PRINCETON UNIVERSITY **PHYSICS 104 LAB**
Physics Department **Week #9**

EXPERIMENT VIII
GEOMETRICAL OPTICS - OPTICAL INSTRUMENTS

Introduction Optics is a practical subject, leading directly as it does to the understanding of common optical instruments: eyes, eyeglasses, cameras, magnifiers, telescopes, projectors, microscopes, medical endoscopes.

This laboratory is the first of two in which we learn about the nature of light. This Lab explores Geometric Optics, *i.e.*, the simple assumption that light travels in straight lines called rays. Next week Lab 9 will explore Physical Optics, in which the wave properties of light are important..

Geometric optics rests on three simple assumptions:

1. That light travels in straight lines, called rays.
2. Light rays cross each other with no interference between them.
3. Whenever the rays strike the interface between two media in which the speed of light is different (*e.g.*, air-glass, glass-air, air-water, etc.) the rays bend (change direction), by an amount given by Snell's Law.

Snell's Law

Experimental verification of Snell's Law, measurement of an index of refraction and measurement of the angle of total internal reflection come in an optional addendum to this Lab.

It is customary to describe the bending (refraction) of rays of light by two angles: the angle between the incident ray and the perpendicular to the boundary; and the angle between the bent (refracted) ray and the perpendicular to the boundary.

As an example, in the figures below, Fig. 1a. shows a ray traveling through water at an angle of 30^o with the perpendicular to the boundary is bent as it crosses the interface into air, and now makes an angle of 41.7^o with the perpendicular. It does not make any difference which way the light is going—if from water to air (Fig.1a) and the angle in water is 30^o then the angle in air will be 41.7^o; if from air to water (Fig.1b) and the angle in air is 41.7^o, the angle in water will be 30^o.

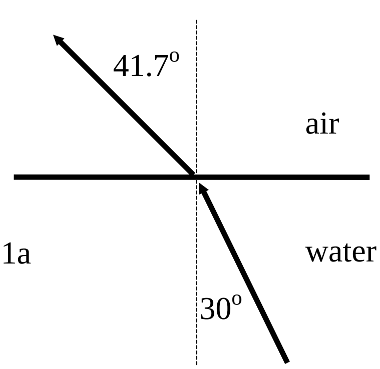


Fig. 1a

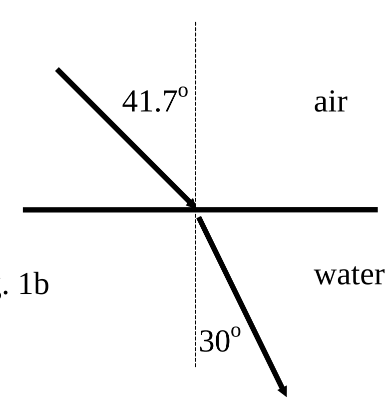


Fig. 1b

That is, for an air/water interface, the angle 30^{o} in water is permanently paired with the angle 41.7^{o} in air. The same is true for other pairs of angles. The nature of this pairing was a mystery until 1621 when Snell found the rule:

$$n_{air} \sin \theta_{air} = n_{water} \sin \theta_{water}.$$

Where "*n*" is the index of refraction which, as you see, figures prominently in the relation between the two angles. The index of refraction of a particular medium has a fundamental physical significance, in that it depends on the speed of light in the medium. It is defined by the equation $n = c/v$; where *c* is the speed of light in a vacuum and *v* is the speed of light in the medium. Every transparent material has its own index of refraction. The values of the indices of refraction for light of wavelength 450 nm are given in the table below for a variety of materials. Typically the index of refraction is larger for shorter wavelengths.

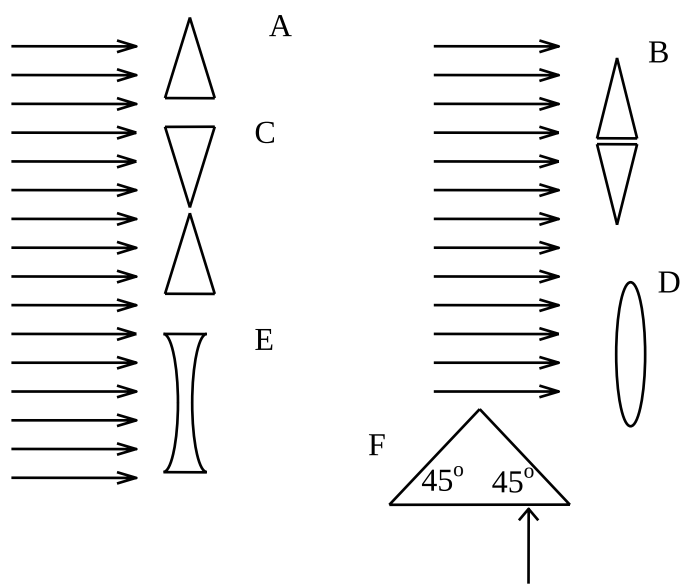
Vacuum (by definition)	1	Crown Glass	1.52
Air	1.0003	Crystalline Quartz	1.54
Water	1.33	Heavy Flint Glass	1.65
Ethyl Alcohol	1.36	Sapphire	1.77
Fused Quartz	1.46	Diamond	2.42

The index of refraction of air is so close to 1.00 that we take it to be 1 in this Lab.

1. Rays Passing Into and Through Variously Shaped Pieces of Glass

In the box on your lab bench, are several pieces of glass or glass-like plastic shapes. Using other apparatus on your bench, produce one or several rays as called for in the illustration to the right. Place the pieces, in turn, so that the ray (or rays) strike the glass as shown in the illustration.

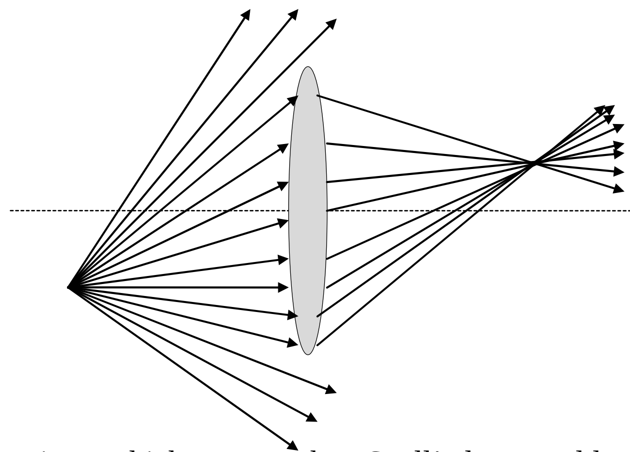
[To make configurations B and C, borrow a second prism from another group in the Lab.}



For each of the shapes above, first discuss with the other members of your group the direction you expect that the ray(s) will go after it (they) emerge from the glass, based on Snell's Law --- then observe how they actually do go in situations A through F. Each person on the research team should sketch the results in his/her lab book.

A triangular prism such a shape **A** deflects rays of light, and so can be regarded as a kind of building block to obtain converging or diverging rays, as illustrated by configurations B and C.

A lens does more than merely deflect rays of light. It can gather a bundle of rays coming from one point and bring them all together through another point. This requires are variable deflection of the rays, in amounts proportional to the distance between the center of the lens and the intercept of a ray with the lens. Optical elements with curved surfaces, such as D and E, accomplish this task.



Shape F provides an example of total internal reflection., which occurs when Snell's law would require $\sin\theta_{\text{refracted}} > 1$. Shapes like this one are used to turn light rays back on themselves --- they are used for folding a telescope into the size of a binocular.

2. Measuring the Focal Length of Lenses

2a. Using a Distant Object

1. Mount the screen and one of the two lenses provide, on the optical bench.

2. Use the pair of bright light bulbs in one corner of the Lab as the distant object, and focus their image on the screen. Measure the image distance *i* between the lens and the image on the screen, and the object distance *o* between the lens and the object, by pacing it off, or measuring it with the long measuring tape.

3. Compute the focal length *f* of the lens, using the (thin) lens formula: $\frac{1}{o}+\frac{1}{i}=\frac{1}{f}$.

Q: *Why is a crude measurement of the object distance adequate*?

Q: *How close does the image distance come to being equal to the focal length*?

4. Compute the lateral magnification, $m=\frac{|h_i|}{|h_o|}=\frac{|i|}{|o|}$, and measure it, if possible. Here, the object height h_o is the vertical separation of the two light bulbs.

2b. Using a Near Object

5. Mount the blacked-over bulb on the table-edge clamp, with its top facing the optical bench. The bulb should be about 10 cm beyond the end of the your optical bench. Place the screen at the other end and the lens in between. Slide the lens along the bench until it focuses an enlarged

image of the “15” on the screen (the wattage of the bulb). (You may have to adjust the height of the components to have the light through the lens fall on the screen.)

Q: *Is the image upright or inverted? Is it real or virtual?*

Now measure: lens-bulb distance o; lens-screen distance i; height of numerals on the screen, h_i; height of numerals on the bulb itself, h_o. Compute the focal length, compare it to the focal length you got using the distant light source. Calculate the lateral magnification directly using h_i and h_o. Compare it to the magnification computed from distances o and i.

Q: *There are two locations of the lens which yield a focused “15” --- why?* (Hint: Look at the lens equation.)

Q: *Would this second image be enlarged or reduced?* Try it.

6. Repeat steps 1-5 for the other lens.

3. Optical Instruments

What follows are a series of sections, each concerning a particular optical instrument. For each, the optical problem to which the instrument is a solution is stated. There then follows an explanation of how the instrument solves the optical problem, and instructions for constructing the instrument and exploring its use.

3a. Pinhole Camera

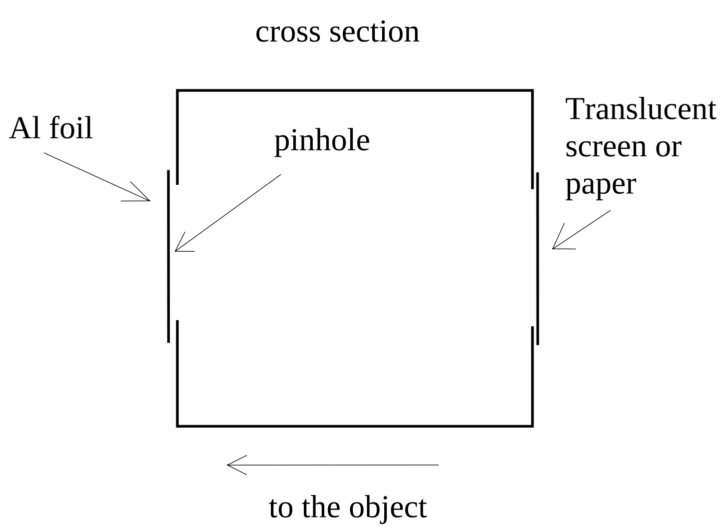
The optical problem: to create a real image on the screen of objects in front of the camera.

The pinhole camera is a simple device which depends for its operation solely on the first two assumptions of geometric optics: light travels in straight lines called rays; the rays cross each other without affecting each other. Construct and use a pinhole camera as described below.

1. Unfold the folded up box you were provided. Use the knife to cut two square holes (approximately 5 cm on a side) in two of the opposing faces.

2. Cover one of the holes with a piece of aluminum foil, and the other hole with a sheet of translucent paper or plastic --- non-shiny side to the outside. Use adhesive tape to hold them in place.

3. Make a pinhole in the aluminum foil, using a pin or needle. Your pinhole camera is now complete.



4. Use the pinhole camera to view (form a picture of) the filament of a clear glass light bulb, or the array of colored light bulbs, by pointing the pinhole side toward the bulb(s) and looking at the plastic covered hole, keeping it at a comfortable distance from your eye. Watch the image as you move toward or back away from the light bulb, or the array of colored bulbs. Have your partner stand in front of a spotlight and use the pinhole camera to see a picture of her/his face. Explore...

If there is daylight, see if you can get a picture of the outdoors, though the Lab window. You may have to put a black cloth over your head and the camera to ge block extraneous light, and you may even want to enlarge the pinhole slightly with a sewing needle to get a bit more light.

Q: *Were the images erect or inverted?*

Q: *Did the object have to be at any particular distance for the image to be in focus?*

For those of you who wear glasses to read, a pinhole held at your eye will serve in lieu of your eyeglass lens, if there is enough light. Try reading this writeup through a pinhole in a 3X5 card.

People with poor vision often squint their eyes in an attempt to see more clearly. In doing so, they use their eyelids to temporarily reduce the aperture of their eyes, making them into pinhole cameras.

[Camera is Italian for room – as in a small room in which someone would hide to spy on activities in the next room, viewed through a tiny hole in the wall.]

3b. A Camera with Lens

The optical problem: to create a bright, real image on the screen of objects in front of the camera..

A typical camera uses a lens of large diameter to gather more light than is possible with a pinhole camera. A simple camera consists of a converging lens and a box. The lens on one side of the box brings a real image of the objects in front of the camera to a focus (*i.e.*, to make the real image) on the opposite side of the box, where the screen (or film or CCD sensor) is. Since we want the real image exactly in the plane of the screen, focusing is important. The lens can be moved toward or away from the screen until the image distance (according to the lens formula) equals the distance from the lens to the screen.

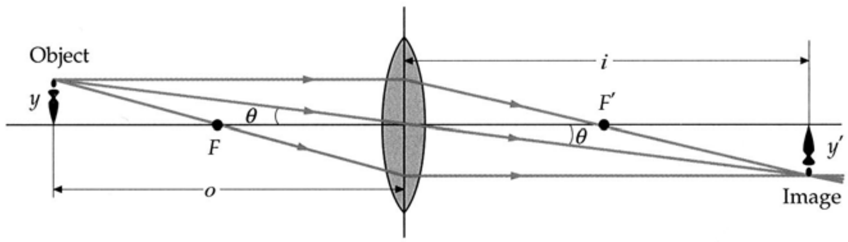
Using your pinhole camera, look once more at the scene outside, or your partner's illuminated face, or at one of the other bright objects in the room, to remind yourself of the brightness of the resulting images. Then remove the aluminum foil from your camera. Hold the stronger (shorter focal length) of the two lenses from your lab bench in front of the hole in the box of your camera, and move the lens toward and away from the hole in until you get a crisp image on the translucent screen.

Q: *What is the difference in the image between what you remember of the pinhole camera image and what you see now?*

3c. Projector.

The optical problem : to make a, much enlarged, real (inverted) image on a screen or wall at a great distance of a small picture (such as a 35mm slide).

The solution is to place the object to be magnified just outside the focal point of a relatively short focal length lens. The relatively short object distance (o), just outside the relatively short focal length (f), gives a very long image distance (i), and therefore a very large magnification ($m = h_i/h_o = y'/y$). The projectors in the Ph104 lecture hall and in movies theaters, *etc*., are based on this principle.



1. Using a 35 mm slide projector and a 35 mm slide, project the image of the slide on a wall or screen. Measure: the size of the picture on the 35 mm slide (h_o); the size of the picture on the wall or screen (h_i); , and the distance from the projector lens to the screen (i).

2. Compute and record the magnification. Compute and record the object distance (o); Compute and record the focal length (f) of the projection lens (assuming it to be a thin lens).

3d. The Eye as a Camera

The optical problem: The eye has a fixed image distance (i) but we want to be able to see clearly (bring into focus) objects over a great range of object distances (o).

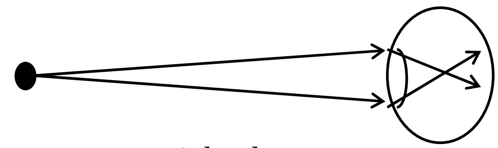
The eye is a camera with a fixed image distance (i), but in which the focal length (f) of the (converging) lens can be changed by muscular action. The change in shape changes the focal length and therefore its converging power (by a process called “accommodation”). When a normal eye is relaxed (least converging power, longest focal length) it can bring parallel rays (from an object at “infinity”, *i.e.*, very far away) to a focus on the retina. For nearer objects it can “accommodate” (*i.e.*, shorten its focal length, and increase its converging power) so that it can then bring the nearer objects (whose rays are more divergent) to a focus on the retina.

The normal eye can accommodate and produce an image on the retina for objects as close as 15 centimeters. The closest distance onto which the eye can focus is called the “near point”.

Measure your own near point without glasses: bring a book to where it is comfortable to read; now bring it even closer to your eyes so that it becomes uncomfortable to read, and somewhat blurry; Now move it back away from your eyes until it just becomes clear and comfortable to read. Have your partner measure the distance from the book to your eyes --- that is your “near” point distance. Record it since you will use it in calculating the magnification of a simple magnifier.

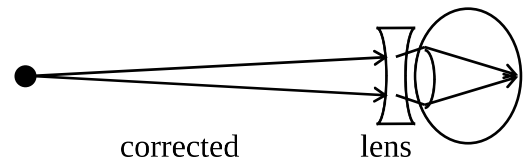
An eye that is not "normal" may have:

a) the "far point" too close (nearsightedness or myopia) so that it can not focus distant objects, this relaxed eye is too convergent.



nearsighted eye

Note that a near sighted eye was corrected by giving it a divergent (negative) eyeglass because its convergent power had to be reduced.

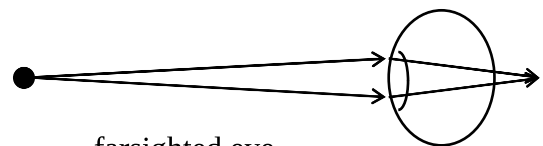


corrected nearsighted eye

lens

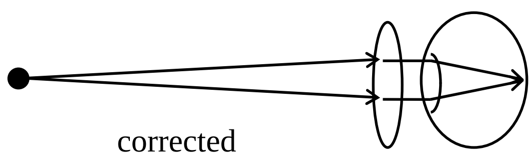
OR,

b) the "near point" too far (farsightedness or hyperopia), when the eye cannot become convergent enough to focus on close objects.



farsighted eye

Note that a farsighted eye which does not have sufficient converging power has its converging power added to by the addition of a converging (positive) lens.



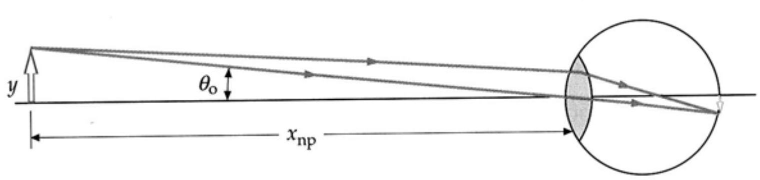
corrected farsighted eye

lens

3e. A Simple Magnifier (or Eyepiece)

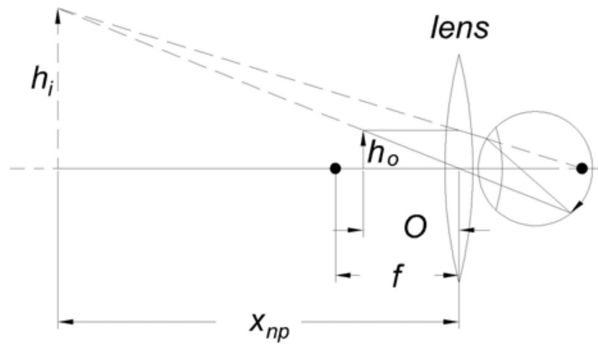
The optical problem: to make a nearby object appear larger.

To make an object appear larger to your eye, simply bring it closer. But once the object is at the near point of your eye, shown as x_{np} in the figure below, you cannot make it appear larger, by bringing it even closer, without it becoming blurry. So, the problem is the make the object appear larger and "sharp" = in focus.



The solution is a simple magnifier, which is converging lens, placed immediately in front of the eye's lens, where it adds to the converging power of the eye so that the object can be brought even closer than the near point and still be in focus on the retina.

In practice, you hold the magnifying lens close to your eye, and then move the object around until it appears the largest. This is accomplished when the object is slightly closer than one focal distance f in front of the magnifying lens, such that the virtual image is located at distance x_{np} from your eye, as shown in the figure below.



To use a virtual image in the lens formula, we treat the image distance x_{np} as negative. Hence,

$$\frac{1}{O} = \frac{1}{f} + \frac{1}{x_{\mathrm{np}}}, \qquad \text{so that} \qquad O = \frac{x_{\mathrm{np}} + f}{x_{\mathrm{np}} f}.$$

The angular size of the object is $\theta = h_o / O = h_o\left(x_{\mathrm{np}} + f\right) / x_{\mathrm{np}} f$. From the figure on p. 7, we see that without the magnifying lens, the maximal angular size of the object – when it is still in focus – is $\theta_0 = h_o / x_{\mathrm{np}}$. Hence, the resulting magnification factor is

$$m = \frac{h_o\left(x_{\mathrm{np}} + f\right) / x_{\mathrm{np}} f}{h_o / x_{\mathrm{np}}} = \frac{x_{\mathrm{np}} + f}{f}.$$

Most textbook derivations are slightly different. They suppose that you “relax” your eye when using a magnifier so that the image distance is ∞ rather than x_{np}. You can readily verify that this assumption leads to the prediction that the magnification is $m = x_{\mathrm{np}} / f$. After performing the experiment described below, comment as to which prediction is best for your eye.

1. Place one short piece of plastic ruler in a spring clip, and get as close to it as you can and still see it distinctly and comfortably (that is, place it a distance x_{np}).

2. Hold the shorter focal length lens in front of and close to one eye and bring the piece of plastic ruler as close to the lens as you can and still see its enlarged image through the lens distinctly and comfortably. Looking through the lens with one eye, and at another plastic ruler at your near point with the other eye you should see the magnified image superimposed on the non-magnified ruler. This is a bit tricky, as the two images tend to wander around, but with perseverance, it can be made to work.

3. Observe how many millimeters (or cm) on the scale seen through the lens corresponds to the millimeters (or cm) on the scale seen without the lens. This is the magnification. This cannot easily be done with high precision -- just try to get a good approximation, and compare it with the result gotten from the formula for magnification above.

Q: *What magnification did you expect? What magnification did you get?*

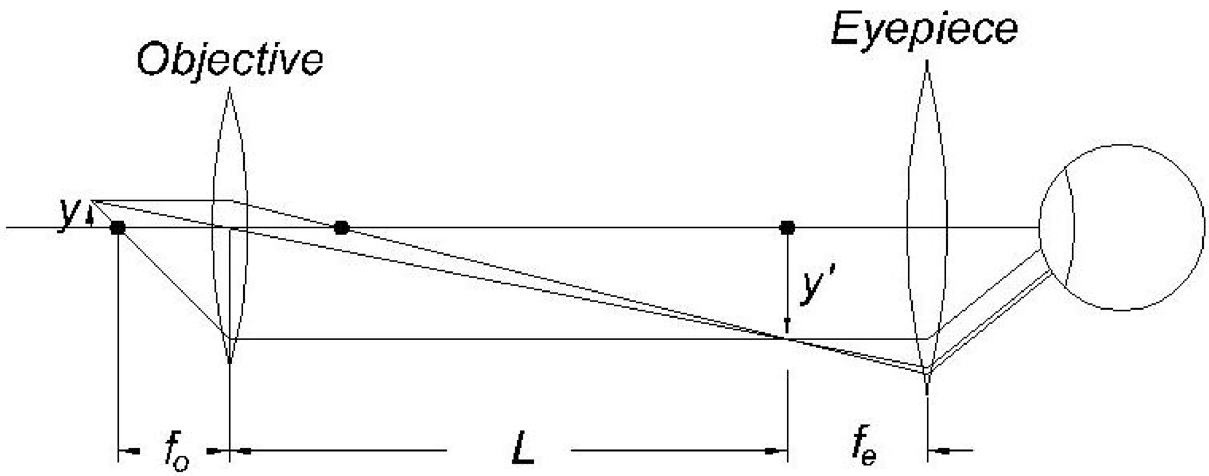
Each of you should make your own, albeit crude, measurement of the magnification

3f. Compound Microscope.

The optical problem : to obtain much more magnification of a small object than is possible with a simple magnifier.

Suppose we desire a magnification factor of 1000. To obtain this with a simple magnifer would require a lens whose focal length is 15 cm / 1000 = 0.015 mm, which is less than the diameter of a human hair.

The solution is a compound microscope, consisting of two lenses called the objective and the eyepiece, arranged as shown in the figure below.



The objective lens, of focal length f_o, acts as a kind of projection lens to create image y' of object y which is just over one focal distance from the lens. The magnification of this part of the microscope is $m_o \approx L / f_o$, where $L + f_e \approx L$ is the length of the microscope tube. Then, the eyepiece (whose focal length is f_e) acts like a simple magnifying lens on the image y' to provide an additional magnification factor of $m_e = x_{np} / f_e$. The combined magnification is therefore

$$m = m_o m_e \approx \frac{L x_{np}}{f_o f_e}.$$

Standard microscope eyepieces are marked with a magnification (*e.g.*, 10x) which is calculated by the ratio of 25 cm (the nominal value of the near point distance) to the focal length f_e. A 10x eyepiece therefore has a focal length of 2.5 cm.

Each of you should find a kit on your lab bench with parts for a compound microscope and Keplerian telescope, as detailed on the following page.

First, measure the focal lengths of the two lengths that you find in your kit.

To make a compound microscope you will need to combine parts from two kits. Use the inner tube from one kit, and the eyepiece lens (= smaller lens in the foam foam holder with tiny cardboard sleeve) from both kits. Insert one eyepiece in each end of the inner tube, and you have built a microscope. Take care that the axes of the two small lenses are aligned along the axis of the tube.

Use the partially blackend bulb as a (bright) object, again mounting it with a table-edge clamp so the axis of the bulb is horizontal. Mount the microscope tube horizontally on the optical bench using the forked clamp. Arrange the microscope to have its "obejective" lens close to the bulb. Slide the microscope clamps along the optical rail to focus the microscope (taking care that sideways motions are not too great in the process.

Learning Technologies, Inc.
40 Cameron Avenue ★ Somerville, Massachusetts 02144 ★ USA
Phone: 800-537-8703 or 617-628-1459 ★ Fax: 617-628-8606

PS-04B Refracting Telescope Kit (for 10)

Item#	Qty	Description
H-05	10	Foam Lens Holders
H-06	10	Lenses (43mm dia)
H-07	10	Lenses (17.5 mm dia)
H-11 A &B	10	Pairs of Telescoping Tubes
H-28	10	Eyepiece Spacers
H-32	1	Set of Instructions
H-39	10	Cardboard Washers
H-43	10	Plastic Caps

Refer to Figure 1 for the following instructions.

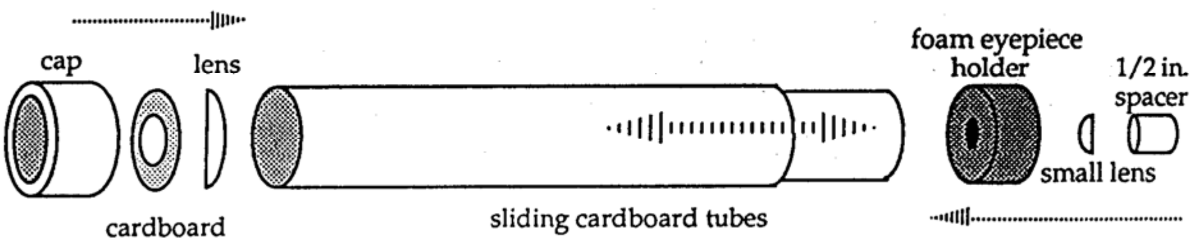


Figure 1

1. Pick up the large lens, being careful not to smudge it with your fingers. Fit the curved side of the lens snugly against the front of the outer tube, making sure it is positioned perpendicular to and centered on the tube. Slip the plastic cap over this end of the tube so that the lens is firmly held in place.

2. Using the small piece of cloth or tissue to prevent smudging, push the small lens into the foam lens holder.

3. Slide the spacer into the foam holder such that it pushes against the flat part of the lens. Push the spacer into the holder just far enough so the end of the spacer is flat with the end of the foam holder.

4. With the curved side of the lens facing toward the large lens, slide the foam holder into the end of the smaller of the sliding tubes. The foam holder should be flat with the end of the tube.

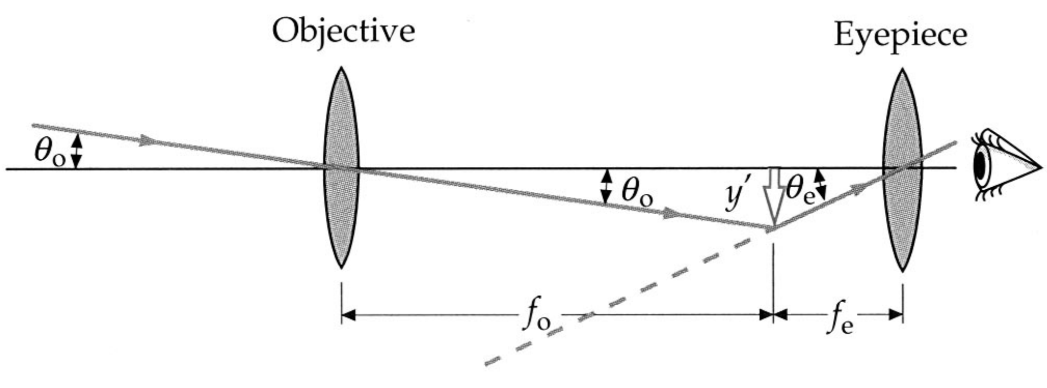
The magnification calculated from the above formula is quite high! Therefore, the field of view of your microscope is much less than the area of the clear partch on the bulb. To figure out what you are looking at, you may want to twist the microscope slightly so that you are viewing the edge of the bright patch on the bulb.

Once you identify some enlarged feature on the bulb, as viewed through your microscope, estimate the (angular) magnification of that feature.

3g. The Keplerian Astronomical Telescope

The optical problem : to magnify (spread it out over the retina) a distant object to which you can not get any closer.

When you wish to examine a distant object, such as the moon, or Jupiter and its moons, or Saturn and its rings, in more detail from earth, you do not have the option of moving it closer to your eye. You can however use a converging lens (the objective lens) to form a real image in front of your eyes. If you choose a lens of suitable focal length, the real image can be examined in more detail than can the original object. (*i.e.*, even with just an objective lens you can already have an angular magnification at the eye). But then of course you have one additional advantage, you can now examine the real image even better, by using a simple magnifier (called the eyepiece lens).



As is readily seen from the above figure of a Keplerian telescope, the angular magnification is

$$m = \frac{\theta_e}{\theta_0} = \frac{y'/f_e}{y'/f_o} = \frac{f_o}{f_e}.$$

Each person should construct his/her own telescope using the kits provided.

<u>NOTE: NEVER, REPEAT NEVER, LOOK DIRECTLY AT THE SUN WITH A TELESCOPE, OR FOR THAT MATTER, NEVER LOOK DIRECTLY AT THE SUN WITH THE NAKED EYE. YOUR MACULA COULD BE DESTROYED IN VERY FEW SECONDS AND WITH IT YOUR ABILITY TO READ</u>

1. Calculate the magnification you expect with your telescope, using the focal lengths that you have measured for the objective (larger lens) and the eyepiece (smaller lens)

2. Use your telescope to sight a distant object (outside if you can). Focus the image by sliding the inner tube in or out of the outer tube, as appropriate. A good place to start is with the inner tube slid out so that the distance between objective and eyepiece lens is greater than the sum of the focal lengths. Then slowly slide the inner tube in, until you have the focused image.

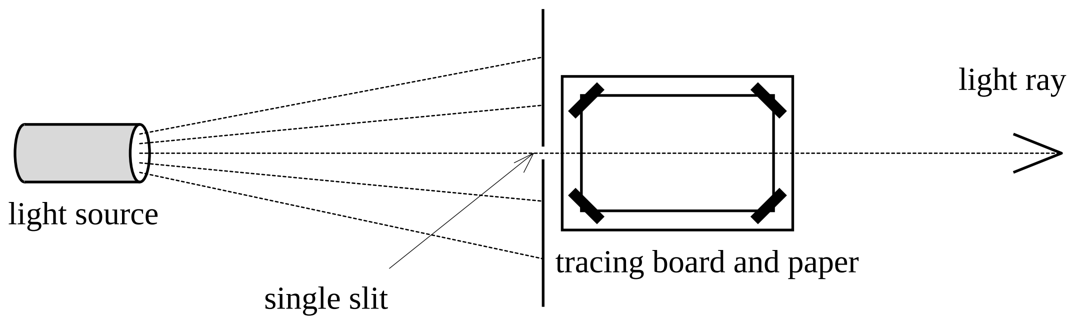
Q: *When you get it focused, do you find that what you see is right side up or inverted? Is the image real or virtual?*

3. Choose a distant object (a brick wall is useful for what follows). Look at the object through the telescope at the same time that you are looking at the object with the other eye unaided -- you can in this way measure the magnification directly. (Trying to look at two objects simultaneously is difficult but if you relax your eyes -- try not to stare -- you should be able to do it.)

Q: *Are the computed magnification and the measured magnification close to one another? How much % error? This is a hard measurement, even for a rough value.*

NOTE: THE TELESCOPE IS YOURS TO KEEP.

OPTIONAL: Snell's Law Measurements



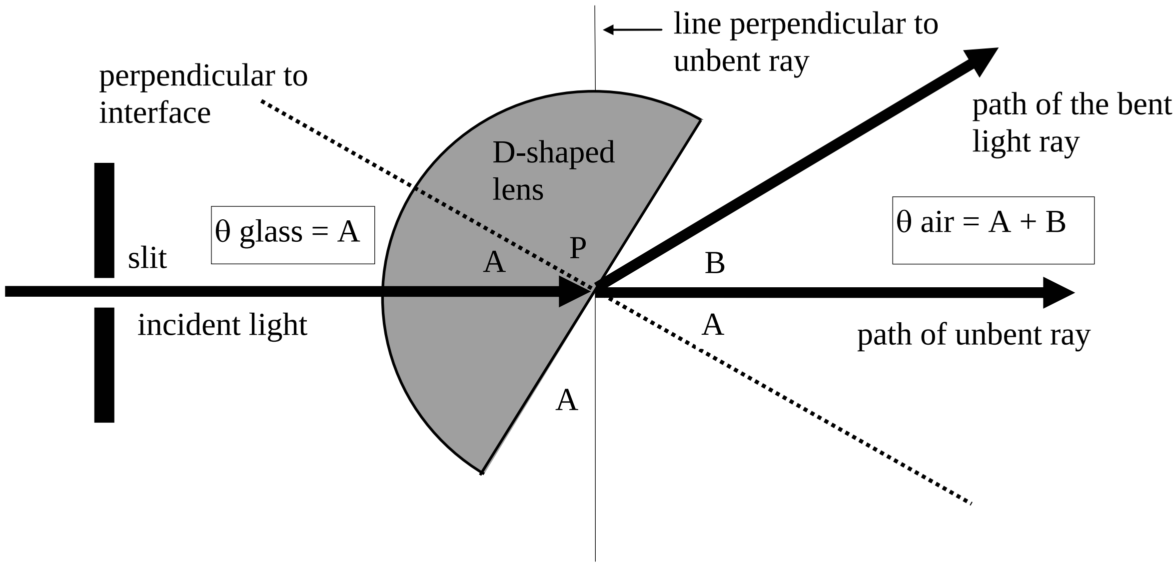
1. To produce one sharp non-diverging light ray, block off all but one slit. Position the light source, as shown in the diagram, and rotate the housing and light bulb until the filament of the bulb is vertical (as evidenced by sharp shadows).

2. Tape down the tracing paper, and using a straight edge, draw a long, straight line along the single light ray coming through the slit.

3. Using the protractor, carefully draw a line perpendicular to the ray about 10 cm from the slit.

4. Now place the D-shaped lens on the board, with its straight edge along your perpendicular line. Slide the lens along the line until the ray leaving the lens follows the line you drew along the original ray. This guarantees that the center of curvature (P) of the circular side of the lens lies on the original ray, and that the incident ray suffers no angular deviation at the curved surface. Using a sharp pencil, trace around the circular side of the lens. Before you move the lens, note the spacing of this line from the glass (due to the finite size of the pencil line).

(Note: If you rotate the lens around P so that P remains in its original position then the incident ray through the curved surface will always be perpendicular to the curved surface and no bending of the ray occurs there. All the bending you are measuring takes place when the ray passes <u>from</u> <u>glass</u> <u>to</u> <u>air</u> through the straight side.)



5. Rotate the lens approximately 5˚, (angle A on the diagram), carefully centering the lens by fitting the circular edge to your traced line. Draw a line along the straight edge of the lens, and label it (1); also make a mark and write an (1) on the paper in the center of the outgoing, bent ray about 10-15 cm from the lens.

6. Rotate the lens approximately another 5˚, and repeat step 5, this time labeling with a (2).

7. Continue turning the lens in 5˚ steps, labeling with successive numbers until you find that there is no emerging ray.

8. Draw lines along the paths of the outgoing rays (through your marks and the center of curvature, (P). Measure the angle B between the outgoing ray and the incident ray's direction, and the angle A between the line drawn along the straight edge of the lens and your perpendicular line. Do this for each of the positions of the lens.

9. Make a table showing the measured angles A, B, and the pair of computed angles $\theta_{glass} = A$, and $\theta_{air} = A + B$.

10. Plot $\sin\theta_{air}$ *vs.* $\sin\theta_{glass}$ with appropriate error bars that stem from the uncertainty in your reading the angles.

Q: *What is the value of the slope? What does the slope represent?*

Q: *What is the value of the index of refraction of the glass in the D-shaped lens? Give the estimated value (the best slope) and the limits on the error. The largest and smallest slopes consistent with the error bars.*

Q: *What kind of glass is the D-shaped lens made of, comparing to the table on p.2?*

Total Internal Reflection

1. As a check on your Snell's Law results, using your measurement of the glass' index of refraction, compute the critical angle $\theta_{critical}$ for total internal reflection within the glass. Then measure $\theta_{critical}$ -- it is the value of θ_{glass} for which θ_{air} is exactly 90^o.

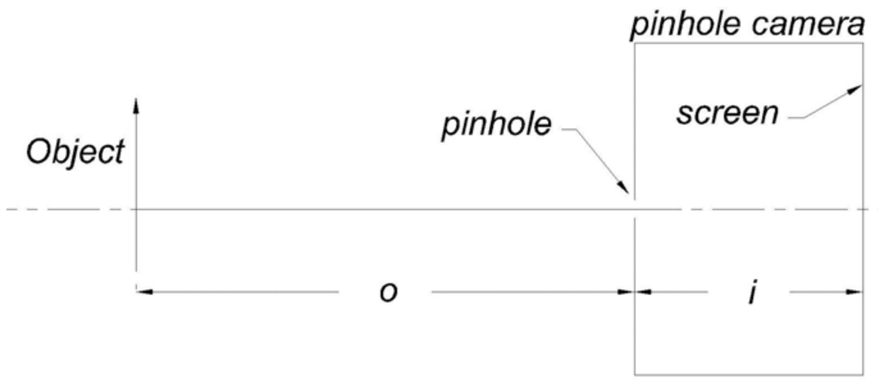
Q: *Do experiment and prediction agree?*

Q: *What happens when the angle of incidence* θ_{glass} *is greater the angle of reflection.*

PRINCETON UNIVERSITY **PHYSICS 104 LAB**
Physics Department **Week #9**
Name:______________________________ **Date/Time of Lab:_____________**

EXPERIMENT VIII PRELAB PROBLEM SET

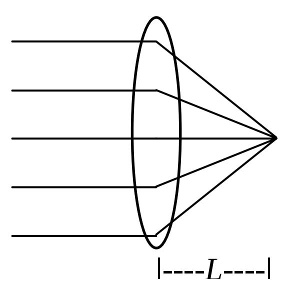
1. Sketch the rays that emanate from the two ends of the object to form the image on the screen of the pinhole camera shown in the figure below.



Is the image upright or inverted?

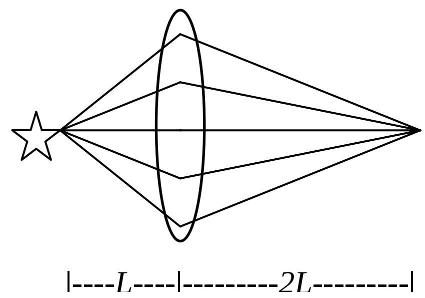
The pinhole camera does not have a lens, and is "in focus" for any choice of object distance *o*. If you wanted a brighter image, you could replace the pinhole by a lens. What focal length *f* would be required to produce an "in focus" image on the screen of an object a distance *o* from the lens?

2a. If parallel rays enter a lens of diameter *D* and converge to a point a distance *L* past the lens, what is the focal length *f* of the lens?

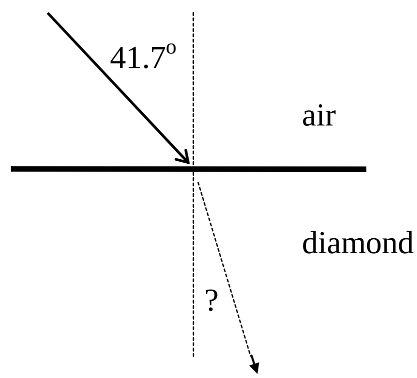


Continued on reverse.

2b. Rays emerge from a point on an object *L* to the left of a lens and converge back to a point *2L* to the right of it. What is the lens's focal length, *f*? What is the magnification *m* of the image, relative to the object?



3. Light traveling in air at an angle of 41.7^o with the perpendicular to the surface of a diamond, is bent on entering the diamond. At what angle does light travel through the diamond? Is the angle larger or smaller than the 30^o you would observe in water?



Repeat, changing 41.7 to 90 degrees. In other words, find the critical angle in diamond. Compare with the critical angle in water.