# OPTICS — LENSES AND TELESCOPES

**SYNOPSIS:** In this lab you will explore the fundamental properties of a lens and investigate refracting and reflecting telescopes.

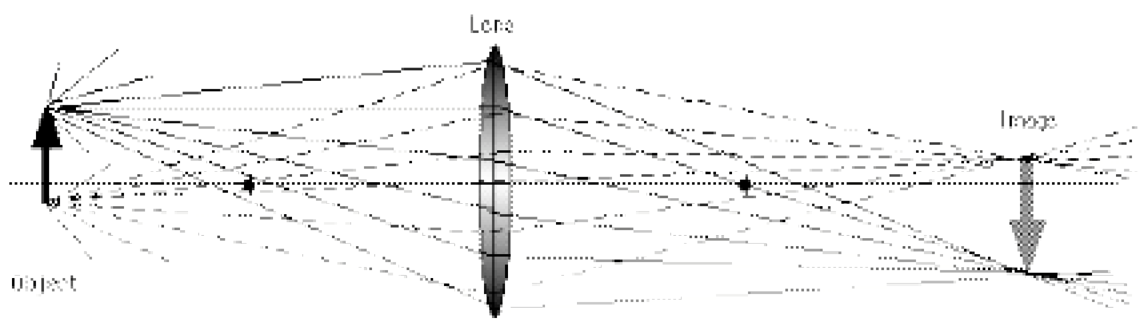
**EQUIPMENT:** Optics bench rail with 3 holders; optics equipment stand (lenses L1 and L2, eyepiece lenses E1 and E2, image screen I, object mount O, flashlight, iris aperture A, objective mirror M, diagonal mirror X); object box.

**LENGTH:** Two lab periods.

> *NOTE: Optical components are delicate and are easily scratched or damaged. Please handle the components carefully, and avoid touching any optical surfaces.*

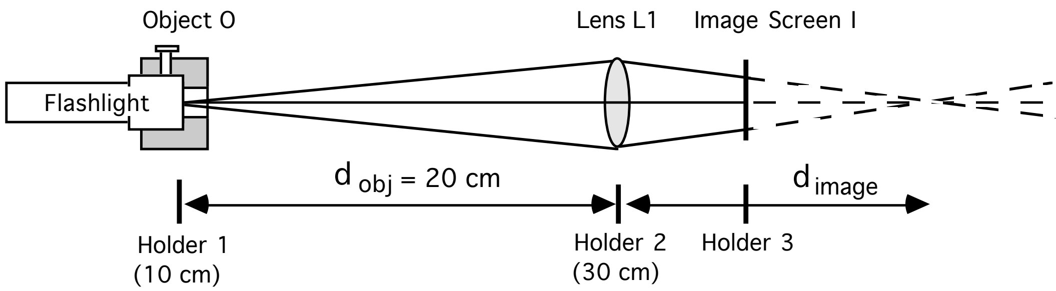
## Part I. Image Formation by a Lens

In optical terminology, an **object** is any source of light: it may be self-luminous (a lamp or a star), or may simply be a source of reflected light (a tree or a planet). Light from an object is **refracted** (bent) when passed through a **lens** and comes to a **focus** to form an **image** of the original object.




Here's what happens: From *each* point on the object, rays are emitted in all directions. Those that pass through the lens are refracted into a new direction - but in such a manner that they all converge through one single point on the opposite side of the lens. The same is true for rays *from every other point* on the object, although these rays enter the lens at a different angle, and so are bent in a different direction, and again pass through a (different) unique point. The image is composed of an infinite number of points where all of the rays from the different parts of the object converge.

To see what this looks like in “real-life”, arrange the optical bench as described below:




Position holder #2 at the 30 cm mark on the rail, and clamp it in place. Install lens L1 in the holder, orienting it so that the lens faces squarely down the rail, and clamp it in the holder.

Slightly loosen the clamp of holder #3, and slide it to just behind the lens (at about the 35 cm mark). Put the image screen I (with white card facing the lens) in the holder and clamp it in place.

Turn on the flashlight by rotating its handle. The markings on the face of the flashlight will serve as the physical **object** which we will use in our study: in particular, the outer black ring is a circle 1 cm (10 mm) in diameter. Insert the flashlight into mount O as shown in the diagram, so that its face is lined up with the center of the mount, and secure it with the clamp.

Install the flashlight mount O in holder #1, and clamp it so that the flashlight points directly at the lens. Finally, slide holder #1 to the 10 cm mark on the rail, and clamp it in place.

On the white screen, you'll see a bright circular blob, the light from the object that is passing through the lens.

I.1 Slowly slide the screen holder #3 away from the lens. Does the spot of light become smaller (converging rays of light) or larger (diverging rays)?

I.2 At some point, you'll notice that the light beam coalesces from a fuzzy blob into a sharp image of the object. Describe what happens if you continue to slide the screen outward beyond the focus.

Use the following table to keep track of your measurements for Part I:

| Lens | Lens position | Object distance | Image distance | Object size | Image size | Magnification (Equation 1) | Magnification (Equation 2) |
|---|---|---|---|---|---|---|---|
| L1 | | | | | | | |
| L1 | | | | | | | |
| L2 | | | | | | | |

The separation between the lens and the object is called the **object distance,** $d_{object}$. Since the lens is located at the 30 cm mark on the rail, while the object is at 10 cm, the *difference* between the two settings gives the object distance: 20 cm.

Not surprisingly, the distance from the lens to the in-focus image is called the **image distance**, $d_{image}$. You can determine this distance by taking the *difference* between the location of the image screen (from the rail markings) and the location of the lens (30 cm). Note that *distances are always given in terms of how far things are from the lens.*

I.3 Return the screen to where the image is sharply focused. Read the position of the screen to the nearest tenth of a cm (one mm), and calculate the image distance.

I.4 Use a ruler to measure the diameter of the outer black circle of the image.

**Magnification** refers to how many times larger the image appears compared to the true size of the object (in this case, 1 cm):

$$\text{Magnification (definition)} = \frac{\text{Image Size}}{\text{Object Size}} . \qquad \text{(Equation 1)}$$

I.5 What is the magnification produced by this optical arrangement?

I.6 Divide your measurement of the *image distance* by the *object distance*, and show that this too gives the magnification produced by the lens:

$$\text{Magnification} = \frac{\text{Image Distance}}{\text{Object Distance}} .. \qquad \text{(Equation 2)}$$

I.7 Now reposition the object (flashlight) holder so that it is at the 3 cm mark on the rail, so that the new object distance is (30 - 3) = 27 cm. Refocus the image. What is the new image distance (lens to white screen)? The new magnification?

Now let's see what will happen if we use a *different* lens. Replace lens L1 with the new one marked L2; but leave the positions of the object (holder #1) and the lens (holder #2) unchanged.

1.8 What is the object distance? Refocus the image; what's the new image distance? The new magnification?

## Part II. Ray Tracing

Is there any way to predict where an image will be formed? The answer is “yes” - by noting certain properties of a lens, and then choosing specific rays whose behavior is easy to predict.

First, any ray which enters a lens exactly *parallel* to the **optical axis** (the line of symmetry through the center of the lens) will *always* pass through a unique point on the optical axis on the other side of the lens, called the **focal point** of the lens. The distance from the lens to this fixed point is called the **focal length** of the lens. (The focal length is a fundamental property of the lens itself; it does *not* depend on the location of the object or image.)

Second, any ray passing through the exact *center* of the lens will *not* be refracted, but will continue to travel in a straight line. (This is because both faces of the lens at its center are parallel to each other - just like looking through a pane of window glass.)

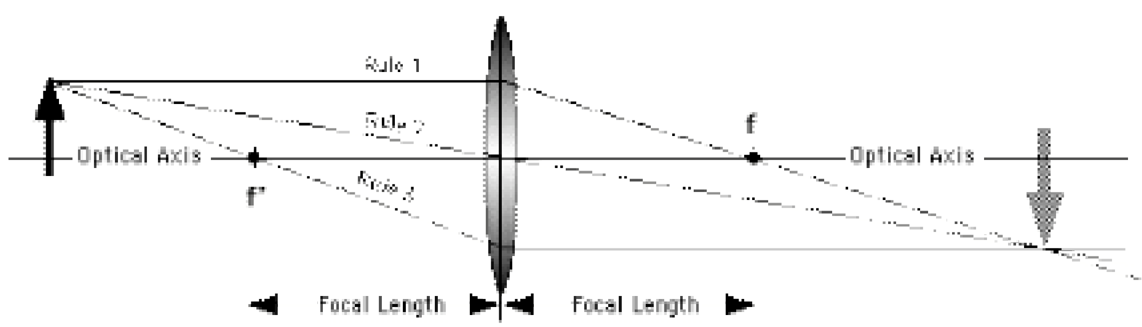
Third, the path of a ray of light is reversible: it will follow the same route regardless of whether it is moving from right-to-left, or left-to-right through a lens. Thus, lenses have two symmetrical focal points - one in front and one behind, both of which are the same distance from the lens.

These properties lead to the three rules of **ray tracing**, which allow you to determine where an image is formed simply by drawing any two of the following three sets of lines from a point on the object through the lens, and finding their intersection:

(Rule 1) A ray which enters *parallel* to the optical axis will be bent at the lens to pass exactly through the back focal point **f**.

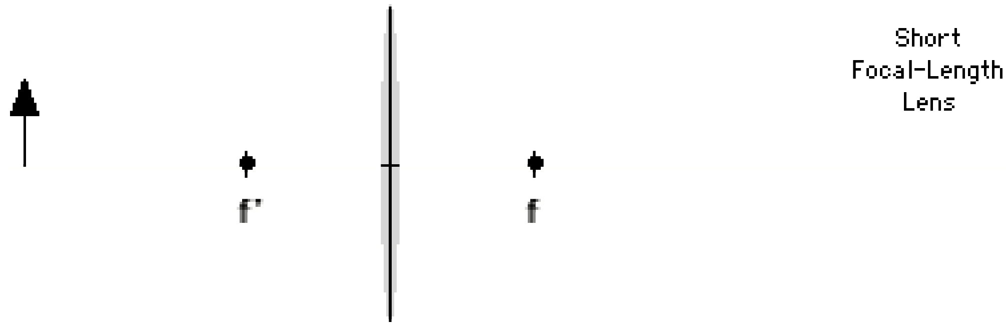
(Rule 2) A ray which passes through the exact center of the lens continues in a straight line.

(Rule 3) A ray which passes through the front focal point **f’** of the lens will leave the lens parallel to the optical axis. (This is just Rule 1 in reverse - remember that lenses are symmetric.)

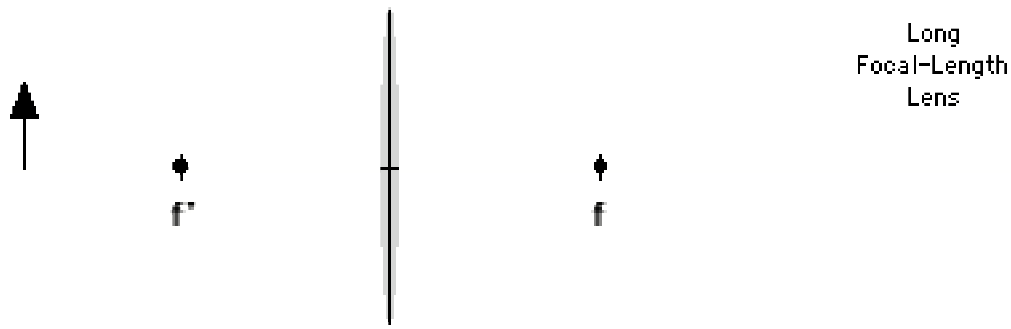



On the next page, you can try some ray-tracing for yourself to find out where an image is formed once you know the object placement and lens focal length.

II.1 Use ray-tracing to find the image of the "object" shown below, using a lens with a short focal length.



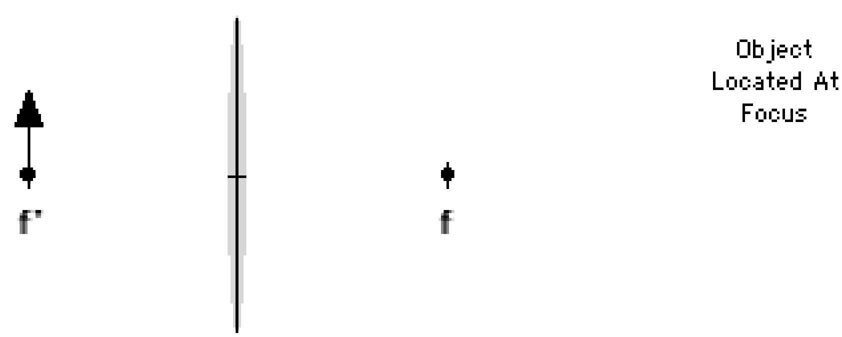

II.2 Now do the same for a lens with a longer focal length:




II.3 Are images always right-side-up, or up-side-down?

II.4 Measure the height of the object and the images with a ruler, and calculate the magnification produced by each arrangement according to the definition (Equation 1). Also measure the image and object distances, and compute the magnification predicted by Equation 2. Does the formula "work"? Which yield greater magnifications - lenses with shorter or longer focal lengths?

II.5 Now try a "tricky" case: with an object positioned exactly at the focal length of the lens, as shown below. (Hint - you won't be able to use Rule 3, but Rules 1 and 2 work exactly as before.)



II.6 In this case, does an image *ever* form? Explain why not. What common household object forms a beam of light similar to that represented by this configuration?

II.7 In this last case, imagine that the direction of the light rays are *reversed*, so that they are coming in (along the same paths) from right to left. How far away is the object emitting the rays coming from the right? Where is the image formed? What would happen if a piece of photographic film were placed at the location of that image? What other modifications would you have to add to build yourself a **camera**?

## Part III. The Lens Equation

You may suspect that there is a mathematical relationship between the object and image distances and the focal length of a lens. You won't be disappointed - it's called the **lens equation**:

$$\frac{1}{f} = \frac{1}{d_{object}} + \frac{1}{d_{image}} \quad . \qquad \text{(Equation 3)}$$

The value *f* in the formula is the focal length, the distance from the lens to the focal point.

III.1 Calculate the focal length *f* of lens L1, using your measured image distance $d_{image}$ and object distance $d_{object}$ (from step I.3, or step I.7, or both). What is the focal length of lens L2 (step I.8)?

HELPFUL HINT: When using your calculator with the lens formula, it is simpler to deal with *reciprocals* of numbers rather than with the numbers themselves. Look for the calculator reciprocal key labeled [1/x] . To compute

$$\frac{1}{2} + \frac{1}{4} \, ,$$ hit the keys [2] [1/x] [+] [4] [1/x] [=] .

You should get the result 0.75 ( = 3/4 ). Now if 1/f equals this quantity, just hit [1/x] again

to get $$f = \frac{1}{0.75} = 1.33.$$

III.2 Which lens, L1 or L2, has the longer focal length? Which produced a larger image? Which would better serve as a "telephoto" lens in a camera?

Let's look at the special case ray traced in II.6. There, $d_{object}$ was equal to *f,* so that $1/d_{image} = 0$, implying that the distance to the image was extremely large indeed - essentially, "at infinity"!

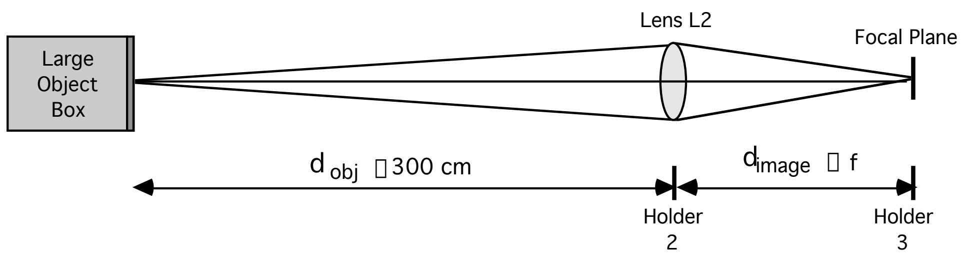
III.3 Position the object along the rail of your optical bench so that it is at a distance from lens L2 equal to its focal length (III.1). Confirm that an image *never* forms.

The special case considered in II.7 is just the reverse: when the distance to an object is *extremely* large, then ($1/d_{object}$) *is extremely* small, and for practical purposes can be said to equal zero. For this special case the lens equation then simplifies to:

$$\frac{1}{f} = 0 + \frac{1}{d_{image}} \qquad \text{or merely} \qquad f = d_{image}$$

In other words, when we look at an object very far away, the image is formed at the **focal plane** - the plane one focal-length away from the lens. Since everything we look at in astronomy is very far away, images through a telescope are *always* formed at the focal plane.

Let's now look at an object that is far enough away to treat it as being "at infinity." Remove the flashlight and mount from holder #1. Instead, use the large object box *at the other end of the table*. It should be at least 3 meters (10 feet) from your optics bench. Focus the screen. Your arrangement should look like the following:

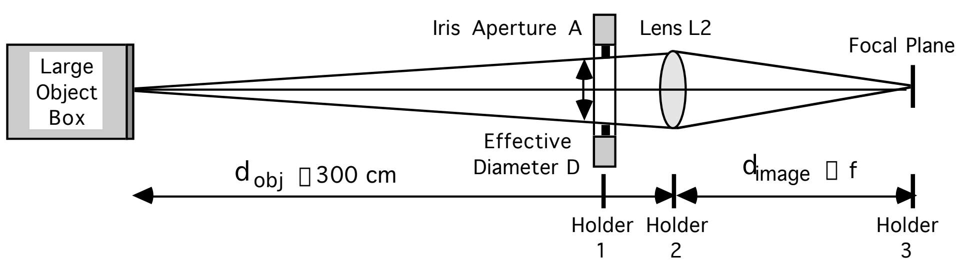



III.4 Is the image distance approximately equal to the focal length of the lens?

## Part IV. Lens Diameter and Focal Ratio

Another important property of a lens is the size of its **aperture**, or diameter *D*.

IV.1 Place the iris aperture A in holder #1. Slide the aperture holder until it is just in front of the lens. Your arrangement should look like this:




If you close, or **stop down** the iris, you effectively reduce the diameter of the lens (that is, you reduce the portion of the lens that actually "sees" the light).

IV.2 Analyze the effect of reducing the aperture: As you slowly stop down the lens, what happens to the brightness of the image?

IV.3 Does the image distance change? That is, does the **focal plane** (where the in-focus image is formed) shift when the lens diameter is decreased?

IV.4 Does the image size shrink with smaller aperture? Does a portion of the image get "chopped off" because of the smaller lens opening?

Although you may be surprised at these findings, they merely point out the fact that *each tiny portion of a lens forms a complete image*; the final observed image is simply the sum of all of the independent contributions!

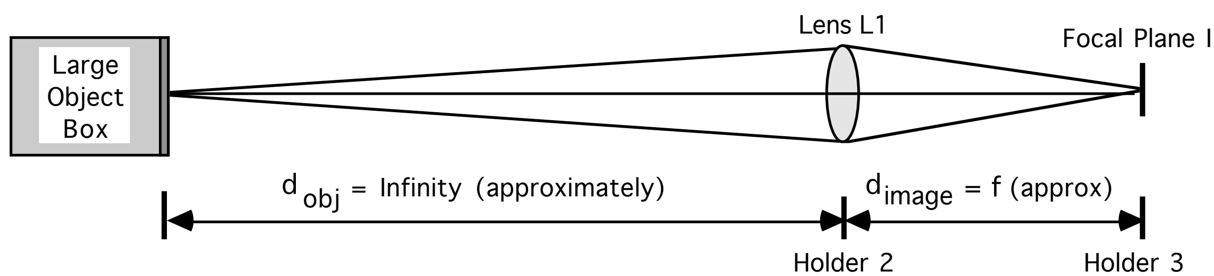
The **brightness** of an image formed by a lens (amount of light per unit area) is actually determined by the *ratio* (called the **f-ratio)** of the len's focal length to its effective diameter. This ratio is of great importance to astronomers and photographers, since it determines how faint we can observe:

$$\text{f-ratio} = \frac{f}{D} \quad . \qquad \text{(Equation 4)}$$

IV.5 As you stop down the aperture, are you increasing or decreasing the f-ratio of the lens? Do larger f-ratios produce brighter or darker images?

**Part V. The Refracting Telescope**

V.1 Assemble the optical arrangement: install lens L1 in holder #2, the image screen I in holder #3, and position the object box at least 3 meters (10 feet) from the lens.




Use the following table to keep track of your measurements for Part V:

| Lens & Eyepiece | Lens position | Image distance | Focal length (objective ) | Focal length (eyepiec e) | Lens separat ion | Magnification (estimated) | Magnification (calculated) |
|---|---|---|---|---|---|---|---|
| L1 & E1 | | | | | | | |
| L2 & E1 | | | | | | | |

We'll assume that the box represents an object "at infinity", so that when you measure the image distance, you have also measured the focal length of the lens.

V.2 Determine the focal length of lens L1 by focusing the screen and measuring the lens-to-image distance.

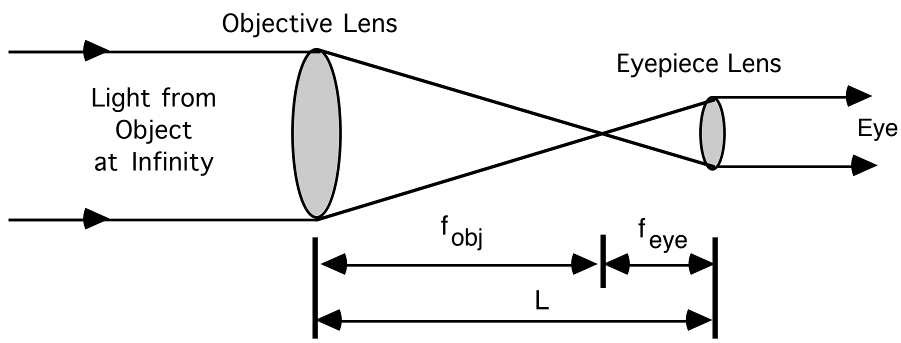
If the screen were not present, the light rays would continue to pass through and beyond the focal plane. In fact, the rays would diverge from the image exactly as if it were a real object, suggesting that *the image formed by one lens can be used as the object for a second lens.*

V.3 Remove the white card from the screen to expose the central hole. Aim the optics bench so that the image disappears through the opening.

V.4 Place your eye along the optical axis about 20 cm behind the opening in the screen. You'll be able to see the image once again, "floating in space" in the middle of the opening! Move your head slightly from side-to-side; confirm that the image appears to remain rigidly fixed in space at the center of the hole. (By sliding the screen back and forth along the rail, you can observe that the opening passes around the image, but the image itself remains stationary as if it were an actual object.)

The *real* object appears small to the unaided eye because it is far away. The *image* of that object is nearby, but is too tiny to show much detail. A magnifying glass would be helpful, since it would allow you to inspect the image more closely:

V.5 Remove screen I, and replace it with the magnifying lens E1. Observe through the magnifier as you slowly slide it away from the image. At some point, a greatly enlarged image will come into focus. Clamp the lens in place where the image appears sharpest. Your arrangement will be as follows.




You have assembled a **refracting telescope,** an apparatus which uses lenses to observe distant objects. The main telescope lens, called the **objective lens,** takes light from the object at infinity and produces an image exactly at its focal length $f_{obj}$ behind the lens. Properly focused, the magnifier lens (the **eyepiece**) does just the opposite: it takes the light from the image and makes it appear to come from infinity. The telescope itself *never forms a final image*; it requires another optical component (the lens in your eye) to bring the image to a focus on your retina.

To make the image appear to be located at infinity (and hence observable without eyestrain), the eyepiece must be positioned behind the image at a distance exactly equal to *its* focal length, $f_{eye}$. Therefore, the total separation $L$ between the two lenses must equal the sum of their focal lengths:

$$L = f_{obj} + f_{eye} \quad . \qquad \text{(Equation 5)}$$

V.6 Measure the separation between the two lenses, and use your value for the objective lens focal length to calculate the focal length of eyepiece E1.

In Part I, we used the term "magnification" to refer to the actual *size* of the image compared to the actual *size* of the object. This definition can't be applied to telescopes, since no final image is formed. Instead, we use the concept of **angular magnification**: the *ratio* of the angular size of an image appearing in the eyepiece compared to the object's actual angular size.

V.7 Visually estimate the magnification produced by the telescope: Look at the image through the eyepiece with one eye, while your other eye focuses directly on the object itself. Compare the relative sizes of the two views. Estimate how many times taller the image appears than the object. (This “double vision” technique takes a little practice; keep trying!)

The amount of angular magnification *M* can be shown to be equal to the ratio of the focal length of the objective to the focal length of the eyepiece:

$$M = \frac{f_{obj}}{f_{eye}}. \qquad \text{(Equation 6)}$$

V.8 Calculate the magnification using the ratio of the focal lengths of the two lenses, and compare with your visual estimate.

Equation (6) implies that if you used a telescope with a *longer* focal length objective lens (make $f_{obj}$ bigger), the magnification would be greater:

V.9 Replace objective lens L1 with objective L2, and focus the eyepiece again. Measure the lens separation *L*, compute the objective focal length, and calculate the magnification. Visually confirm your result using the "double vision" method.

But equation (6) *also* implies that you can increase the magnification of your telescope simply by using an eyepiece with a *shorter* focal length (make $f_{eye}$ smaller)!

V.10 Eyepiece E2 has a focal length of 1.8 cm. Use equation (6) to calculate what the magnification would be using eyepiece E2 with the objective lens L2.

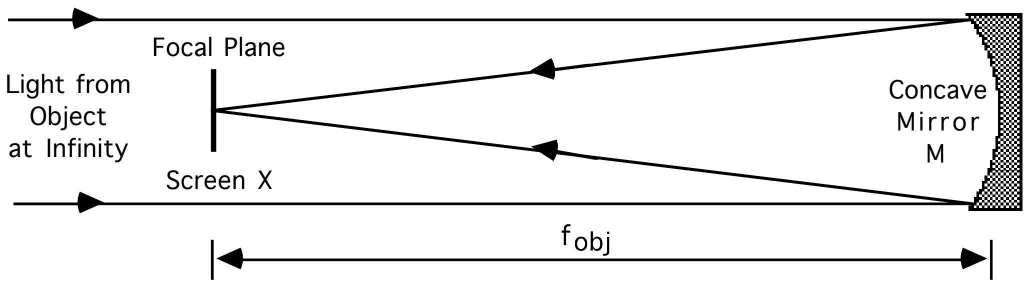
V.11 Replace eyepiece E1 with E2, and refocus. Does the image become bigger or smaller?

A *warning* to the telescope shopper! Some telescopes are advertised on the basis of their “high power.” From equation (6) you now know that a telescope can have a large magnification by using an eyepiece with a very short focal length. However, good short-focal-length lenses are difficult to make, and high-quality lenses are very expensive. A low-quality eyepiece will magnify the image, but it will only make a larger, fuzzy image rather than show more detail. So, if a manufacturer offers a telescope with “high power” optics, they may only be including a cheap short-focal-length eyepiece to try to impress the buyer, rather than promising a telescope with high-quality optics.

## Part VI. The Reflecting Telescope

Concave mirrored surfaces can be used in place of lenses to form **reflecting telescopes** rather than refracting telescopes. All of the image-forming properties of lenses also apply to reflectors, except that the image is formed *in front* of a mirror rather than behind. As we'll see this poses some problems! Reflecting telescopes can be organized in a wide variety of configurations, three of which you will assemble below.

The **prime focus** arrangement is the simplest form of reflector, consisting of the image-forming objective mirror and a flat surface located at the focal plane, as shown below. A variation on this arrangement is used in a **Schmidt camera** to achieve wide-field photography of the sky.




VI.1 Assemble the prime-focus reflector shown above:

° First, return all components from the optical bench to the stand.

° Then move holder #2 to the 80 cm position on the optics rail, and install the large mirror M into it.

° Carefully aim the mirror so that the light from the object is reflected straight back down the bench rail.

° Place the mirror/screen X into holder #1, with the white screen facing the mirror M.

° Finally, move the screen along the rail until the image of the object box is focused onto the screen.

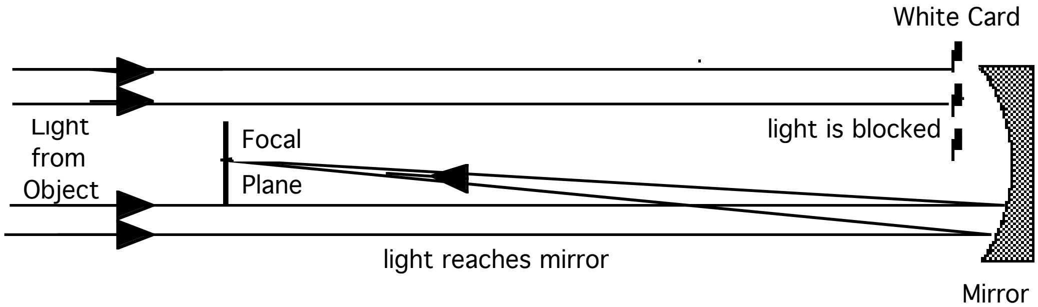
VI.2 Is the image right-side-up, or inverted?

VI.3 Measure the focal length of the mirror M (the mirror-to-screen spacing).

VI.4 The mirrored surface is 7.0 cm in diameter. Calculate the focal ratio (focal length divided by diameter) of the mirror M.

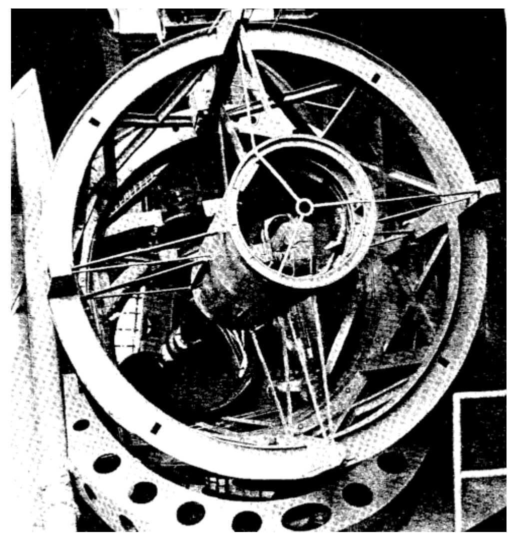
Since the screen X obstructs light from the object and prevents it from illuminating the center of the mirror, many people are surprised that the image doesn't have a "hole" in its middle.

VI.5 Hold the white card partially in front of a portion of the objective mirror, blocking off a portion of the beam. Demonstrate that *each small portion of the mirror forms a complete and identical image* of the object at the focus. (The principal difference between using the whole mirror rather than just a portion is that more light is collected, and therefore the image is brighter.)

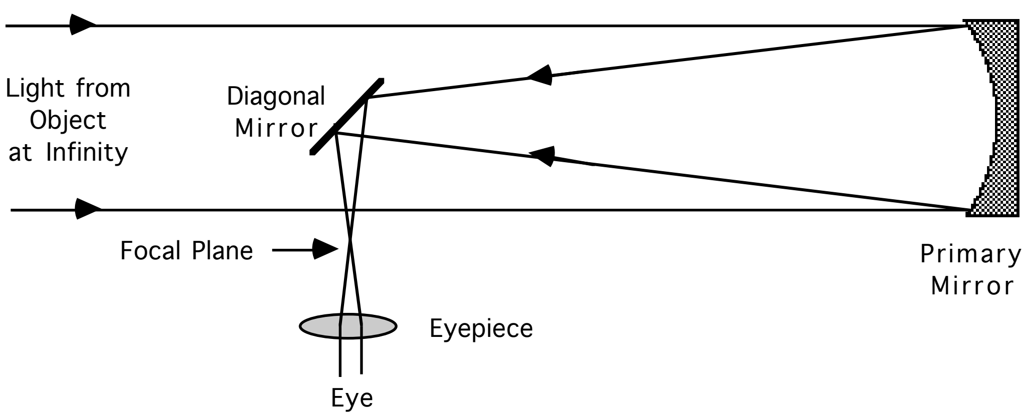



VI.6 Discuss the similarity between this phenomenon and your use of an iris aperture with lenses in Section IV.

The previous arrangement can't be used for eyepiece viewing, since the image falls inside the telescope tube; if you tried to see the image with an eyepiece your head would also block all of the incoming light! (This wouldn't be the case, of course, if the mirror were *extremely* large: the 200-inch diameter telescope at Mount Palomar has a cage in which the observer can actually sit inside the telescope at the focal plane, as shown here!)



Isaac Newton solved the obstruction problem for small telescopes with his **Newtonian reflector,** which uses a flat mirror oriented diagonally to redirect the light to the side of the telescope, as shown below. The image-forming mirror is called the **primary** mirror, while the small additional mirror is called the **secondary** or **diagonal** mirror.



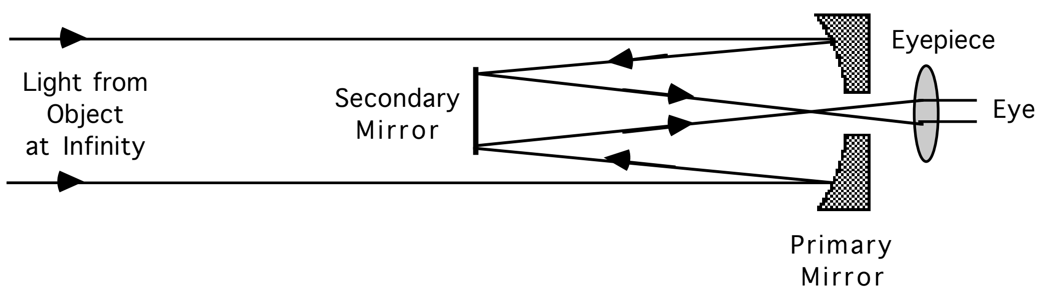
VI.7 Convert the telescope to a Newtonian arrangement. Reverse the mirror/screen X so that the mirror side faces the primary mirror M and is oriented at a 45° angle to it. Slide the diagonal approximately 5 cm closer towards primary. Hold the image screen I at the focal plane (see diagram) to convince yourself that an image is still being formed.

VI.8 Now position your eye a few cm behind the hand-held image screen, remove the screen, and look into the diagonal mirror; if your eye is properly placed and the optics are properly arranged, you can directly observe the image. Because you aren't using an eyepiece, you can also see the outline of the primary mirror, and the shadow of the diagonal.

VI.9 After you have located the image, try observing it through the (hand-held) eyepiece E1. When the image is in focus, why do you think you are no longer able to see the primary mirror or the diagonal?

VI.10 Calculate the magnification produced by this arrangement.

Large reflecting telescopes (including the 16-inch, 18-inch, and 24-inch diameter telescopes at Sommers-Bausch Observatory) are usually of the **Cassegrain** design, in which the small secondary redirects the light back towards the primary. A central hole in the primary mirror permits the light to pass to the rear of the telescope, where the image is viewed with an eyepiece, camera, or other instrumentation.




VI.11 Arrange the telescope in the Cassegrain configuration: Move the secondary mirror X closer to the primary mirror M until the separation is only about 35% of the primary's focal distance. Reorient the secondary mirror to reflect light squarely back through the hole in the primary, and visually verify the presence of the image from behind the mirror. (Note - it can be difficult to get all of the components aligned just right - keep trying!)

VI.12 Install eyepiece E1 into holder #3, and focus the telescope. Both visually estimate the magnification, and calculate the magnification using equation (6).

VI.13 Why doesn't the hole in the primary mirror cause any additional loss in the light-collecting ability of the telescope?

VI.14 Think of some possible advantages of the Cassegrain's "folded optics" design over the Newtonian design for large telescopes. Some points to consider: how much room does it take up? where does an observer get to stand? what if you wanted to mount heavy instruments, instead of an eyepiece, on the telescope?

## Part VII. Follow-up Questions

VII.1 You now know the importance of focal length when choosing a telescope. The other factor to consider is the telescope's light-gathering power (LGP) which is proportional to the square of the diameter of the lens or mirror. What is the LGP of the SBO 16-inch telescope compared to that of the human eye (which has a diameter of about 5 mm)? What about the 24-inch compared to the 18-inch?

VII.2 The 18-inch telescope at SBO can be used in either f/8 or f/15 mode (this means you can have an f-ratio of 8 or 15). It also has a choice of eyepieces with focal lengths ranging from 6 mm to 70 mm. You are planning on looking at some features on the surface of the Moon. First you need to orient yourself by identifying the maria (large dark regions). Which mode of the telescope do you use, and which eyepiece? Explain.

Now that you have oriented yourself, you want to find a rille (a trench on the lunar surface). Which mode and which eyepiece do you choose now? Explain.

VII.3 Most Cassegrain telescopes use curved mirrors for both the primary and secondary as shown in the diagram below. The arrows indicate the path of light through the telescope. The dashed line shows where the image from the primary mirror would be if there were no secondary mirror. How far is the final image from the secondary mirror in this telescope? Assume you have an f/8 primary mirror (i.e. the f-ratio is 8) with a diameter of 1 meter, an f/6 secondary mirror that is 1/3 the size of the primary, and the mirrors are separated by 2 meters (Note: the diagram is not drawn to scale).