Telescopes

Introduction:

In this lab, you will investigate the properties of lenses and build a simple telescope. The telescope you will build is similar in design to the telescopes used in the time of Galileo and Kepler. Telescopes have two main functions: to gather more light and bring it to the observer's eye and to magnify distant objects. The telescope you build will have a magnification of 25 times, which is comparable to Galileo's best telescope and to commercial binoculars today. This magnification is useful for observing the Lunar surface and the moons of Jupiter.

Background material:

When light travels through space, or inside something transparent like air or glass, it travels in a straight line. If light reflects off an object, such as a mirror, it will change direction at the surface. If light moves from one medium to another, such as from air to glass, it can change direction again at the surface. However, once it has changed direction, it will continue along a straight line. We call the straight paths of light "light rays."

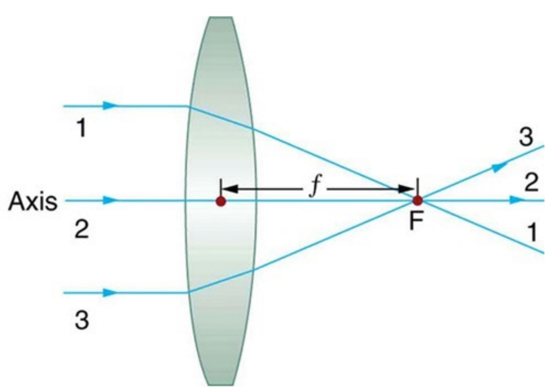
The bending of a light path as the light moves from one medium to another is called refraction. It changes the angle the light makes with the surface. When the surface is curved, such as in a typical water glass, this bending makes the light seem like it came from a different place: if you put a pencil into a glass filled with water, the pencil will seem to be at a different angle when viewed through the water.

In a telescope, as well as in microscopes, magnifying glasses, cameras, and the human eye, lenses are used to modify the path of light. The word "lens" comes from the Latin for "lentil bean," and is named after the shape of a convex lens.

Converging (convex) and diverging (concave) lenses

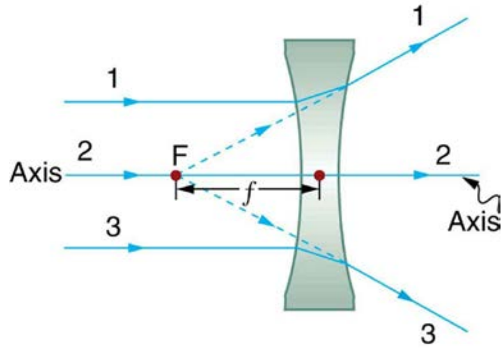
A convex lens is thicker in the middle and thinner on the outer edges. Light rays passing through a convex lens are bent so that they come closer together (converge). Light rays from a very distant source, such as the sun, come toward the lens in parallel and will meet at a focal point *F,* which is a distance *f* past the center of the lens.

Figure 1.



A concave lens is thinner in the middle and thicker on the outer edges. Light rays passing through a concave lens are bent so that they diverge, moving further apart. Light rays from a distant source will seem to have come from a focal point *F,* which is a distance *f* before the center of the lens.

Figure 2.



To predict the effect of a lens on the light coming from a particular object, we construct a schematic diagram of light paths seen from the side. Typical sources of light, or everyday objects reflecting light, give off light in all directions. We focus on three representative light rays for each light-producing or light-reflecting object.

Converging lens rules

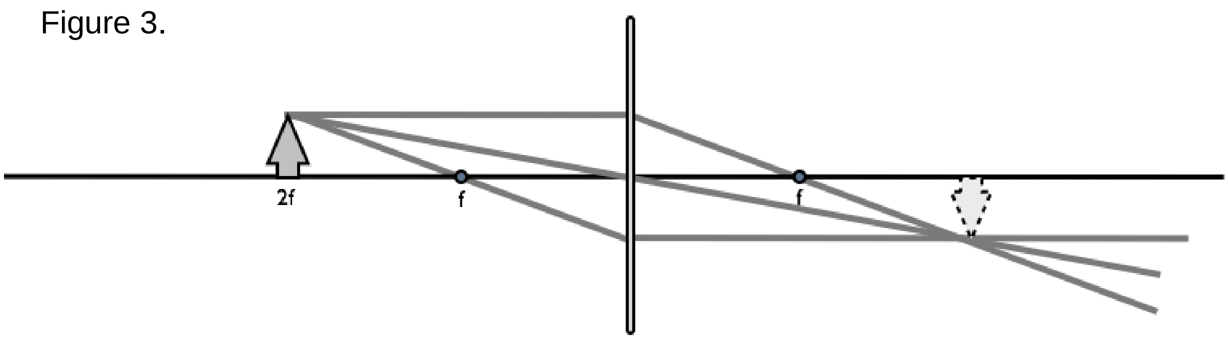
I. If a light ray travels perpendicular to the lens (horizontally) from the object to the lens, it bends to travel through the focal point after the lens.

II. If a light ray goes from the object through the center of the lens, it continues long in a straight line

III. If a light ray passes through the focal point on the same side of the lens as the object, it bends to come out traveling perpendicular to the lens (horizontally).

1. **LABEL THE THREE RAYS** (I, II, and III) IN THE DIAGRAM BELOW:

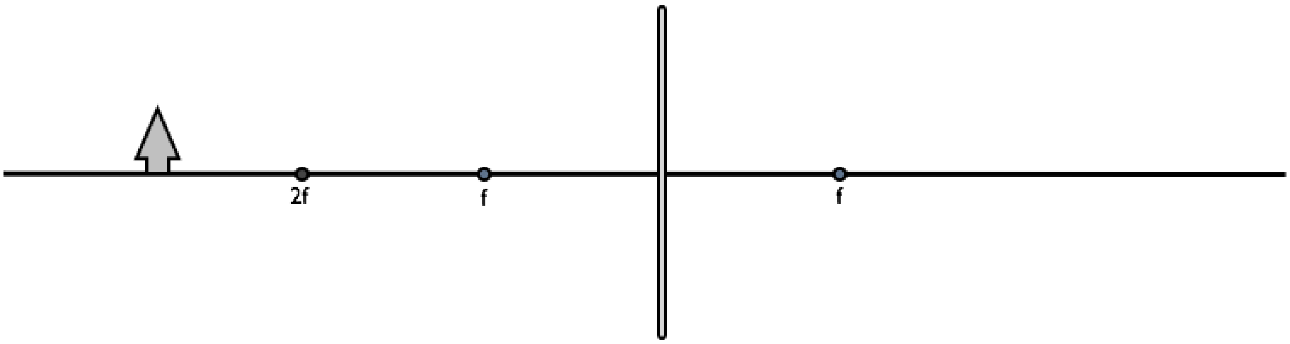
Figure 3.



After the three light rays pass through the lens, they meet at a point, and then continue. An observer sees the light rays as if they are coming from the tip of a new image object after the lens. The image is upside down (“inverted”) compared to the original. If we put a projection screen right where the image is formed, we create a clear image from the focused light. This is how projectors and cameras work.

(Note: in these images, twice the focal length is labeled “2f”)

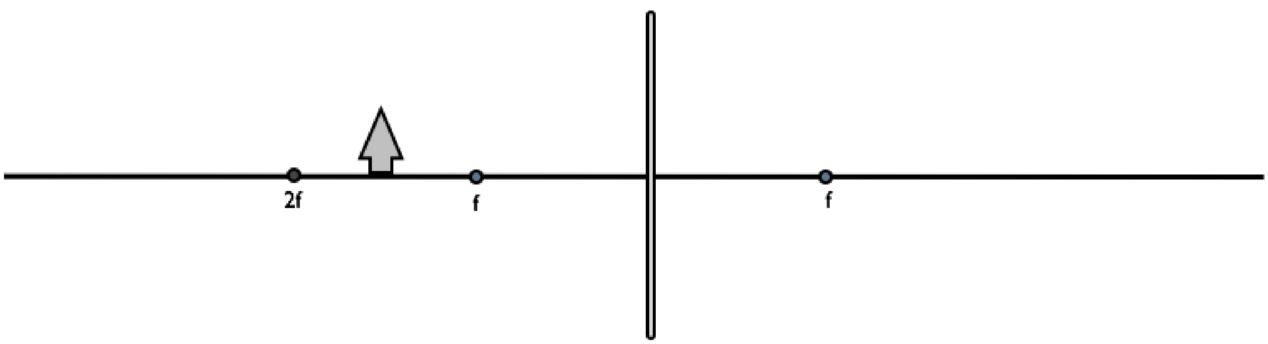
2. **A distant object.** Complete the drawing below. Using the above rules, draw three example light rays from the tip of the object. Note that the rays go through the focal points. USE A RULER! Figure out the new position of the image and sketch it in.



Is the resulting image inverted or upright?

Is the resulting image larger or smaller than the original?

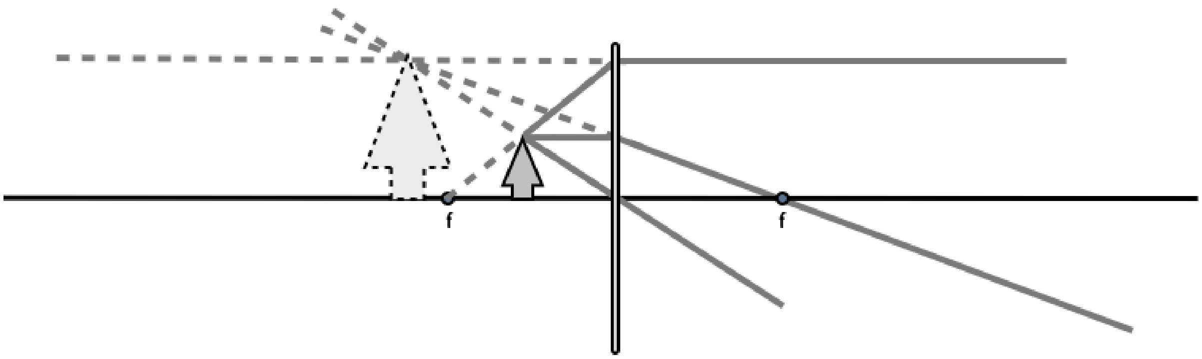
3. **A closer object.** Complete the drawing below. Using the above rules, draw three example light rays from the tip of the object. Note that the rays go through the focal points. USE A RULER! Figure out the new position of the image and sketch it in.



Is the resulting image inverted or upright?

Is the resulting image larger or smaller than the original?

4. **A very close object.** If the object is too close to the lens, we can use the same rules as before, but we run into a problem: the rays don't meet up again after the lens. When we look through the lens, we will still see an image. By tracing the light rays back, illustrated below by dashed lines, we see that the light seems to come from a point on the opposite side of the lens. This image can't be projected onto a screen, so it's called "imaginary."



Is the imaginary image inverted or upright?

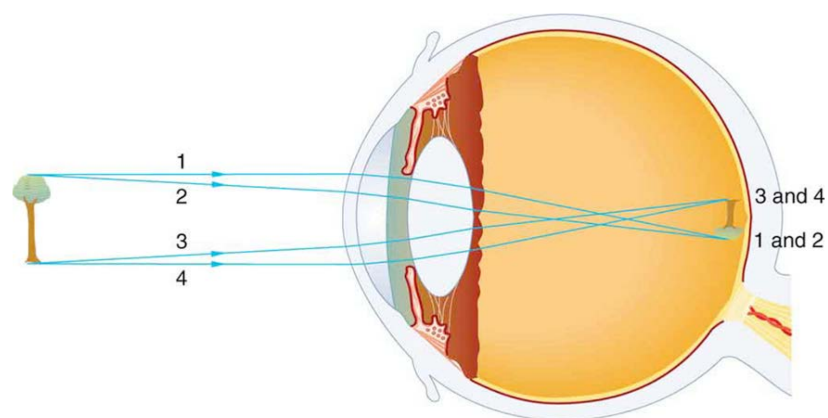
Is the imaginary image larger or smaller than the original?

Magnification

The magnification of an image is defined as the ratio of the height of the image object (h_i) to the height of the original object (h_o): $m = h_i / h_o$

The human eye

To the right is a picture of your eye. It consists of a lens at the front and retina at the back. An image is formed on the retina, as in Figure 3, and Questions 2 and 3, above. However, in those cases, an object at a different distance formed an image at a different location each time.



The lens of our eye can change its focal length - the ciliary muscle around the lens can change its thickness. This is why our eyes can see clear images at various distances. Notice that the image formed on the back of the eye is inverted: our brains automatically correct for this, so we perceive everything right-side-up.

Investigating Lenses

Each student will get a telescope kit containing:

Assembly Instructions, Large and small red caps, Two sliding cardboard tubes, Cardboard washer, Foam lens holder, Cardboard spacer, Large and small lenses

You will also need a ruler, a picture on the wall, and a distant light source set up across the classroom.

Focal Lengths and Image Properties

Take the two lenses from the Telescope Kit and analyze them.

1. Look at the lens shape. Are those lenses convex or concave lenses? Explain why.

2. What are their focal lengths? Refer back to Figure 1, where a distant light source focuses light to the focal point. Use the lamps in the classroom as a distant light source to determine the focal length of the lenses. Estimate the uncertainty in your measurement (e.g., f = 15 ± 2 cm means that you think the length is 15 cm, but you wouldn't assume something had gone wrong if you saw another student get a number between 13 and 17 cm.)

Small Lens f = ____ ± ____ cm

Large Lens f = ____ ± ____ cm

Summarize your procedure for measuring the focal lengths below:

3. Hold the two lenses very close to each other to make a combined lens, and measure its focal length.

Joint Lens f = _______ ± cm

How does the combined focal length compare to the individual lenses?

4. When you look through the lens, the resulting image can have various appearances. We will first compare the effect of the two lenses in the telescope kit.

    a. Look at an object that is roughly 2 cm from the lens.

	Large Lens	**Small Lens**
Is the image larger or smaller?		
Is the image upright or inverted?		
What background material category would this be (distant, closer, very close, or none of the above)?		

	Large Lens	**Small Lens**
Is the image larger or smaller?		
Is the image upright or inverted?		

    b. Hold the lenses close to your eye, as if you were wearing glasses, and look at an object on the other end of the lab room. The image will look blurry because you are changing your eye's effective focal length by making a combined lens.

This isn’t like any of the introductory situations since light hits the eye before the image would be formed.

c. Hold the lenses at arm's length and look at an object at the other end of the lab room.

	Large Lens	**Small Lens**
Is the image larger or smaller?		
Is the image upright or inverted?		
What background material category would this image be (distant, closer, very close, or none of the above)?		

a)

5. Take the small lens and hold it at arm's length roughly thirty centimeters away from a picture. Describe what happens as you decrease the distance between the lens and the picture to less than a centimeter.

a. What happens to the size of the image?

b. What happens to the orientation of the image?

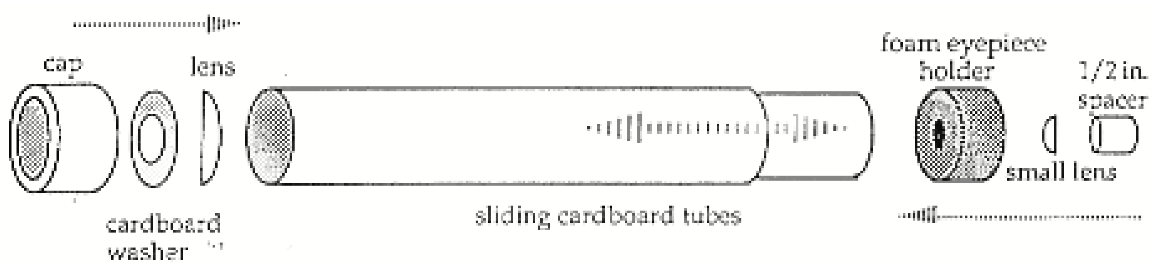
c. At some point, the image will get blurred and disappear. Where?

Distance at which there is no image: _______ ± ________ cm

d. How does the distance in c compare to the focal length of the small lens? Can you explain why? (Hint: compare the schematic diagrams of closer and very close objects)

Build a Telescope

Now that you've played with lenses and the formation of images, you should be able to understand how a telescope is put together. Using a single lens, we can't magnify very distant objects *and* get a clear picture. However, by combining two lenses in a certain configuration, you can get an image that is both large and clear.



After you build the telescope, slide the cardboard back and forth until you get a large, clear image of a distant object. You may wish to go into the hall and outside through the doors at either end to check out how your telescope works on distant objects outside.

1. The telescope instructions use the small lens as an eyepiece and the large lens as the objective lens at the other end of the tube.

   a. Which has the longer focal length, the eyepiece, or the objective?

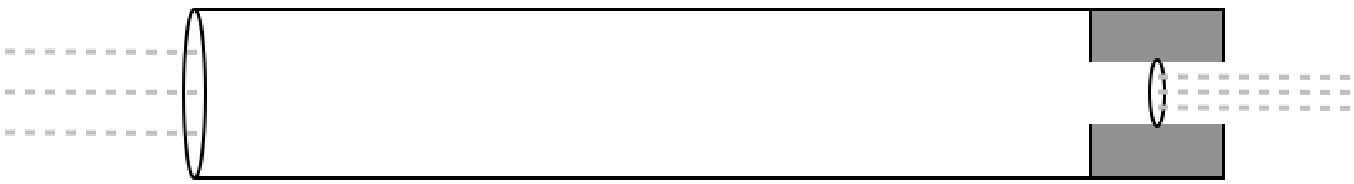
   b. If you reverse the eyepiece and objective lenses (look through the telescope backward), what happens to the image?

2. Measure the distance between the two lenses when the telescope is in focus.

   distance between lenses = _________ ± __________

   a. Is the distance between lenses larger or smaller than the focal length of the large lens?

Keplerian Telescope:



Keplerian, Galilean, and reflecting telescopes

The telescope that you have built is a “Keplerian” telescope. Consider Figure 1 in the background information, and recall that light rays that appear to come from the focal point will be bent to travel parallel after a convex lens.

1. Draw the path of parallel rays of light from a distant star in the diagram above. They enter a Keplerian telescope, are focused by the objective lens, and then pass through the eyepiece to leave the telescope traveling parallel again.

2. Label the focal length of the objective lens and the focal length of the eyepiece lens.

3. Predict what would happen if half of the objective lens was blocked off. Consider Figure 3 in the background material, with half of the lens blocking light. Does an image still form at the same place? Does the same amount of light reach the image?

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

Galileo actually constructed his telescope using a combination of a convex objective lens and a **concave** diverging lens. Review Figure 2 in the background information; a concave lens can also take the light that seems to come toward a focal point, and bends it to leave the lens traveling horizontally.

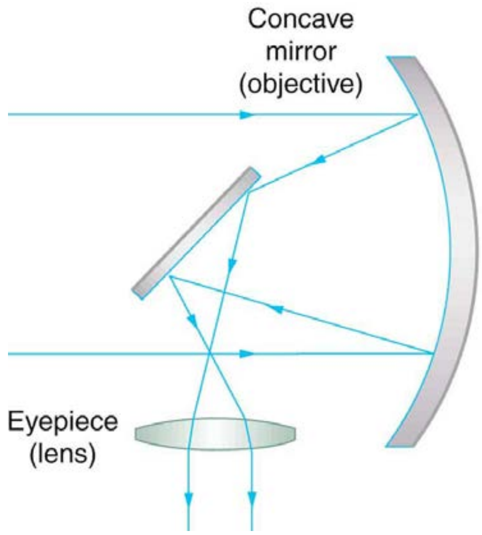
Galilean Telescope:

5. Draw the path of parallel rays of light from a distant star in the diagram above. They are focused by the objective lens and then pass through the **concave** eyepiece to leave the telescope traveling parallel again.

6. Label the focal length of the objective lens and the focal length of the eyepiece lens.

   a. Would the distance between lenses in a Galilean telescope be larger or smaller than the focal length of the large lens?

Many modern telescopes use a curved mirror instead of a lens to reflect the light. An example ray diagram for a reflecting telescope is shown below. An intermediate mirror bounces the light from the objective (a concave mirror) to the eyepiece. You can see an example at the front of the class.



6. Would you see a shadow from the central mirror? Why or why not? (Compare question 4)

Light collection

Magnifying distant objects is not the only important function of a telescope. A telescope also gathers light and funnel it into the observer's eye. The larger the telescope, the greater the amount of light captured. This can allow dim but large objects to be seen by eye: for example, the Andromeda galaxy is as large on the sky as the Moon but much fainter.

Light gathering ability is proportional to the of the objective lens (or mirror). We usually measure the size of a telescope by its aperture or the diameter of the objective lens. The light-gathering area is then:

$$\text{Area} = \pi\,(\text{aperture} / 2)^2$$

Your eye has an aperture of about 7mm = 0.07 cm when your pupil opens up fully on a dark night.

7. What is the area of your pupil in square centimeters?

8. Measure the aperture of the telescope: What is the diameter of the objective lens in centimeters?

9. What is the area of the telescope objective lens in square centimeters?

10. How much brighter would a star look through your new telescope?