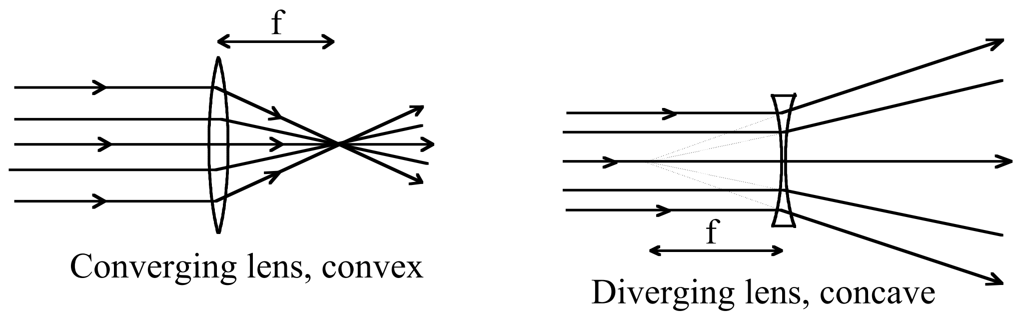
Lab 8. Lenses & Telescopes

INTRODUCTION AND BACKGROUND:

In this experiment, you will study **converging** lenses and the lens equation. You will make several measurements of the focal length of lenses and you will construct a simple astronomical telescope.

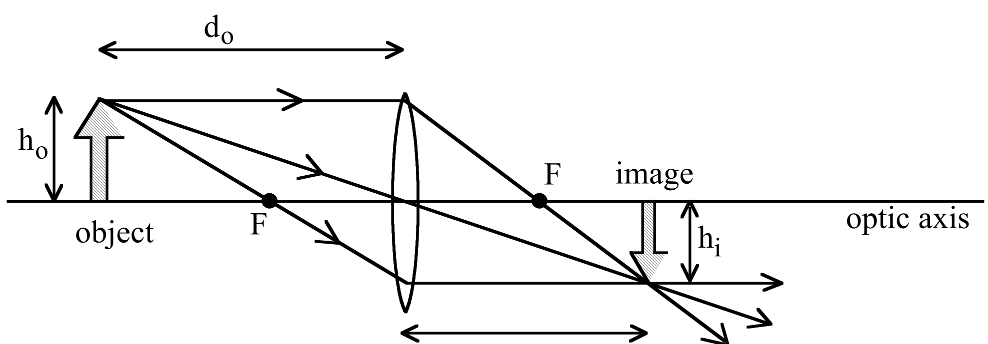
When a bundle of **parallel** light rays enters a converging lens, the rays are focused at a point in space a distance **f**, the focal length, from the lens. A converging lens is convex in shape, that is, thick in the middle and thin at the edges. A diverging lens is concave in shape, i.e. thin in the middle and thicker near the edges.



A converging lens can be used to form an **image** of an object on a screen. The **lens equation** relates the focal length **f** of a lens, the object distance $\mathbf{d_o}$ and the image distance $\mathbf{d_i}$:

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

(This equation can used for both converging and diverging lens; the only difference is that the focal length f is positive for converging lenses, negative for diverging lenses.)



In the diagram above, the points labeled **F** are the focal points of the lens – the distance from the lens to either of the points **F** is the lens **focal length**.

The *magnification* m of the image is defined as $m = \left|\frac{h_i}{h_o}\right|$. From the diagram above, one can use congruent triangles to show that m can also be written as $m = \left|\frac{d_i}{d_o}\right|$.

In the preceding figure, there are two important points to note: First, notice that the distance from the lens to the image is **not** the focal length of the lens, but is related to it through equation 1. Secondly, note that light is being reflected off of the object in *many* directions. The amazing thing about lenses is that all of the light rays that **originate at some specific point on the object** (pointing in all different directions) and then **go through the lens** are redirected to **arrive at a single point on the image**.

Re-draw a simplified version of the preceding drawing, but without the lens. Namely, draw the arrow-shaped **object**, and draw rays of light coming from the tip of the object going out in many directions. Now draw rays of light coming from the middle of the object going out in many directions. If you were to expose a piece of photographic film to this mess of rays at some distance away, what would it look like? Would it form an image?

Re-sketch the same drawing, but now with the lens in place. Duplicate the drawing with the object, the lens, and 5 different rays coming from the tip of the object through the lens, and converging at the image location. Draw 3 rays coming from the middle of the object and converging at the image location. (Draw carefully and precisely, or your drawing will be a mess…)

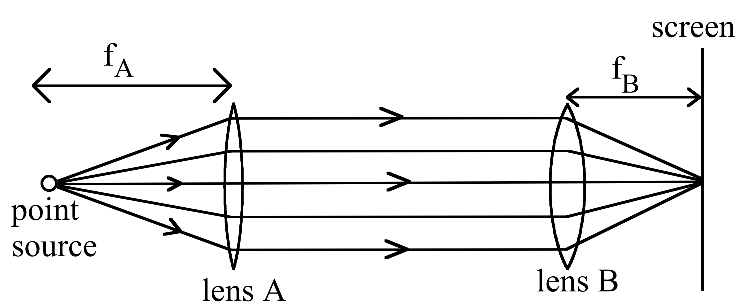
If you were to expose a piece of film to the rays that arrive at the image location, what would it look like? Would it form a picture?

In this lab, you will use three different techniques to measure focal lengths.

Method I: How can you use equation (1) to determine the focal length (**f**) of a lens, if you can measure $\mathbf{d_i}$ and $\mathbf{d_o}$?

Method II: If $\mathbf{d_i}$ were set to ∞ in equation (1), and we could measure $\mathbf{d_o}$, how could we measure the focal length (**f**)? What would the rays of light look like near the lens if the rays converged to an image "at infinity"? Make a diagram below, indicating the lens, the rays which converge at a distance $\mathbf{d_o}$ on one side and "at infinity" on the other. Indicate the focal length **f** on the figure.

Method III: If a point source and a lens have been set up to produce a collimated beam (i.e. parallel rays), then the focal length of another lens can be easily measured. The second lens (lens B) is placed in the collimated beam, and the place where the rays are brought to focus is measured. The distance from lens B to the focal point is $\mathbf{f_B}$, the focal length of lens B. How is equation (1) used in this situation?



PART I: MEASURING FOCAL LENGTH BY METHOD I: IMAGE FORMATION

In this lab, you will use an optics bench, which is simply a rail on which lenses are placed, with a ruler on the side for measuring distances. The other equipment includes a bright light source, which acts almost like a point source, and three converging lenses labeled A, B, and C. There is a frosted glass screen, labeled "I", on which you can view images. Finally, there is a metal plate with an aperture (a hole) in the shape of an arrow. The hole is covered with a frosted, translucent material (scotch tape). When this aperture is placed in front of the light source, it forms a convenient object for image-forming experiments.

Place the light source at the end of the optics bench and attach it with the thumbscrew in the slot. Place the arrow aperture on the front of the light source; there is a magnet to hold it in place. It will save a little trouble in your calculations if you position the source so that the object (the frosted arrow) is **exactly** beside an integer mark (e.g. 2.0 cm) on the scale of the bench. Gently tighten the thumbscrew to secure the source, and record the position of the object. Connect the light source to the power supply and momentarily depress the "start" switch to turn on the light.

Place the frosted screen, I, at the far end of the bench. Again, it will save some trouble if you locate it a convenient integer mark, like 90.0 cm or 92.0 cm. Record its position, as indicated by the ring inscribed on the housing.

Now put lens B on the bench close to the light source and move it slowly away from the source until you see a clear image on the screen. The image is most easily seen looking through the screen towards the light source, but it can also be seen from the other side. Adjust the position of the lens to give the sharpest image and record the position of the lens (as indicated by the ring on the housing). Draw a sketch of the setup, labeling the appropriate parts:

Measure $\mathbf{d_o}$ and $\mathbf{d_i}$. From equation (1), calculate the focal length $\mathbf{f_B}$.

If the image is not centered on the screen, adjust the position of the object plate on the front of the light source until the image is centered. Now measure h_o and h_i, the heights of the object and image. Compute the magnification $m = \left|\frac{h_i}{h_o}\right|$ and compare with the expected value $\left|\frac{d_i}{d_o}\right|$. Are they the same? If not, why not?

Move the lens B to the **screen-end** of the bench and then slide it away from the screen until you get a sharp image on the screen. It is easiest to see the focused image if your eyeball is not too close to the screen – something like 10 inches away works well. Repeat the measurements above for $\mathbf{d_o}$, $\mathbf{d_i}$, $\mathbf{h_o}$, and $\mathbf{h_i}$. Recompute f_B and m. How do these compare to your previous determinations of $\mathbf{f_B}$ and **m**?

Measure the focal length f_A of lens A using method I. (Don't bother with the magnification m).

PART II: MEASURING FOCAL LENGTH BY METHOD II: COLLIMATED BEAM

Here you will use method II to measure the focal length of lens A. Remove the frosted arrow plate from the light source. The source itself is very small and can be considered to be a point source. Readjust its position so that the source is at a convenient integer mark on your bench. Now place lens A close to the source and slide it away until it produces a parallel, collimated beam. A good way to check that it is parallel is this: Point the beam at a nearby wall where it will produce a disc of light. Why does a collimated beam produce a disc of light?

Adjust the position of lens A until the diameter of the disc is exactly that of the lens opening. Now measure the distance from the point source to the lens; this is the focal length f_A. Compare your measurement of f_A with your previous value. Compute a final best value.

PART III: MEASURING F BY METHOD III: COLLIMATED BEAM FOCUS

Now you will use method III to measure the focal lengths of lenses B and C.

Without moving lens A, place lens B just beyond A, at a convenient integer mark, and put the frosted screen beyond B. Now move the screen until you jet a sharp image of the **point source** on the screen. The distance from lens B to the screen is f_B.

Repeat the previous step with lens C in place of lens B.

PART IV: THE ASTRONOMICAL TELESCOPE

In the last part of this lab, you will construct a simple astronomical telescope. The astronomical telescope consists of two lenses: an *objective lens* with a long focal length f_o, and an *eyepiece lens* with a short focal length f_e . The objective lens forms an image of a distant object (an object "at infinity"). By the lens equation, if the object distance is $d_o = \infty$, what is the image distance $\mathbf{d_i}$?

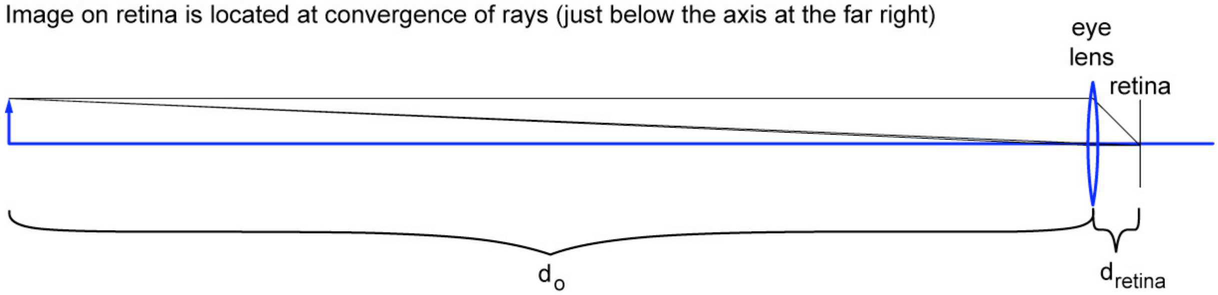
This image, which appears a distance f_o behind the objective lens, is called an **intermediate image**, because it is intermediate between the objective and eyepiece lens. The observer views *this* image through the eyepiece lens, which acts as a magnifying glass.

The diagram below shows what happens inside our eye if we look at a distant object.

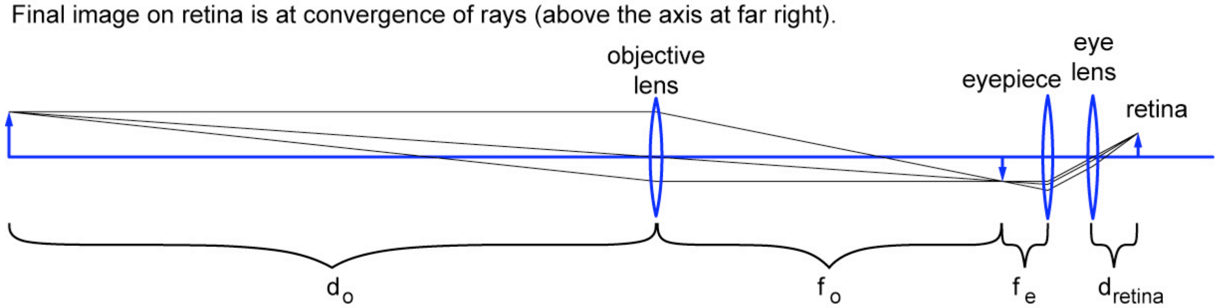
In the first diagram, a tiny little image is formed on our retina by the lens in our eye – that is why distant objects appear small. (The image, which is too small to make out in the diagram, is located where the rays converge, a tiny bit below the axis at the right).

The second diagram represents what happens to the image with the help of a telescope. Notice the intermediate image formed between the telescope lenses. Also notice how much larger the image on our retina is with the help of the telescope!

Viewing of distant object with no additional optics:
Image on retina is located at convergence of rays (just below the axis at the far right)



Viewing of distant object with telescope optics:
Intermediate image is formed between telescope lenses
Final image on retina is at convergence of rays (above the axis at far right).



In the first diagram on the previous page, it appears that *top* of the object gets imaged just *below* the middle of our retina. Why doesn't everything look upside down to us?

In the second diagram (the one with the telescope lenses), the orientation of the image on our retina is reversed with respect to the case with no telescope. What do you expect to see when you look through your telescope?

In the diagram above, the distance between the telescope lenses is set to be the sum of the focal lengths of the objective lens and the eyepiece. That way, the objective lens forms the intermediate image, and the eyepiece magnifies it. Recalling that the magnification of a lens or lens system is given by the ratio of the object and image distances $M = \frac{d_i}{d_o}$, we can calculate the magnification of the telescope as follows:

From the diagram above, the magnification of the **objective lens only** is:

$$M_{objective} = \frac{f_o}{d_0}$$ (since the intermediate image is located at f_o)

The magnification of the eyepiece and our eye lens together is:

$$M_{eyepiece+eye} = \frac{d_{retina}}{f_e}$$

So the total magnification of the object through the telescope onto our retina is given by:

$$M_{telescope} = M_{objective} M_{eyepiece+eye} = \frac{d_{retina}}{d_0} \frac{f_o}{f_e}$$

But remember that without a telescope, the magnification of the object onto our retina is:

$$M_{no-telescope} = \frac{d_{retina}}{d_0}$$ (from first diagram on previous page)

So the relative magnification that the telescope gives us is:

$$\boxed{M = \frac{M_{telescope}}{M_{no-telescope}} = \frac{f_o}{f_e}}$$

(the ratio of the objective focal length to the eyepiece focal length).

Choose the lens with the longest focal length. This will be the objective lens with focal length f_o . Also choose the lens with the shortest focal length. This will be the eyepiece with focal length f_e. Place the eyepiece at one end of the optics rail and place the objective lens a distance $\ell = f_o + f_e$ from the eyepiece.

Aim the telescope towards the far end of the room, where there is an arrow and a graduated scale mounted on the wall, and adjust the telescope position until you can see the arrow through the telescope. It may be difficult to find the image since your telescope has a narrow field of view. Also, you may need to adjust the position of the eyepiece lens to get a sharp image. Is the final image you are looking at upright or inverted? Explain why it appears as it does with words and diagrams.

Based on the telescope/lens configuration, calculate the theoretical value of **M**.

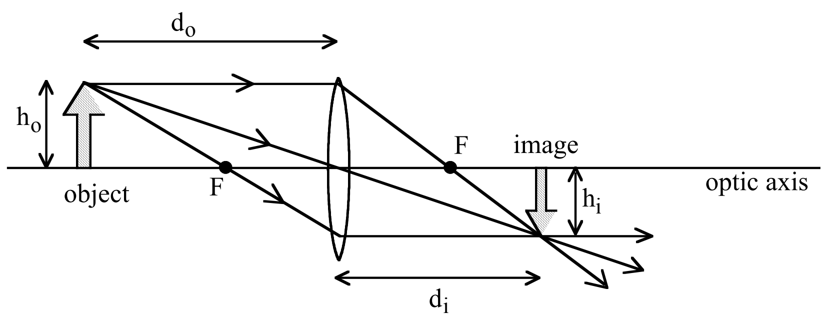
Once you have found a clear image looking through the telescope, open your other eye so that you can look simultaneously at the enlarged image with one eye and the unenlarged image with the other eye. If you position the telescope just right, you can see the two scales side by side and hence estimate the angular magnification **M** of your telescope. Record your “by eye” estimate of the telescope magnification. Does it match the theoretical value of **M**? If not, why not?

What do expect will happen to the image if you block half of the lens? Look at the diagram at the bottom of page 1 and imaging blocking half of the rays that are going through the lens. Would you still form an image? Would there be any differences?

Have one of your lab partners block half of the objective lens with a piece of paper. What happens to the image? While you are looking through the telescope, have them remove the paper. What happens?

POTENTIAL EXAM QUESTIONS:

1. Consider the following diagram, in which a single lens is used to form an image of an arrow-shaped object. Which of the following statements is true?



a) If the object is moved to the right, the image will also move to the right.

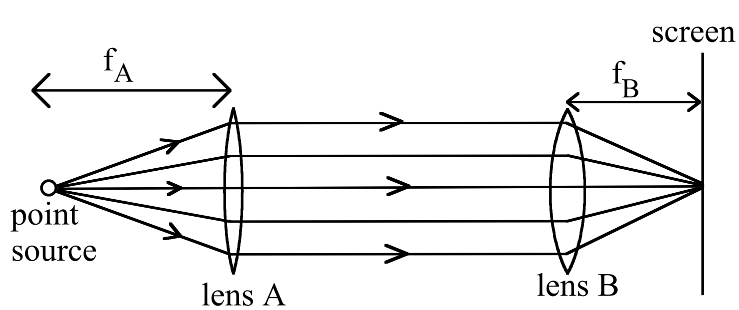
b) If the object is moved to the right, the image will move to the left.

c) If the object is moved to the right, the image will not move since the focal length of the lens has not changed.

d) If the top half of the lens is blocked, only the bottom half of the image will form.

e) Both (c) and (d) are true.

2. Consider the following diagram, in which light from a point source is converted into a collimated beam, then re-focused to a point on a screen. Which of the following statements is true?



a) If the point source is moved to the left, the spot on the screen will become larger and dimmer.

b) If the point source *and* lens A are moved *together* to the left, the spot on the screen will become larger and dimmer.

c) If the point source is moved up, the spot on the screen will move up.

d) Both (a) and (c) are true.

e) Both (b) and (c) are true.