

## THIN LENSES

**Objectives:** • To investigate the image-forming properties of thin lenses.

**To Do Before Lab:** • Read this lab

**Apparatus:** several lenses in holders, ray optics kit, optical bench with a screen and a light source

### Introduction:

A thin lens is a lens whose thickness is small compared to the distance between the lens and the object and the distance between the lens and the image. As a first approximation, the lenses used in cameras, binoculars, microscopes, the eye, eyeglasses, and contacts, and many other optical instruments, can be treated as thin lenses.

Light travels through a uniform medium in a straight path. However as you saw in the Snell's Law lab, when light crosses a boundary between two different media its path is bent (unless it is travelling at right angles to the boundary). This phenomenon is called **refraction**, and it is due to the fact that the speed of light is different in the two media. When light travelling in air enters a piece of glass its speed decreases and it bends toward the normal. When it leaves the glass and reenters the air, its speed increases and it bends away from the normal. By carefully designing the shape of a piece of glass we can get light to bend in just the right way and we can make useful optical components such as lenses and prisms. Today we will explore two classes of lenses - converging and diverging lenses. We will not concentrate on analysis of the refraction at the air/glass boundaries; rather we will learn about the most basic property of a lens, its **focal length**, and will develop an understanding of some applications of lenses.

### Part I: Ray box

The first part of the lab involves some qualitative observations about the effects of converging lenses, diverging lenses, prisms, and curved mirrors on the path of light rays.

(1) Orient the light source so that it produces a set of "rays" on a piece of paper laid flat on the tabletop. Use the rays to determine how the path of a light ray is bent after an encounter with the concave and convex lenses and the concave mirror in the ray optics kit. In your notebook, draw ray diagrams describing what you observe. In your diagrams include the distance from the lens to the point where the rays (i) do or, (ii) would, converge. What is the case (ii) called?

### Part II: Converging Lenses

Rays of light travelling parallel to the axis of a converging lens are bent by the lens (by refraction at the air - glass and glass - air interfaces) and pass through a single point on the axis. This point is called the **focus** or **focal point** and is commonly labeled F, as in Fig. 1. Rays of light travelling parallel to the axis, but coming from the right in Fig. 1 will also be focussed to a point. For a thin lens, the distance from the center of the lens to either focal point is the same, and is called the focal length,  $f$ .

The two **planes** that are perpendicular to the axis and which contain the focal point are called the **focal planes**. For ideal lenses, parallel rays entering the lens at a given angle to the axis will come to

a focus at a point in the focal plane, as shown in Figure 2.

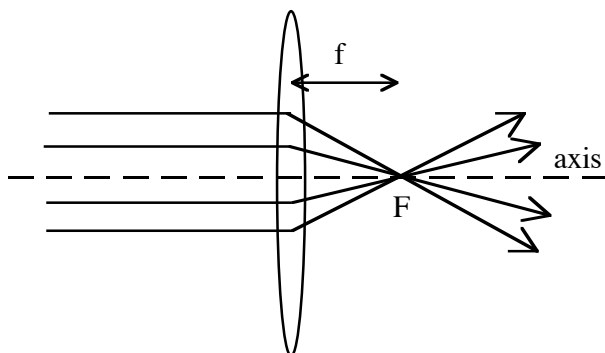


Figure 1

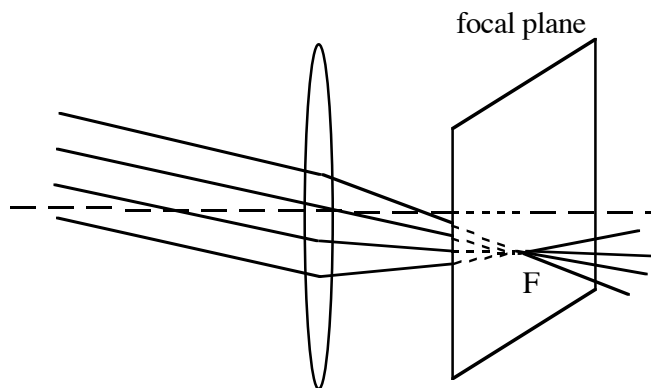


Figure 2

(1) The focal length of a converging thin lens can most easily be found by forming an image of a very distant object (such as something seen through a window). Because the object is far away from the lens, light rays from any point on the object that reach the lens will be travelling essentially parallel to each other. Therefore the image will be formed in the focal plane. Use this information to find the focal length of all three converging lenses that you have, and record your results. Include a diagram that describes your procedure.

(2) When an object is not very far from the lens, but is still further than the focal length, light from the object that passes through the lens is focussed and forms an image beyond the focal plane. When analyzing such a situation, it is useful to consider the path taken by three “construction rays” which come from a single point on the object and which pass through the lens. The reason these rays are useful is because their paths are simple to follow. (Actually, only two rays are needed to determine the image point; the third ray is useful as a check.) The three rays are:

- a) a ray that travels parallel to the axis of the lens and therefore passes through the far focal point,
- b) a ray that passes through the near focal point and emerges parallel to the axis, and
- c) a ray that passes through the center of the lens and continues travelling along the original path.

See Fig. 3.

Employing these rays, a geometrical argument shows that:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \quad (1)$$

where  $d_o$  is the distance between the object and the lens,  $d_i$  is the distance between the image and the lens, and  $f$  is the focal length of the lens. This is called the **thin lens formula**.

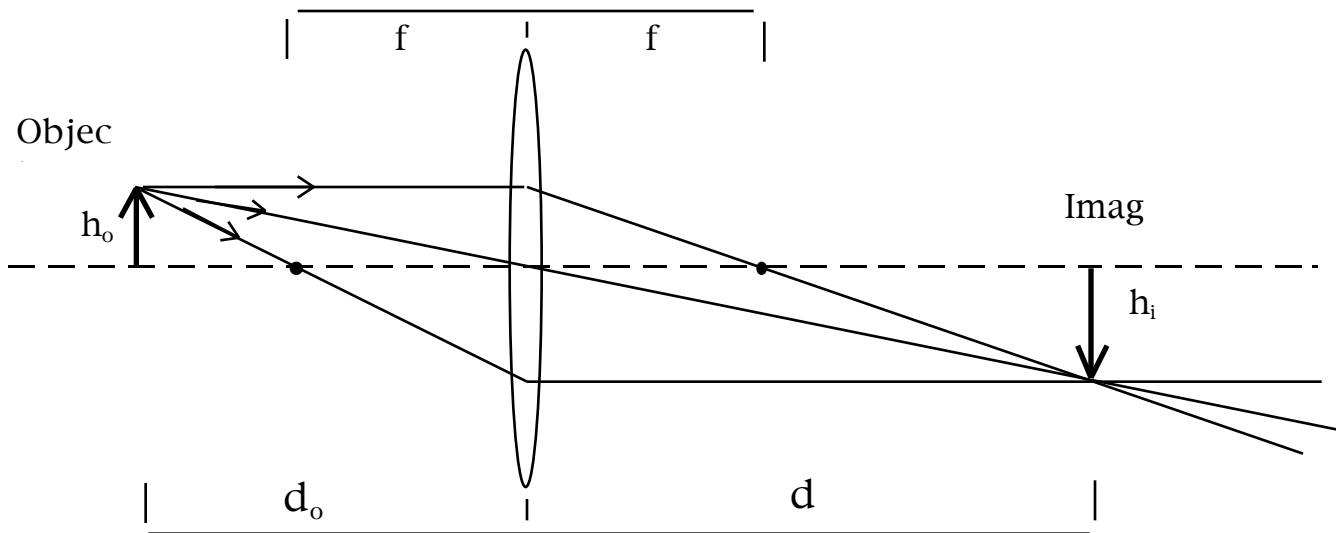


Fig. 3

(3) To test the above formula, choose the lens of shortest focal length and measure  $d_o$  and  $d_i$  for various positions of the lens relative to the illuminated object. Also determine how large the image is relative to the object in each case. Include a rough estimate of the error for each measurement. Using  $d_o$ ,  $d_i$ , and  $h_o$  for one of your object positions, draw a *scaled* ray diagram to determine  $h_i$ . Does the image size in your drawing agree with experiment? Graph  $\frac{1}{d_i}$  vs.  $\frac{1}{d_o}$ . From the graph, determine the focal length  $f$  of the lens.

(4) Refer to the above diagram and derive an expression for the **lateral magnification**

$$M \equiv \frac{\text{image size}}{\text{object size}} = \frac{h_i}{h_o} \quad (2)$$

in terms of  $d_o$  and  $d_i$ . Go back to your data table and consider the measurements for the largest  $d_o$ . For the data with the largest  $d_o$ , find the uncertainty in the measured lateral magnification ( $h_i/h_o$ ).

You may be able to make your life easier by using the formula for the relative error ( $\sigma_M^2/M^2$ ) and ignoring the smaller terms. You have several error contributions of different sizes. You only need to consider the dominant source of error if you can show that the other sources of error are much smaller than the dominant source of error. For example, if  $\frac{\sigma_M^2}{M^2} = 0.1^2 + 0.01^2$  then the second term contributes very little to the total uncertainty and  $\frac{\sigma_M}{M} \approx 0.1$ .

### Part III: Magnification

You have probably used a magnifying glass before, perhaps even to bring Saharan temperatures to small bugs. This short section explores the simple principle behind these tools. There is one confusing point, however. In the interest of reducing suspense in our busy, jet-setting lives we will announce right away that this involves a new, distinct definition of magnification.

The apparent size of an object is determined by the size of the image on the retina. This in turn depends on the angular size of the object. To look closely at an object we increase its angular size by bringing it closer to our eye. However, at some point it “goes fuzzy” and we can not focus on it. This is called the **near point**. Find your own near point. Call this distance  $n$ .

(1) We can aid our eye and “get a lot closer” with a convex lens. Use the #1 or 2 lens as an eyepiece and magnify the print on a page. Neat! About how much bigger is the print as observed through the lens as compared to using your naked eye?

The magnification is due to a larger angular size. This **angular magnification** is defined by

$$m = \frac{\theta'}{\theta} \quad (3)$$

in which  $\theta$  is the angular size of the object without the lens and  $\theta'$  is the angular size of the object as it appears to you through the lens. N. B.:  $m \neq M$ !

By the way, why does the image look “smeary” around the edges? This effect can occur in mirrors as well (as it did during the manufacture of the primary mirror in the Hubble Space - Ooops.)

(2) Draw ray diagrams of an object at your near point and of an object as viewed with the magnifying glass. Is this image real or virtual? How does the glass bring the object “a lot closer”? Use geometry to show that

$$m = \frac{n}{f} \quad (4)$$

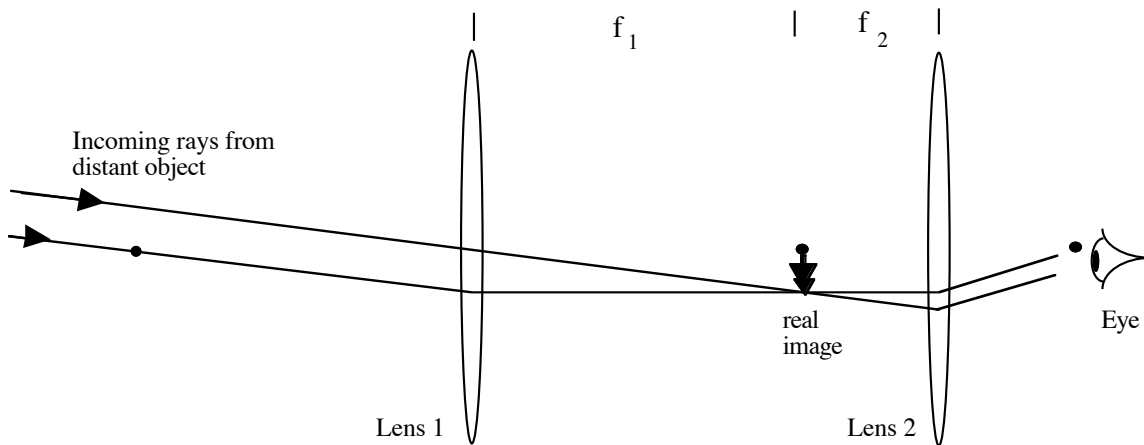
Compute this number for your lens and check to see whether it agrees with your estimate in (2).

### IV. The Telescope

A converging lens produces a small image on the screen of distant objects. If the screen is removed, the real image is still there in space. You can look from behind the lens and see this image directly. Alternatively, you can use a second converging lens as a magnifying glass to enlarge this image. Based on your observations in Part III what is the point of bringing a small image up close?

This configuration of two convex lenses is called an astronomical refractor. Below is a diagram for the

refractor.



The angular magnification of a telescope is given by  $m = \frac{f_1}{f_2}$ , so it makes sense to have a large  $f_1$  and a small  $f_2$ . **Extra:** Derive this formula for  $m$ .

(1) Construct a telescope using two of your lenses and use it to view an object outside the window. Convince yourself that the second lens must be placed behind the real image. Telescopes are focused by changing the distance between the two lenses. If you want to focus on an object closer than outside the window, should you increase or decrease the distance between the lenses? Explain. Test your prediction by using your telescope to look at the light source at the opposite end of the optics bench.