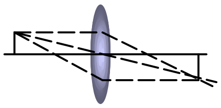


Geometric Optics

I. OBJECTIVES

Galileo is known for his many wondrous astronomical discoveries. Many of these discoveries shook the foundations of Astronomy and forced scientists and philosophers alike to rethink their beliefs. The argument that Earth had to be the center of the universe because the moon orbited it and would be left behind if Earth moved through space fell by the wayside as Galileo reported four moons orbiting a moving Jupiter. The belief that heavenly objects must be perfect spheres was completely refuted by Galileo's reports of craters and mountains on the moon. Scientists were astounded when they heard about the mysterious phases of Venus and sunspots! These discoveries were all made possible by the telescope, which although he did not invent, Galileo pointed to the sky.

The purpose of this lab is to acquaint you with the basics of lenses and mirrors and how they can be used to magnify and clarify objects. By the end of this lab, you will be able to:

- Find the focal lengths of lenses and mirrors;
- Draw and understand ray diagrams; and
- Build a simple telescope

II. PRE-CLASS PREPARATION

A. Concepts. Read section III of this lab concerning geometric optics. Understand what is meant by the terms refraction, reflection, concave, convex, convergent, divergent, lens, mirror, ray tracing, magnification and telescope. Review all rules of ray tracing and all sign conventions for lens and mirror equations.

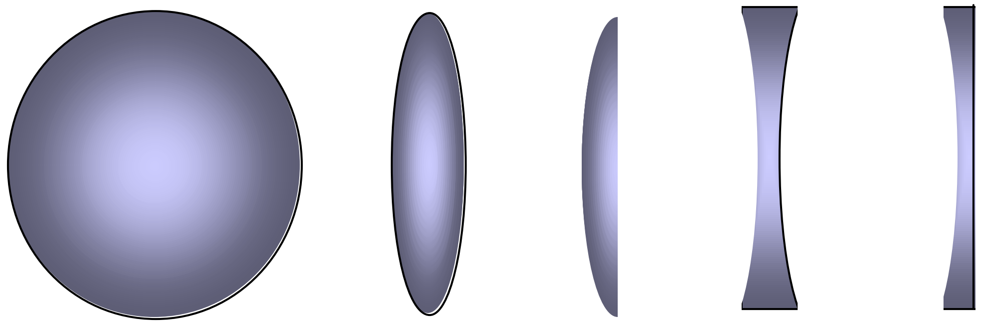
Read the experimental Error appendix and understand what is meant by accuracy and precision.

B. Apparatus. Make sure you understand lenses and mirrors and how to accurately and precisely use a ruler.

III. OPTICS

A. Lenses and Ray Diagrams. When light passes from one medium to another (say from air to glass), part of the incident light (incoming light hitting the boundary) is reflected at the boundary while the rest passes into the new medium. If the ray of light is incident at an angle to the boundary (other then perpendicular), the ray of light is bent, or **refracted**, as it enters the new medium. The angle of refraction is based upon the composition of the two media and the angle of incidence.

Lenses use refraction to **converge** (focus) or **diverge** (spread apart) incident light. Lenses have been used for telescopes, microscopes, binoculars, and a variety of medical instruments. The earliest record of lenses used for eyeglasses dates to the late thirteenth century, although rounded gemstones used for magnifiers probably date from much earlier.

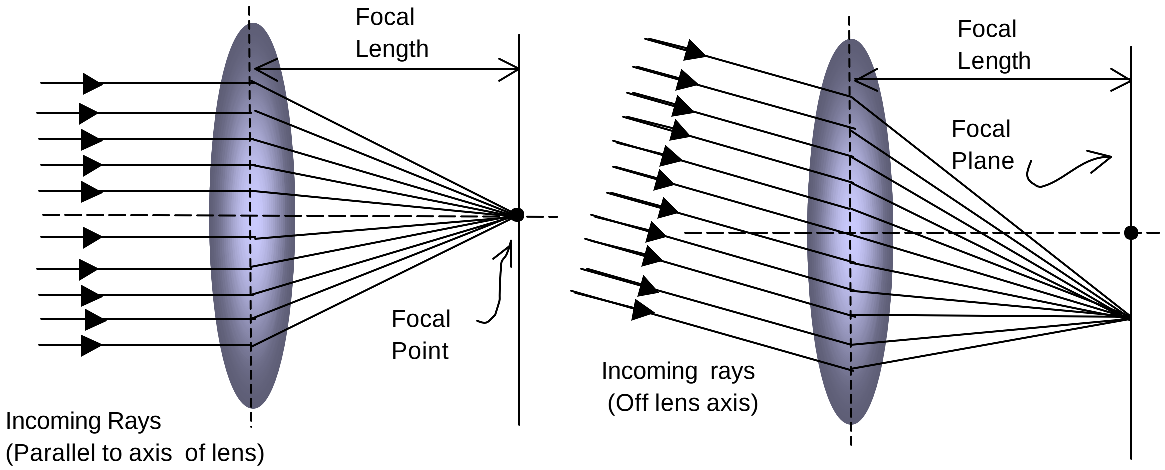


Face-on view of a lens: a disk of transparent material (usually glass) whose surfaces have been ground and polished into a curve.

Edge –on view: The edge-on view of a lens depends on the type of curve which has been ground and polished onto its surface

A thin lens is usually circular with two faces that are portions of spheres. These faces can be concave, convex or plane.

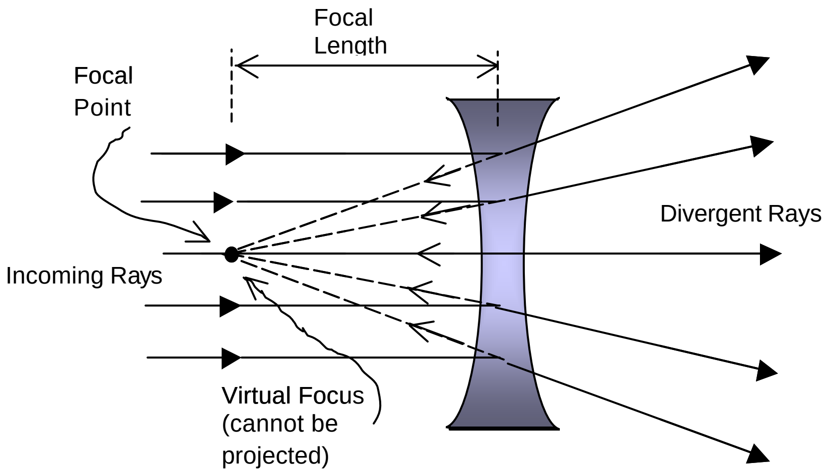
Convex lenses (those thicker in the center than at the edges) are called converging or convergent lenses because they make parallel light rays converge. If parallel rays of light fall on the convex lens, they will be focused to a point called the **focal point** (**F**). The rays from a very distant object are essentially parallel, and therefore, the focal point is also the image point for an object at infinity (infinitely distant) on the principle axis (labeled axis in Figure 2). When the light comes in at an angle, the image is formed within the **focal plane** at the image point. The focal point is in the focal plane along the principal axis Thus, the focal point of the lens can be found by finding the point where a distant object is brought to sharp focus. The distance between the center of the lens and the focal point is called the **focal length (f).** The focal length of the lens is the same on both sides of the lens.



Convergent Lens

Convex lenses are ***convergent*** that is to say, after passing through the glass, light rays are brought together (I.e., come to a ***focus***). Rays from distant objects are always parallel and parallel rays always come to a focus at the ***focal plane*** of the lens.

Concave lenses (those thinner in the center than at the edges) are called diverging or divergent, because they make parallel light rays diverge. The focal point, F, of a diverging lens is defined as the point from which the refracted light appears to emerge. The distance from the focal point to the center of the lens is called the focal length, f.



Divergent Lens

The lens is ***concave*** on both sides. Light rays which have passed through the lens ***diverge*** (spread out) and will not produce a real image. This type of lens has a ***virtual*** focal point on the same side as the object.

Ray diagrams can be used to find focal points, focal lengths, image points, and magnifications. When drawing a ray diagram, it is important to understand the “rules” of ray tracing.

1. A ray parallel to the principle axis will emerge from the lens refracted to pass through the principal focus (focal point F).

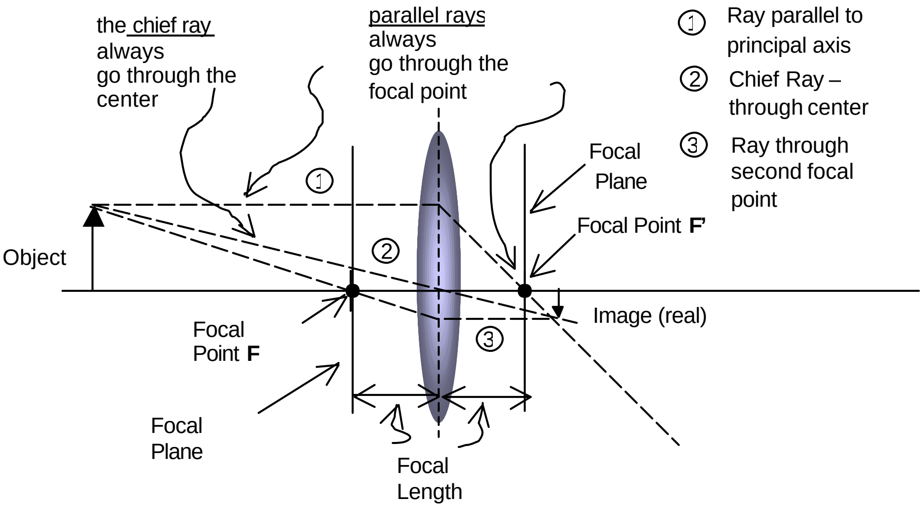
2. The Chief ray will pass from the object through the optical center of the lens undeviated.

3. A ray which passes through the focus (the front focal point F) will emerge from the lens parallel to the principal axis.

4. The intersection of two or more rays will define the location and size of the image.

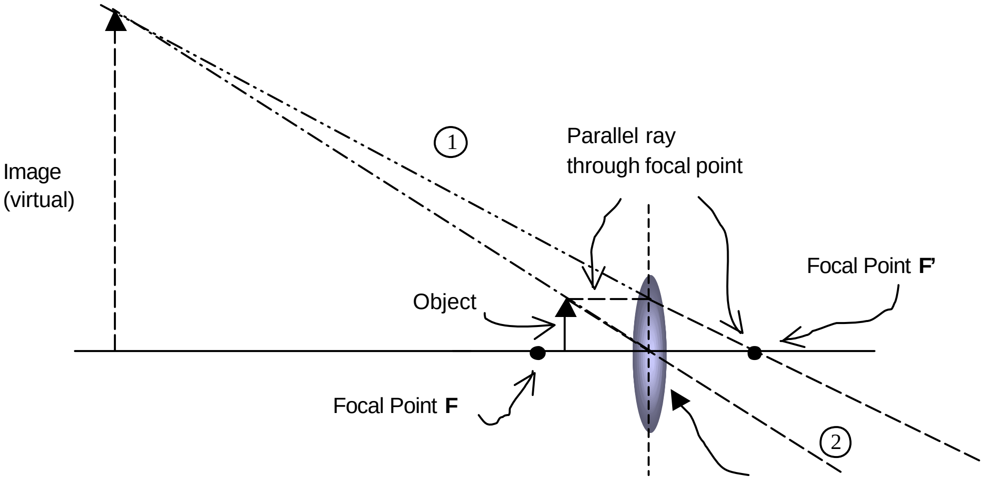
5. When an object is within the focal length of the lens, the rays are not bent enough for them to intersect. Use a ruler to trace the refracted rays backwards to find the **virtual** image. (Note: rule #3 does not work in this case).

When light converges to a point, it is called a **real** image point. In a diverging system, the light seems to diverge from a point and is called a **virtual** image point. A virtual image can still be seen by looking through the lens towards the object. An ordinary magnifying glass is an example of this principle. The object is magnified into a larger virtual image. The eye does not distinguish between real and virtual images.



Converging Lens

The lens is ***convex*** on both sides. An object ***outside*** the focal point will form a ***real*** image on the opposite side of the lens from the object. *A **real image** is one that can be projected on a screen*.



Magnifier

An object ***inside*** the focal point will form a ***virtual*** image on the same side of the lens as the object. *A **virtual image** cannot be projected; it can be seen only through the lens*

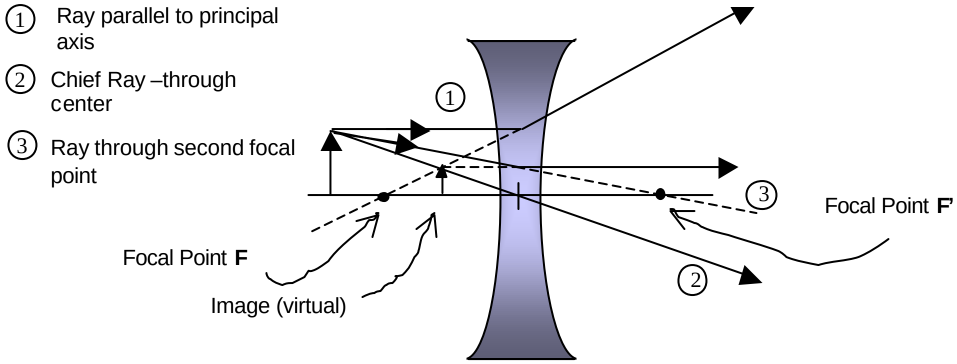


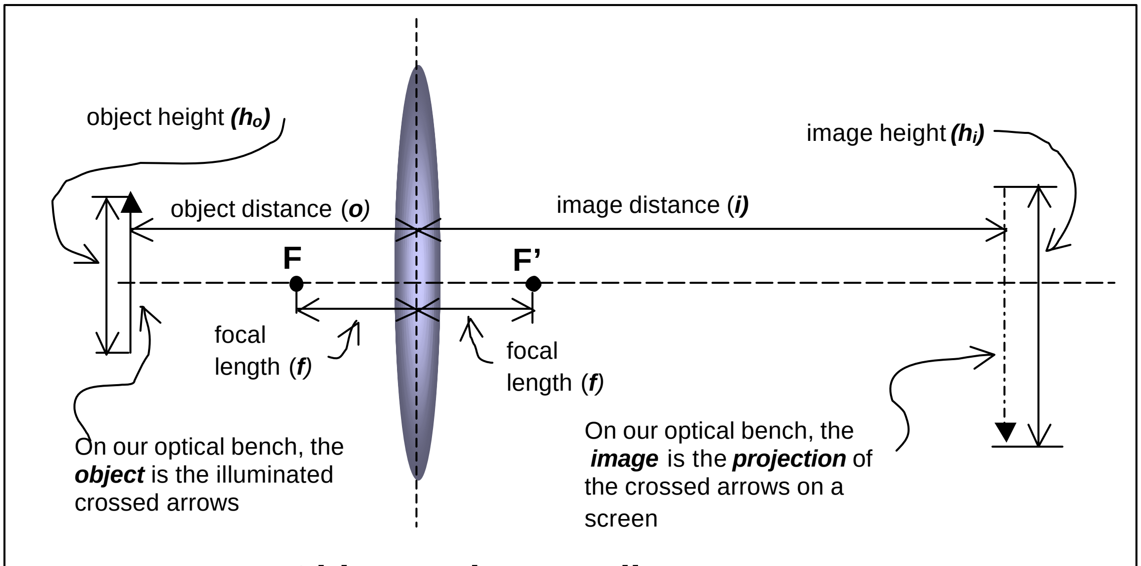
Image Formation by a Divergent Lens

The image formed by a ***divergent*** (concave surface) lens is ***virtual***.

The focal length is related to several other measurements by simple equations. The most useful equation in geometric optics is known as the Lens Equation and states:

$$\boxed{\frac{1}{o}+\frac{1}{i}=\frac{1}{f}}$$

where ***o*** is the distance between the lens and the object, ***i*** is the distance between the lens and the image, and ***f*** is the focal length of the lens. Note that if the object is very far away, o is very large, so1/o is very small. Therefore, an object infinitely far away will have an image distance equal to its focal length (as was stated earlier).



Object and Image distances

When working with physics equations, it is important to note that positive (+) and negative (-) signs only indicate direction. Therefore, it is important to note directions (signs) that are conventional in geometric optics.

- The focal length for a converging lens is always positive, while the focal length for a diverging lens is always negative.
- The object distance (o) is positive if the object is on the same side of the lens as the light source; otherwise it is negative.
- The image distance (i) is positive if the image is on the opposite side of the lens from the light source; otherwise it is negative. Therefore, the image distance is positive for a real image and negative for a virtual image.
- The height of the image, h_i is positive if the image is upright and negative if it is inverted with respect to the object. The object height, h_o, is always positive.

Using these conventions, the magnification, m, is defined by the equation:

$$\boxed{m=\frac{h_i}{h_o}=-\frac{i}{o}}$$

The magnification is positive for an upright image and negative for an inverted image.

B. Mirrors and Ray Diagrams. Most people are used to looking at flat mirrors. However, for astronomy curved mirrors are more practical. Mirrors, like lenses, can be made concave or convex. Convex mirrors are not very useful for focusing light, so most mirrors used by astronomers are concave. Concave mirrors have reflecting surfaces that curve inward (like the inside of a sphere) so that the center of the mirror sinks away from the viewer. These types of mirrors are commonly used as shaving or makeup mirrors as they magnify images.

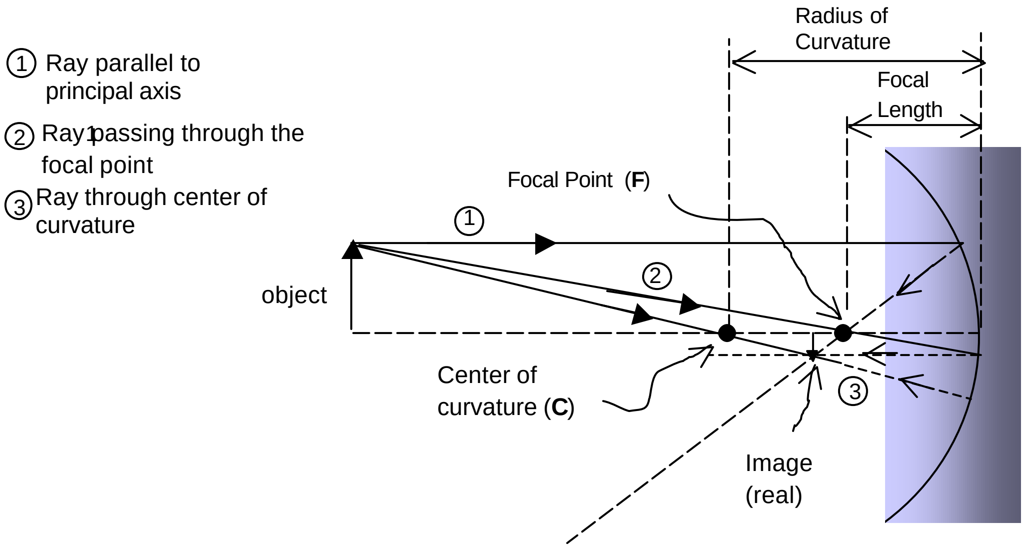
Of parallel rays of light fall on a concave mirror, they will be focused to a point called the focal point F, only if the mirror is small in width as compared to its radius of curvature. A large concave mirror will not focus precisely at a single point, however, if the mirror is small compared to its curvature, the rays will cross in a very small area (nearly a point). The rays from a very distant object are essentially parallel, and therefore, the focal point is also the image point for an object at infinity (infinitely distant) on the principal axis. Thus, the focal point of the mirror can be found by finding the point where a distant object is brought to sharp focus. The distance between the center of the mirror and the focal point is called the **focal length, f. The focal length is always half the radius of curvature**.

As with the lenses, there are “rules” for drawing ray diagrams using concave mirrors.

1. A ray parallel to the principal axis will reflect from the mirror through the principal focus (focal point F)

2. A ray which passes through the focal point (F) will reflect parallel to the principal axis.

3. A ray perpendicular to the mirror will reflect back on itself and pass through the center of curvature (C).



Concave Mirror – Object at Finite Distance

Image formed when object is a finite distance from mirror (greater than the radius of curvature)

4. The intersection of two or more of these rays will define the location and size of the image.

5. When an object is within the focal length of the mirror, the rays are not bent enough for them to intersect. Use a ruler to trace the reflected rays backwards to find the virtual image behind the mirror.

The mirror equations are identical to the lens equations.

$$\boxed{\frac{1}{o}+\frac{1}{i}=\frac{1}{f}} \quad \text{and} \quad \boxed{m=\frac{h_i}{h_o}=-\frac{i}{o}}$$

The sign conventions are similar with one exception. The image and object distances are positive if the image and object are on the reflecting side of the mirror.

IV. EQUIPMENT FOR THE LAB SESSION

Be careful with the optics! Touching the lenses and mirrors will leave fingerprints, oil, dirt, and smudges on the optics. This can damage the optics and can cause your experiments to falter.

Ray box
Bi-Convex lens cross section
Bi-Concave lens cross section
Semi-Circular lens cross section
Lamp
Optical Bench
Graph Paper
Calculator

Lens Holders
Convergent Lenses (Lens 1 and Lens 2)
Divergent Lens (Lens 3)
Concave Mirror
Object (crossed arrows with lamp)
Ruler
Screen (8" x 10" white paper on cardboard)

V. THE LAB LESSON

A. RAY BOX Tracings

STEP 1: Set up the ray box with 5 parallel rays showing on a piece of paper. Place the bi-convex lens section between the middle of the page and the ray box, such that the length of the plate is perpendicular to the rays.

Adjust the lens such that the center is ***not*** deflected (it goes straight through). All of the rays should **converge** to a common point. Mark this point and label it "**F**" (focal point).

Trace the outline of the lens. Trace the rays from the ray box to the lens and from the lens to the focal point.

Remove the lens. Draw a straight line down the center of the length of the lens. Using a ruler continue the ray tracings as dotted lines to the center line you just drew.

Label this ray tracing paper as **Convergent**. Measure the distance from the centerline through the lens to the focal point along the center ray. This is the focal length of the lens. Label the focal length and label all of your other measured lengths.

STEP 2: Set up the ray box with 5 parallel rays showing on a new piece of paper. Place the bi-concave lens section between the middle of the page and the ray box, such that the length of the lens is perpendicular to the rays.

Adjust the lens such that the center ray is ***not*** deflected (it goes straight through). All of the rays should **diverge** from parallel.

Trace the outline of the lens. Trace the rays from the ray box to the lens and from the lens to the edges of the paper.

Remove the lens. Draw a straight line down the center of the length of the lens. Using a ruler, extend the diverging rays towards the central, common point they seem to be coming from and label it "**F**" (focal point). (This should be on the same side of the lens as the parallel rays.)

Label this tracing paper as **Divergent**. Measure the distance from the lens centerline to the focal point along the center ray. This is the **focal length (f)** of the lens. Label the focal length and label all of your other measured lengths.

STEP 3: St up the ray box with 5 parallel rays showing on a new piece of paper. Place the concave mirror between the middle of the page and the ray box.

Adjust the mirror such that the center ray is reflected straight back towards its origin. All of the rays should **converge** to a point.

Trace the outline of the mirror. Trace the rays from the ray box to the mirror and from the mirror through the convergent point. Label this focal point "**F**".

Label this tracing paper as **Convergent Mirror**. Measure the distance from the mirror to the focal point along the center ray. This is the **focal length (f)** of the mirror. Label the focal length and label all of your other measured lengths.

B. Focal Length Method I: Using Distant Objects

STEP 4: Take your optical bench to the back of the lab (Carefully)! You will need three lenses. Lenses #1 and #2 are convex (converging lenses) and lens #3 is concave (a diverging lens). You will also need an 8.5 x 11" white screen. You should use the pull down screen in the front of the lab and the overhead projector.

Lens #1 should always have the longest focal length and lens #2 should always have the shortest focal length.

The front screen should be illuminated. Have one person from your group go to the front of the room and stand in front of he screen and wave his/her hand overhead.

Place lens #1 in a lens holder on the optical bench. Use lens #1 to focus the image of your classmate on the white screen. Move the lens so that the image is as sharp as possible.

Measure the distance between the lens and the white screen with the ruler on the side of the optical bench. Record the date below.

Focal Length (Lens #1) = _____________ mm

STEP 5: Remove lens #1 and replace it with lens #2. Repeat step 4 with lens #2. Record the data below.

Focal Length (Lens #2) = ______________mm

Which lens has the longer focal length? Is this lens more or less curved? Is there a correlation between curvature of the lens and the focal length? **Explain**!

STEP 6: Find the focal length of a **diverging** lens (lens #3) by placing it in contact with lens #2 (the diameter of this lens should be close to that of lens #3), and finding the focal length of the combined unit. Record your data below.

Focal Length (Lenses 2 and 3 combined) = ________________mm

Let f_2 = the focal length of lens #2 and let f_3 = the focal length of lens #3. Then $f_{ombined}$ = the focal length of lenses #2 and #2 combined. We know f_2 and $f_{Combined}$ and f_3 is unknown. Thus, find f3 using the equation:

$$\frac{1}{f_2}+\frac{1}{f_3}=\frac{1}{f_{combined}} \quad \text{solving for } f_3 \text{ we have} \quad \boxed{f_3=\frac{f_2 f_{combined}}{(f_2-f_{combined})}}$$

Record your data below.

Focal Length (f_3) = _____________mm

STEP 7: Determine the focal length of a concave mirror by shining a flashlight at the mirror. Use a transparency to find the focal length of the mirror.

Focal Length (mirror) = _____________mm

C. Focal Length Method II: Using the Optical Bench and Nearby Objects

STEP 8: Return to your table with your equipment Place a lamp at one end of your optical bench. Warning: The lamp gets hot, so pay attention not to burn yourself or set anything on fire!

Turn on the lamp with the inlaid crossed arrow and ball. Place lens #1 in the middle of the bench and an 8.5 x 11" screen on the opposite side of the bench from the lamp. Make sure they are all at the same height. Move the lens and screen until the image (of the object) is as sharp as possible. Measure the distances between the object and the lens, and the image (on the screen) and the lens. Record your data below.

Object Distance (o) = __________________mm

Image Distance (i) = ___________________mm

Use the equation below to solve for f_1, where f is the focal length of lens #1.

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f_1} \quad \text{or} \quad \boxed{f_1=\frac{oi}{(o+i)}}$$

Record your data below.

Focal Length (f_1) = _______________mm

STEP 9: Repeat Step 8 with lens #2.

Record the data below.

Object Distance (o) = __________________mm

Image Distance (i) = ___________________mm

Use the equation below to solve for f_2 where f is the focal length of lens #2.

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f_2} \quad \text{or} \quad \boxed{f_2=\frac{oi}{(o+i)}}$$

Record the data below.

Focal Length (f_2) = _______________mm

Now you have measured the focal length of lenses #1 and #2 by two different methods. In steps 4 and 5, the object was at a simulated infinite distance and the focal length was measured directly, while in steps 8 and 9, the object was at a finite distance and the focal length was calculated. Compare the two methods.

	Method 1 (steps 4 & 5)	Method 2 (steps 8 & 9)
f_1	_______________________	_______________________
f_2	_______________________	_______________________

D. Image Heights and Magnification

STEP 10: Using what you learned about lenses, set up your optical bench so that you form a **virtual** image using lens #2 (i.e., use the lens as a **magnifier**). **Draw a diagram of your setup in the box below.**

Lens #2 setup to give virtual image

Measure your distances:

Object Distance (o) = ___________________mm

Image Height (h_i) = _____________________mm

Object Height (h_o) = ____________________mm

Using the equation for magnification shown below, calculate the image distance (i).

$$\frac{h_i}{h_o} = \frac{i}{o} \quad \text{therefore} \quad \boxed{i = o\frac{h_i}{h_o}}$$

Image Distance (i) = ____________________mm

STEP 11: Using what you know about lenses, set up your optical bench so that you form a ***real image*** using lens #1. **Draw a diagram of your setup in the box below.**

Lens #1 setup to project real image

How is this setup different from the one in step 10?

Measure your distances using a ruler.

Object Distance (o) = ________________mm

Image Distance (i) = _________________mm

Object Height (h_o) = _________________mm

Using the equation for magnification below, calculate the image height (h_i)

$$\boxed{h_i = h_o \frac{i}{o}}$$

Image Height (h_i) = _________________mm

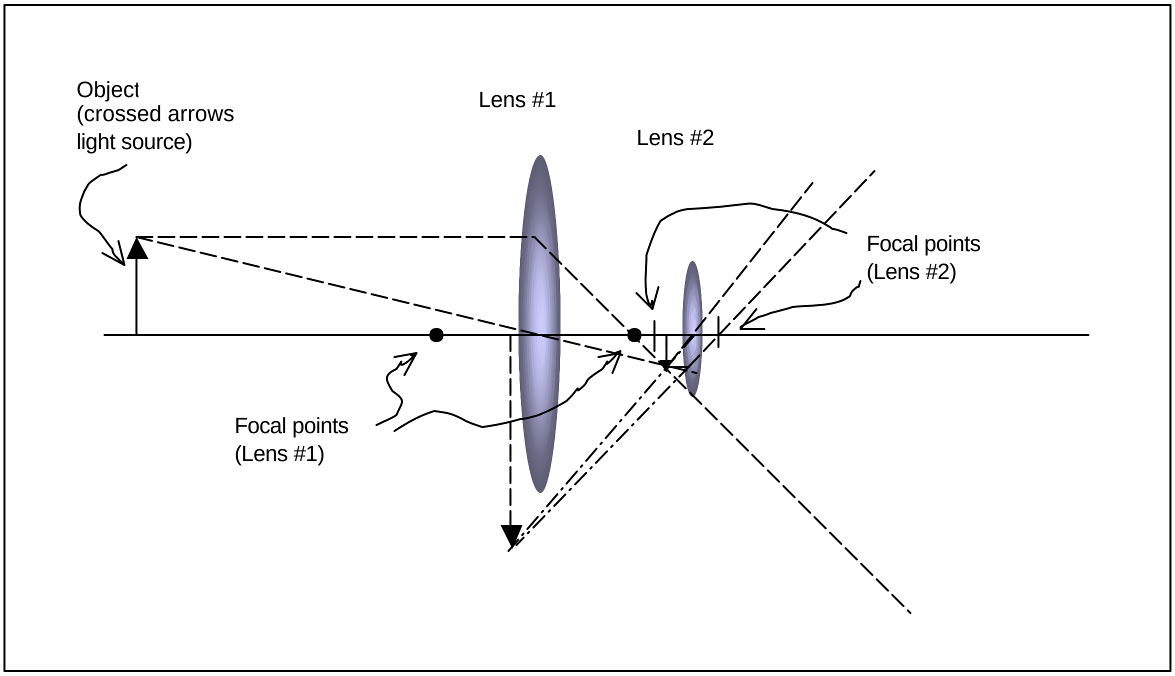
Compare the two image heights from steps 10 and 11. Which is better? Why?

E. Multiple Lenses: Making a Telescope

STEP 12: Using the setup from step 11, remove the screen and replace it with lens #2. Look through lens #2 and move it back and forth until you see can see a sharp image of the object (the crossed arrows). You are now using the *image* formed by lens #1 as the *object* for lens #2, and lens #2 is being used as a magnifier.

Is the image you see real or virtual? How can you tell?

The figure below is a ray trace diagram of your set up. ***Using this diagram explain how the telescope produces a magnified image of the object***. On the diagram, identify the ***image*** formed by lens #1, the ***object*** for lens #2 (they are the same), and the image formed by the combined set of lenses.



STEP 13: Remove the lamp from your optical bench. Find a distant object to view (hallway exit signs work well). Arrange your lenses so that you can see the object from a distance. This is a simple telescope.

Is the image of the target upright or inverted?

Does the target look bigger through your telescope or with the naked eye? Which way is it clearer?

Measure the distance between the objective lens (lens #1) and the eyepiece lens (lens #2).

Distance between lenses = _________________mm

(Note: The eyepiece moves closer to the objective lens as the **target** gets farther away.)

STEP 14: Determine the magnifying power of your simple telescope. Obtain the focal lengths for lens #1 and lens #2 from the results of steps 4 and 5. The equation for magnifying power is:

$$\textit{Magnifying Power} = \frac{\text{focal length of objective}}{\text{focal length of eyepiece}}$$

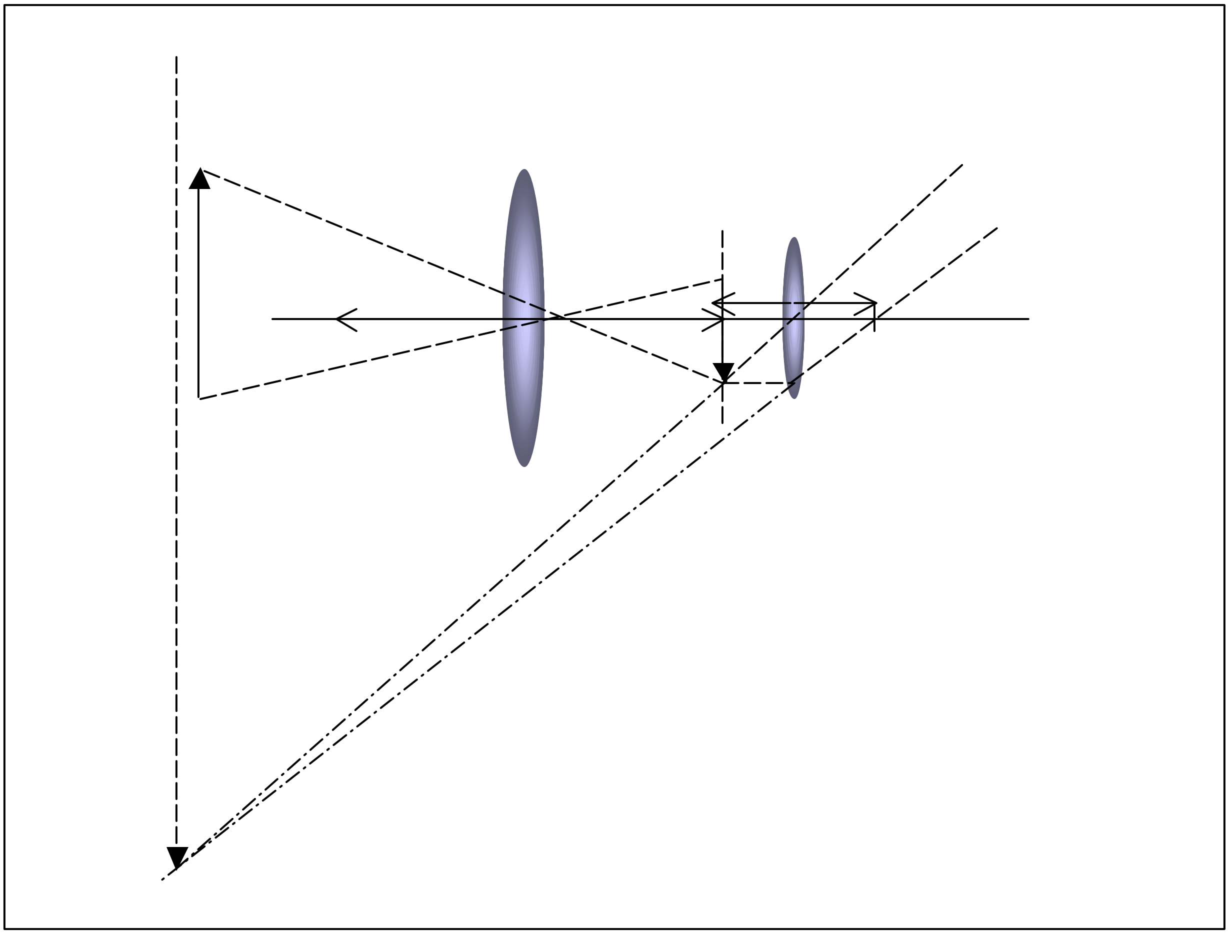
Magnifying Power = __________________

STEP 15: The diagram below depicts a simple telescope like the one you have been working with. **Label this diagram, identifying the following features**:

1. the objective
2. the eyepiece
3. the focal length of the objective
4. the focal length of the eyepiece
5. the focal plane of the objective
6. the object
7. the image formed by the objective
8. the image formed by the telescope

- Use a ruler to measure the lengths of the object and the image and then calculate the **magnification** of this telescope.

  Magnification:______________________



VI. DATA ANALYSIS

The objectives of this section are to organize your observations and then summarize your treatment of them. This section should include:

- data tables,
- observations,
- sketches,
- calculations,
- procedures you improvised, or are different from the write-up,
- comments on anything that may have adversely affected your measurements (accidents, mistakes, etc.)

VII. DISCUSSION

The primary objective of this section is to communicate the critical thinking that you applied to your data, predictions, and observations; that is, how you went beyond just mechanically performing the prescribed steps to get to the intended answer.

vQuestions in the lab (either throughout the lab, on worksheets, or in a discussion section). Make sure you don't miss any.

vWhat does your data tell you and why is it important?

vDiscuss the accuracy and precision of your measurements. Compare different methods of measuring and discuss them.

vWhat are the sources of random and systematic error that you found in this lab?

vWhat is the weakest aspect of your experiment? (Scientifically? Mathematically? Largest source of errors?)

vHow would you make this lab better? (Hint: how would you get rid of errors you have discussed?)

vSuggest future experiments that can build on your work.

vRelate the concepts in this lab to Astronomy and your everyday life. (Hint: How are lenses, mirrors, and optics used in Astronomy and in your life? Why are they important?)