal reflection.
3. Locate images formed by lenses.
4. Build a simple magnifier and measure its magnification.
5. Build a compound microscope and a telescope

## OVERVIEW

In this unit we will 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.

Refraction occurs because 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 30.1 below.



Copyright John Wiley & Sons

**Figure 30.1:** 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  $v$  :

$$n = \frac{c}{v} \quad (30.1)$$

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

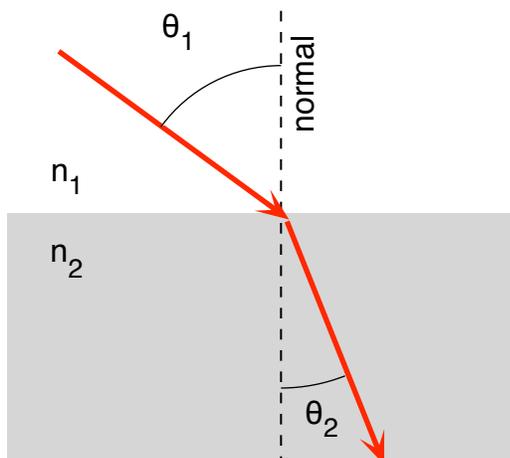
**SESSION ONE: REFRACTION AND IMAGE FORMATION WITH LENSES**

**Refraction and 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:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (30.2)$$

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 30.2 below. In this case  $\theta_1$  is the angle of incidence and  $\theta_2$  is the angle of refraction.



**Figure 30.2:** Angles and indices of refraction.

You are going to study Snell's Law using the basic ray optics kit you used in Unit 29. We will be keeping a logbook for some these experiments.

For the following activities you will need:

- Optics Kit

---

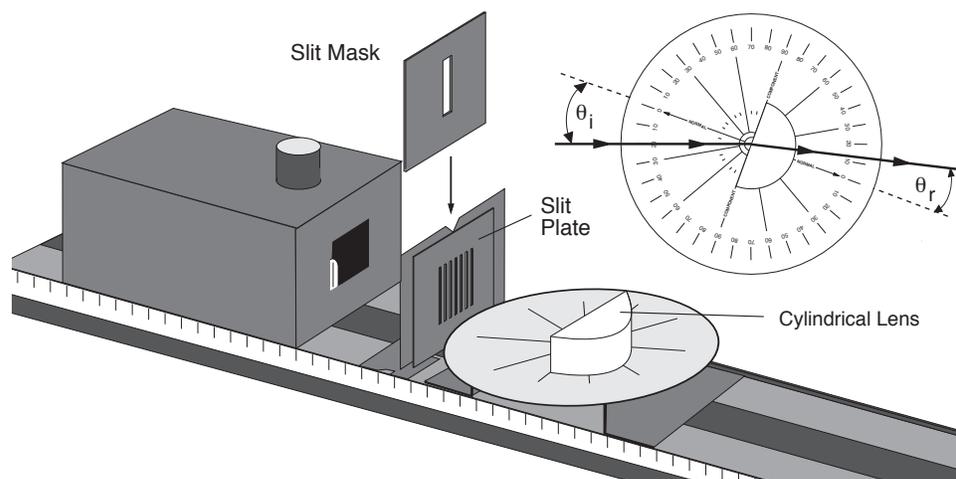
**Activity 30-1: Snell's Law**



**(Record answers to questions and results in logbook)**

- (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. 30.3. 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, the other counter-clockwise. This will compensate for slight misalignment of the lens on the table. Record your values with errors in tabular form in your logbook. Your error estimate should take into account both any differences you see from your two measurements (clockwise and counter-clockwise) and the uncertainty inherent in your measuring device.



**Figure 30.3:** Set up for measuring Snell's Law.

(b) Draw one graph with error bars of  $\sin \theta_r$  vs  $\sin \theta_i$  in your logbook using both the clockwise and counter-clockwise data. Is your curve linear? (It should be.) Record the slope of the line with error in your logbook. (Show your calculation of the slope.) What does the slope of this graph mean? What does the intercept mean? Answer these questions in your logbook.

(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 30.4 below.

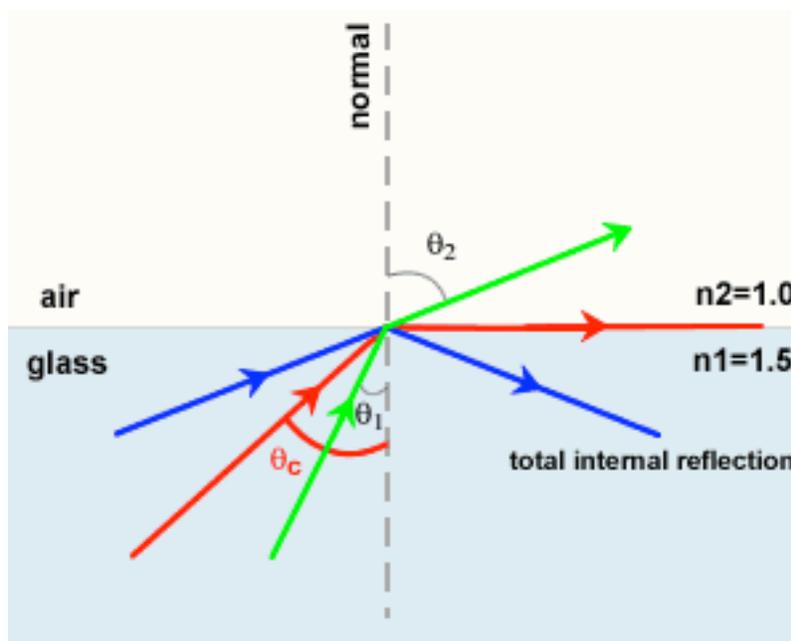


Figure 30.4: Total internal reflection.

---

#### Activity 30-2: Measuring the Critical Angle



**(Record answers to questions and results in your logbook)**

(a) Leave 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 with error in your logbook. 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:

$$\sin \theta_c = \frac{n_2}{n_1} \quad (30.3)$$

(c) Use your measured value for the critical angle to determine the index of refraction (with error) of the plastic the lens is made from. Show these calculations in your logbook. Assume  $n = 1.000$  for air.

---

### Image Formation with a Cylindrical Lens

When light is emitted or reflected by an object, each point on the object serves as a source of light. The light from each of these points spreads out in all directions in space. To understand what we see or how an image is formed by a lens, we must first see what happens to the light from each of these point sources. We will use small light bulbs as our point sources in the following activity.

For this activity you will need:

- light bulb board with 4 bulbs
- 3 D-cell batteries with holder
- alligator clip wires
- cylindrical lens from Optics Kit
- small plastic comb
- an index card
- paper sheet with lens outline

---

### Activity 30-3: Creating a Simple Real Image

(a) Draw an arrow on the sheet provided such that its head is aligned with one bulb and its tail is at an adjacent bulb of the bulb board. Now imagine that the arrow on the sheet is lighted. Every point on the arrow sends out rays in all directions. To simulate this we will place two light bulbs at the head and the tail of the arrow by laying our light bulb board over the arrow with two of the bulbs aligned with the head and the tail. Now connect each of the two bulbs one at a time to one or two D-cell batteries (so the bulb is reasonably bright) and briefly describe what the light from each bulb does.

(b) Place the cylindrical lens from the optics kit in the semicircular outline on the sheet provided. Sketch on the paper sheet the beam of light that comes out of the lens with only the bulb at the tail of the arrow turned on.

(c) Place the comb midway between the bulb and the lens, parallel to the flat face of the lens, so that the light is divided up into rays. Describe what the lens does to the rays. Are the rays leaving the bulb diverging, converging or parallel? What about when they leave the lens?

(d) Remove the comb and place an X at the point where the image of the bulb is formed. Label this point with the letter T for tail.

(e) Now repeat steps (b) and (c) for the bulb at the head of the arrow and label the image point H for head.

(f) Now turn both bulbs on at the same time. (You may need 3 batteries to get enough light.) Draw an arrow on your sheet showing the image of the object arrow that would be formed by the lens. Is the image upright or inverted? Is the image enlarged or reduced in size compared to the object?

(g) How do you think the image will change if you move the lens further away from the object? Try it and see.

(h) How do you think the image will change if you move the lens closer to the object? Try it and see.

(i) Put the lens back on the semicircular outline. Now predict what you think will happen when you cover half of the side of the lens facing the object with a card. How would the image be changed? Would the whole image of the arrow still be formed?

(j) Now block half of the lens with a card and carefully describe what happens. Explain your observations based on what happens to rays from each of the bulbs that hit the unblocked half of the lens.

(k) Suppose that you covered the centre of the lens? How would the image be changed now? Try this and carefully describe what you see.

(l) Suppose that you covered the top half of the object with a card. How would the image be changed? Try this and carefully describe what you see.

(m) Suppose you removed the lens. How would the image be changed? Try this and carefully describe what you see.

---

### Thin Lenses

An important application of refraction is thin lenses. One usually starts studying lenses by assuming that they are thin and spherical. The focal length of a thin spherical lens is determined by the radii of curvature of its two surfaces according to the lens-maker's formula. Let  $r_1$  and  $r_2$  be the radii of the spheres defining the two surfaces of the lens. The focal length  $f$  of the lens is

$$\frac{1}{f} = (n - 1) \left( \frac{1}{r_1} - \frac{1}{r_2} \right) \quad (30.4)$$

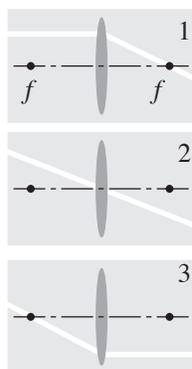
The sign convention follows our textbook where  $r$  is positive if the incident ray hits the convex side, negative if it hits the concave side. (This sign convention may be different in other books.) The lens-maker's formula follows directly from Snell's law where the angles of incidence on the spherical surfaces are small so that  $\sin \theta \approx \theta$ .

Illuminated objects can be thought of as a collection of point light sources. Therefore when we study how lenses make images, we usually consider only a point source and assume that images of many point sources can be superimposed to get the image of a complex object. Light rays fan out in all directions from a point source and some of them hit the lens. If the source is very far from the lens, the rays hitting the lens are almost parallel with each other and are bent by the lens so that they all converge at the focal point a distance  $f$  from the lens. If the source is not at infinity the image position is given by:

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f} \quad (30.5)$$

where  $o$  is the object-lens distance and  $i$  is the lens-image distance. (This equation is the same as for mirrors.)

The optical axis of the lens is the line joining the centres of the two spheres forming the surfaces of the lens. If a point source is on a lens' optical axis, its image is also on the optical axis. If the source is not on the optical axis, its image will also be off the optical axis. The position of the image can be found by tracing two of the rays coming from the source. Some rays, called the principal rays, are easy to trace if we follow some simple rules:



1. Rays hitting the lens parallel to its optical axis are bent to cross the axis at the focal point.

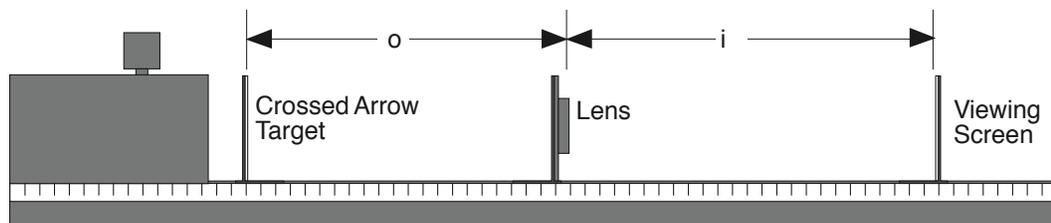
2. Rays going through the centre of the lens are not deflected.

3. Rays from the source passing through the focal point before hitting the lens, emerge parallel to the optical axis after having passed through the lens.

One can use these rules repeatedly together with a little geometry and trigonometry to find the positions of images and the magnification of thin lens systems.

For the following activity you will need:

- Optics Kit



**Figure 30.5:** Setup for measuring object-image relationships.



**Activity 30-4: Object-Image Relationships of a Convex Lens**

**(Record answers to questions and results in your logbook)**

(a) Set up the Crossed Arrow Target, the 75 mm lens and the Viewing Screen as shown in Figure 30.5. With the light on, move the lens until a sharp image of the target appears on the Viewing Screen. Observe the characteristics of the image: Is it magnified or reduced? Inverted or upright? About how far can you move the screen back and forth with the image still appearing sharp? Record this value. This range is called Depth-of-Field which contributes to measurement uncertainty. You should include a contribution from this uncertainty in your errors on the image distances in (b).

(b) Choose five distances between 50.0 cm and 10.0 cm. These are object distances  $o$  for which you should measure the image distances  $i$  and the image heights  $h'$ . Record these values with errors in a table **in your logbook**. Make your table look like the one below. Calculate  $f$  with an error from your  $o$  and  $i$  values using Eq. 30.5 in each instance. Show one of your calculations in your logbook. How do your  $f$  values compare to each other and to the value on the lens' label?

(Sample table for results in logbook - add columns for errors)

$o$	$i$	$h$	$h'$	$f_{\text{calc}}$

(c) For each of the five images found above, calculate the magnification derived from  $h'/h$  with that calculated from  $-i/o$  (with errors). Record your values in your logbook in a table similar to the one shown below. Show at least one sample calculation of each result in your logbook. How well do the values in each instance agree? Answer this question in your logbook.

$m_1 = h'/h$	$m_2 = -i/o$

**SESSION TWO: APPLICATIONS OF LENSES**

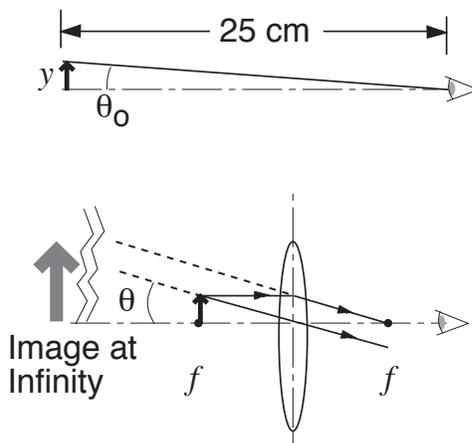
**The Magnifying Glass**

When an object is between a converging lens and its focal point, a virtual image is formed which appears magnified and not inverted. Because the image is virtual it cannot be projected onto a screen; however, a viewer may see it by looking through the lens. This is the secret of Sherlock Holmes.

The angular magnification  $M$  of a magnifying glass is given by the angle subtended by the image  $\theta$ , wherever it may be, divided by the angle subtended by the object at the eye's near point,  $x_{np}$ ,  $\theta_0$ . Usually  $x_{np}$  is set at 25 cm, so the magnification is given by:

$$M = \theta / \theta_0 \sim \tan \theta / \tan \theta_0 = (y/f) / (y/25 \text{ cm}) = (25 \text{ cm})/f \quad (30.6)$$

where  $f$  is in cm. See Figure 30.6 .



**Figure 30.6:** A magnifying glass.

For the following activities you will need:

- Optics Kit

---

**Activity 30-5: Examining a Magnifier**

(a) Place the viewing screen at the 25.0 cm mark on the optical bench. Place the  $f = 15.0$  cm lens between the 0 and 25.0 cm mark. With one of your eyes at the 0 position look through the lens to see a magnified image of the scale on the viewing screen. Move the lens back and forth until you find the largest magnification that is in focus. Use the lens formula to determine what the image distance is. Show your calculation below.

(b) What screen-to-lens distance would you need for the image to be at infinity? (You should be able to calculate this.)

(c) Try to estimate the angular magnification by observing squared graph paper through the lens. Keep the paper about 25 cm from your eye. You should see the unmagnified squares around the lens and magnified squares through the lens. Count how many unmagnified intervals fit in a magnified interval. Compare this with  $x_{np} / f$ .

---

### **The Compound Microscope**

The magnifier is part of a compound microscope as shown in Figure 30.7. First, the objective lens of the microscope forms an inverted real image of the object near the focal point of the eyepiece. This first image is labelled the intermediate image in the diagram. It acts as the effective object for the eyepiece lens. The eyepiece then acts as a magnifier and forms a virtual final image somewhere between infinity and the near point of the eye (25 cm). The distance between the inside focal points of the objective and the eye-piece is the

“optical tube length”  $L$ , and it is usually standardized at 18 cm in modern microscopes.

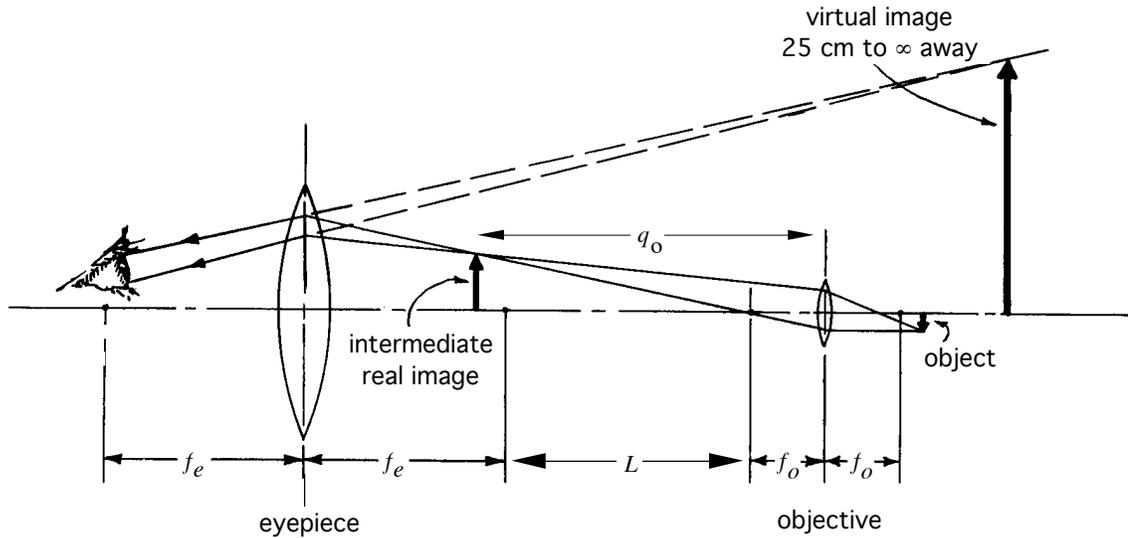


Figure 30.7: A compound microscope.

The overall magnification of the microscope is the product of two terms: the magnification of the objective and the magnification of the eyepiece. We will consider only magnitudes and not use a sign convention.

(i) The magnification of the objective is found from analysing the similar triangles in Figure 30.7:

$$m_0 = \frac{\text{size of first image}}{\text{size of object}}$$

$$m_0 = \frac{q_o - f_o}{f_o} \approx \frac{L}{f_o} \quad (30.7)$$

(ii) The magnification of the eyepiece:

The purpose of using the microscope is to increase the size of the retinal image (in the eye). Therefore we will determine,  $M$ , the angular magnification, which depends on the angle subtended at the eye. As with the magnifier, it can be shown that the angular magnification in this case is given by:

$$M_e = \frac{\text{angle subtended by the final virtual image}}{\text{angle subtended by object seen by naked eye}}$$

$$M_e = \frac{x_{np}}{f_e} = \frac{25 \text{ cm}}{f_e} \quad (30.8)$$

if the virtual image is at infinity and  $x_{np}$  is the eye's near point. Thus the overall angular magnification of the microscope is given by:

$$M_{total} = m_o M_e = \left( \frac{L}{f_o} \right) \left( \frac{25 \text{ cm}}{f_e} \right) \quad (30.9)$$

---

### Activity 30-6: The Compound Microscope

(a) We will use the 150 mm lens as the eyepiece and the 75 mm lens as the objective. Put the crossed arrow target near the far end of the optical bench and project a magnified image of it onto the viewing screen using the 75 mm lens. You will probably have to illuminate the target with the light source. Record the object, lens and image locations on the optical bench for this set-up below.

(b) Now the 150 mm lens, the eyepiece, can be positioned to view the image. After you can see the image on the viewing screen through the eyepiece, remove the screen and turn off the light. Now you can view the magnified image directly through both lenses. To see the best image place your eye 10–20 cm behind the eyepiece, not right up against it. Try to estimate the magnification of the microscope by comparing the size of the magnified target scale to the size of the actual lens.

(c) Use Equ. 30.9 to determine the overall magnification of your microscope using the  $L$  value for your own set-up. How does this result compare with your estimation from part (b)?

(d) Record the eyepiece location of your microscope and use this and the image location from part (a) to determine the object distance for the eyepiece.

(e) Now use the object distance from part (d) to determine the final image location using Equ. 30.5. Does your result agree with where you expect the final image to appear?

---

 **Activity 30-7: The Refracting Telescope**

(a) Look up how to construct a refracting telescope in your textbook. Make one on your optics bench using two converging lenses from the optics kit. Use your telescope to focus on a vertical scale drawn on a whiteboard and adjust the lens positions to get the image in focus. Draw a sketch of your telescope below and label the positions of the lenses.

(b) Ideally how far apart should the two lenses be? How does this compare with how far apart they are in your real telescope? Calculate a percent difference between the two values.

(c) Given your two lenses' focal lengths, what should the angular magnification of your telescope be? How does this value compare with what you estimate when you look through your telescope? Calculate a percent difference between the two values.